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The hydrochemistry and water quality of glacierized catchments in Central Asia: A review of the current status and anticipated change

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ABSTRACT

Study region: Glacierized catchments in Central Asia
Study focus: The literature on hydrochemistry and water quality was reviewed to identify gaps in knowledge required to understand and quantify the impacts of climate change and deglacierization.
New hydrological insights for the region: The main knowledge gap was the characterization of hydrochemistry and water quality along the elevation continuum from glaciers to arid plains. The chemical composition of snow and glacier ice are understood relatively well but the pathways of pollutants stored in glacier ice and released with melt into the aquatic systems are not researched. There is a lack of publications on the release of organic carbon following deglacierization and element leaching from the exposed substrate, permafrost and rock glaciers. Snow and glacial melt dilutes pollutants along the river channels, reducing concentrations and mostly ensuring the compliance with water quality standards including downstream locations. Poor surface water quality is associated with irrigation, the practice of soil washing, and discharge of the untreated sewage. There is a notable lack of information about the links between snow and glacier melt, aquifer recharge and groundwater quality and this is a major gap in knowledge affecting environmental and health protection. Better understanding and quantification of factors and processes controlling hydrochemistry and water quality is needed to adapt to the impacts of the imminent deglacierization.

1. Introduction

Recently, research has been done to understand and quantify the impact of glacier shrinkage on the global water resource in terms of water quantity, but the downstream impact on stream hydrochemistry and water quality remains poorly understood especially in Central Asia (CA) (Karthe et al., 2017; Milner et al., 2017; Rasul and Molden, 2019). The river catchments of CA are diverse and, with headwaters in the glacierized mountains of the Tien Shan, Pamir and Hindu Kush, the rivers flow from the mountain base across arid

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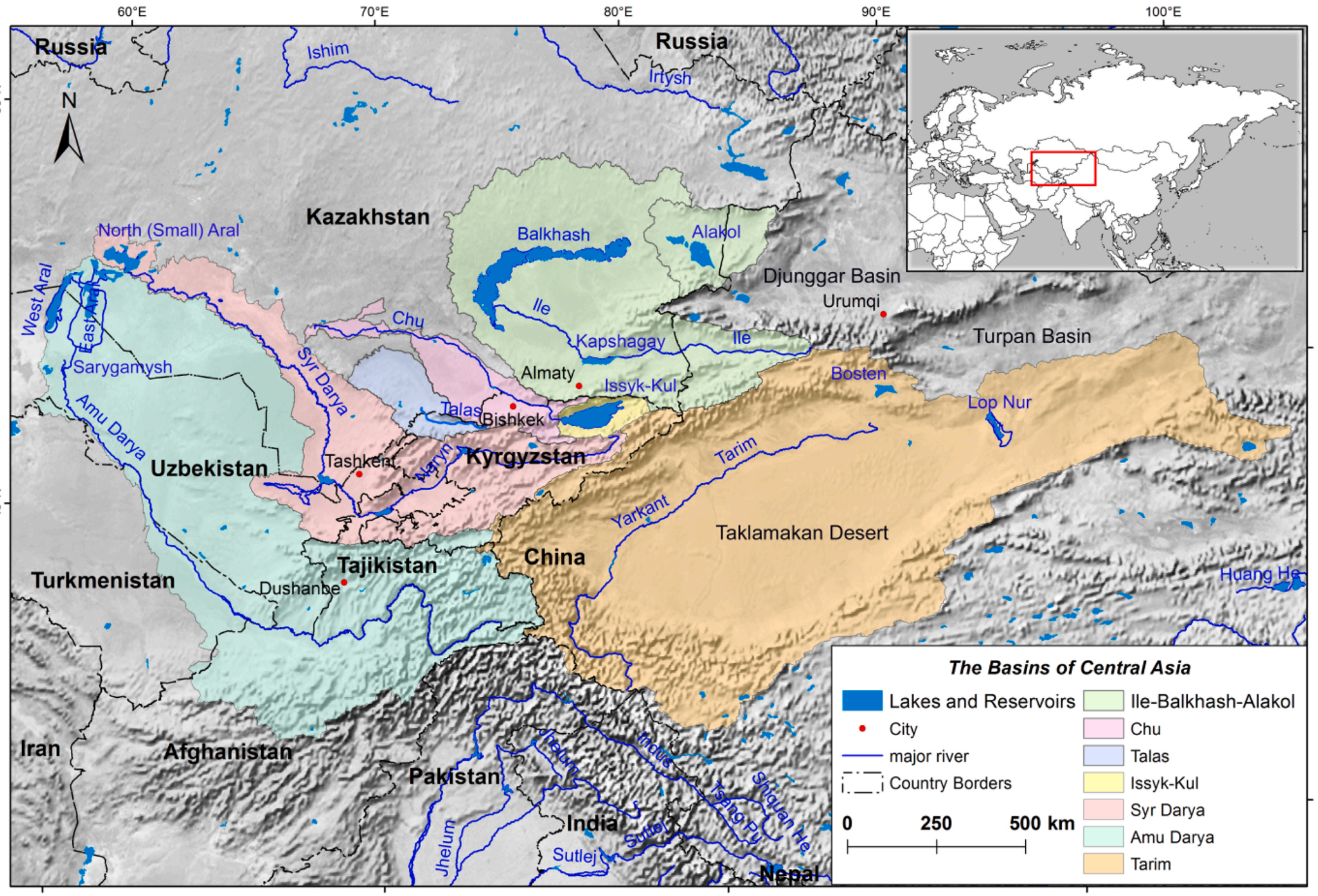

Fig. 1. The basins of Central Asia (WGS-84-UTM42 projection). Table S1 and Fig. S1 provide the main characteristics of the basins.
Data source: https://www.hydrosheds.org/ (Lehner et al., 2008; Lehner and Grill, 2013).

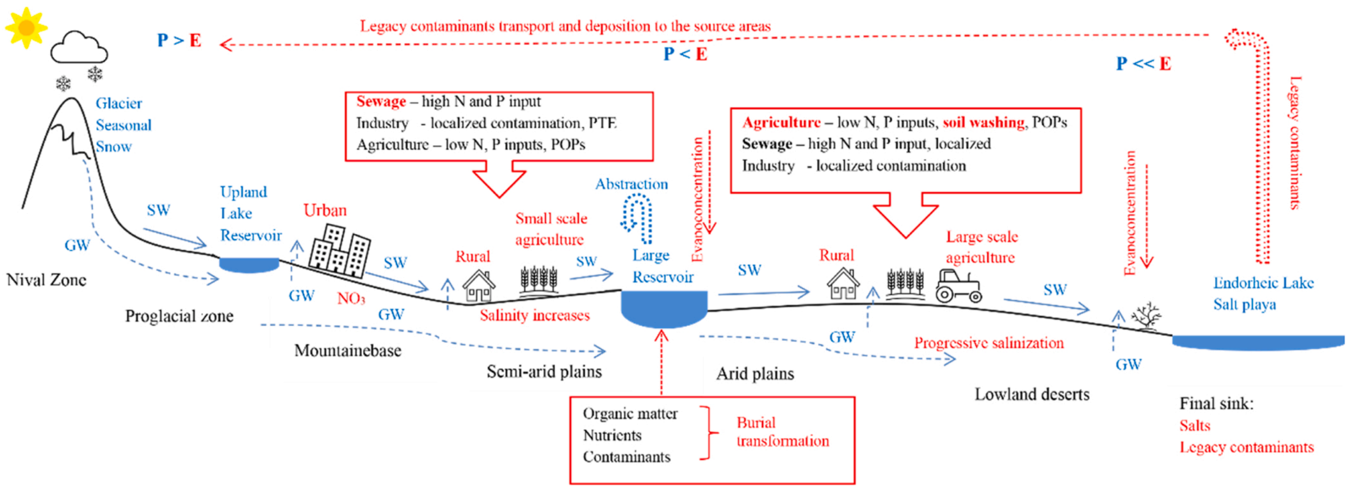

Fig. 2. A conceptualized movement of contaminants along the continuum from glacier-dominated mountains to the lowland deserts in Central Asia. The contaminants are mostly transported along the surface water network. The contaminants are partially returned to the mountains through precipitation and the transportation of desert dust which may be deposited in the same, or different, catchment.

plains and terminate in endorheic water bodies or in deserts. As all rivers are nourished by the mountain cryosphere, the flow is vulnerable to climate change (Chen et al., 2018; Kaser et al., 2010; Reyer et al., 2017; Sorg et al., 2012). To date, regional studies of potential climate-change impacts have focused on air temperature and precipitation (Unger-Shayesteh et al. 2013; Sorg et al. 2012; Mannig et al. 2013; Ozturk et al., 2017); glacier wastage (Kutuzov and Shahgedanova, 2009; Narama et al., 2010; Farinotti et al., 2015; Severskiy et al., 2016, Brun et al., 2018; Sorg et al., 2012; Mölg et al., 2018); water availability and proglacial zone hydrology (Shahgedanova et al., 2018, 2020; Kogutenko et al., 2019; Huss and Hock, 2018; Immerzeel et al., 2012; Hagg et al., 2013; Kriegel et al., 2013; Duethmann et al., 2015; Unger-Shayesteh et al., 2013), the water storage of endorheic lakes (Yapiyev et al., 2017; Liu et al., 2019; Bai et al., 2011), and transboundary water management (Menga, 2017; Wegerich, 2008; Wegerich et al., 2015; Zhupankhan et al., 2017). More recently, impacts of changes in land-use and land-cover, and agricultural water demand on water resources were considered (Barrett et al., 2017; Hamidov et al., 2020; Z. Li et al., 2020a; Qi et al., 2019; Zhang and Ren, 2017; Zhou et al., 2015). Few studies, however, focused on the effects of climate change and continuing de-glaciation on hydrochemistry and water quality (HWQ) although these impacts were highlighted as important by the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Hock et al., 2019).

Changes in mountain hydrochemistry relate to wider environmental change, in particular the deposition of pollutants transported in the atmosphere and those leaching from the substrate, as glaciers and permafrost melt. The importance of water quality reflects a basic need for clean water for human consumption and health of aquatic and terrestrial ecosystems, as specified by the United Nations Sustainable Development Goals (SDG) (United Nations, 2015). The SDG 6 *'Clean water and sanitation for all'* is one of the most relevant for CA. Here, the montane ecosystems are sensitized to small changes in climate because they affect the main source of water – the cryosphere (Kaser et al., 2010; Unger-Shayesteh et al., 2013). The region is home to approximately 72 million people with low income and a high proportion of agriculture in regional economies (Nations, 2019; Balance and Pant, 2003). The large-scale agricultural production relies on irrigation which consumes vast amounts of water and returns contaminants to the environment (Micklin, 2007; Balance and Pant, 2003). A better understanding of the links between the glacierized mountains and the arid lowlands connected by rivers is required to improve integrated catchment-management and to help adapt to future changes in climate, cryosphere, and land use and management.

The aim of this paper is to develop and report the current understanding of the HWQ from source to sink along the mountain to lowland continuum in CA. To achieve this, journal articles and reports, written in a range of languages, have been synthesized. Particular attention was given to the quality of the data in the assessed publications. We selected studies based on longer-term monitoring and shorter-term studies that provided full descriptions of the data collection and analysis thereby enabling a critical evaluation of data quality. Not all local studies comply with these criteria and those which do not, have not been included in the review. Those studies, which have been included, use different ways of reporting measurements. In order to make them comparable, nutrient concentrations were converted: NO_3^- to NO_3^--N and PO_4^{3-} to PO_4-P. The following conversion coefficients were applied: NO_3^- (ion form) was divided by 4.427 to convert to N and PO_4^{3-} (ion form) is multiplied by 0.3261 to convert to P (https://support.hach.com/).

Following this synthesis, we reflect on the water quality issues in the region, and what the next research and management steps might be to help protect and improve the quality of the CA water resource. The emphasis is on understanding the controls on HWQ in five key transboundary, glacierized catchments located in south-eastern Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and north-western China all of which drain glaciers and terminate in endorheic lakes and deserts (Fig. 1; Table S1). We exclude Turkmenistan and central and northern Kazakhstan because these regions have different river regimes and discussion of other regions of High Mountain Asia because of the different socio-economic characteristics. We define '*hydrochemistry*' as the chemical composition of water resulting from natural physical, chemical and biological processes, and use the term '*water quality*' to characterize the state of water properties and constituents evaluated against standards and criteria of suitability for human use and ecosystem function. The review begins with a consideration of the chemical composition of, and contaminants found in, snow and glacier ice. The observed impacts of glacier retreat through weathering of the exposed bedrock and release of legacy pollutants on stream HWQ are considered followed by consideration of HWQ at the mountain base and on the plains. The paper concludes with a perspective on the science needed to address the most pressing knowledge gaps, and recommends directions for research and management.

2. The study region

The general aspects of the environment of CA which affect HWQ (e.g., geology, climate, and soils) are described in detail elsewhere (Shahgedanova, 2002a; see also Table S1 and Fig. S1) with key aspects drawn into the discussion in this paper. Across the region, seasonal snow and glacier melt are the main components of river runoff. In the Amu Darya and Syr Darya, these components account for approximately 70% and 80% of annual runoff, respectively. Snow melt dominates accounting for 89% and 65% of the total melt component in the two catchments (Djumaboev et al., 2019). River flow has a strong seasonal cycle with maximum in summer due to the snow melt in May-June and glacier ice melt in July-August (Fig. S2) although the peak may be less pronounced in the lower reaches because of the water abstraction (Grill et al., 2019; Immerzeel et al., 2012). Most rivers of CA are managed.

Major settlements and industrial activity are concentrated at the mountain base and large-scale arable agriculture extends onto the arid plains (Fig. 2). Arable land accounts for 5–10% of the basin areas (Table S1) and irrigation is the main water consumer especially in Uzbekistan where water withdrawal exceed that in other post-Soviet CA countries, discussed in this paper, by an order of magnitude (Balance and Pant, 2003). Wheat is grown to help ensure national food security in each catchment and nation. The main cash crop is cotton, particularly in the Amu Darya, Syr Darya and Tarim catchments where fertilizer and pesticide use is common (Crosa et al., 2006a; Snow et al., 2020; Törnqvist et al., 2011). Tang et al. (2021) estimated that Kazakhstan and Uzbekistan are among the top 10 countries that are at the highest risk from pesticide pollution globally and the threat is equally high in the Tarim basin. The application of other fertilizers declined in the region in the 1990 s but began to increase again in the 2010 s exceeding the 1990 s level in Uzbekistan (Fig. S3). Across post-Soviet CA, irrigation systems are basic (predominantly furrow) and not well maintained (Barrett et al., 2017; Xenarios et al., 2019). Water is delivered by a system of open canals from rivers but in the vicinity of large cities, treated water is used (Mamadiyarov et al., 2015). On the plains of CA, soils are naturally saline due to evapoconcentration (Yapiyev et al., 2018; Zamotaev, 2002). Irrigation enhances salinization which affects approximately 47% of irrigated land across post-Soviet CA (Hamidov et al., 2016). To mitigate this problem, the practice of soil washing is widely applied. The returned water is accumulated in collectors and discharged into the river systems (Groll et al., 2015; Olsson et al., 2013). Natural lakes are also used as collectors of returned water (Orlovsky et al., 2012; Severskiy, 2004). In the post-Soviet CA, the extent of irrigated land peaked in the 1970–1980 s (Thevs et al., 2017; Xenarios et al., 2019). In the Chinese sector of the Ile basin, irrigated land nearly doubled between the 1970 s and 2010 s (Thevs et al., 2017) and increased by a factor of three in the hyper-arid Tarim basin since the 1990 s with a similar increase in water consumption (Li et al., 2020b; Thevs, 2011).

Heavy industry, especially mining and metallurgy, have been important sectors of the Kazakhstan and Uzbekistan economies since the 1940 s. More recently, industrial-scale gold mining began in the Akshiirak massif in Kyrgyzstan all but destroying the Kumtor glacier (Evans et al., 2015) and causing numerous protests against environmental degradation (Horrocks-Taylor, 2018).

All the major CA basins are transboundary (Fig. 1, Table S1). Water sharing and management arrangements are regulated by bilateral or international agreements and institutions. There are positive examples of collaboration on water sharing and monitoring and managing water quality (e.g., between Kazakhstan and Kyrgyzstan in the Chu-Talas basin; Chu-Talas Commission, 2018). However, more often such arrangements are not mutually beneficial (Bernauer and Siegfried, 2012; Wegerich et al., 2015; Zhupankhan et al., 2017; Menga, 2017). This leads to either an observed or anticipated deterioration in water quality due to transboundary pollutant transfers and the negative effect of increasing water withdrawal in the upstream countries causing deterioration of water quality downstream. An example is the Ile River, flowing between China and Kazakhstan (Stone, 2012; Thevs et al., 2017; Zhupankhan et al., 2017).

3. Rivers as pathways from glaciers to deserts

3.1. The hydrochemistry of glacier snow and ice

The solute chemistry of glacier snow and ice has been studied in CA since the 1960 s (Blagoobrazov, 1969; Blinova, 1962; Fedulov, 1971; Kamalov, 1975; Vilesov and Shabanov, 1971; Vilesov et al. 1980). This knowledge has been significantly enhanced by studies of ice cores obtained from high-elevation glaciers providing a pollution history dating back to the 1900 s (Grigholm et al., 2016; Kreutz and Sholkovitz, 2000; Wake et al., 1990; Zhao et al., 2011). In all high-elevation regions, the composition of snow and ice depends on atmospheric deposition (Kang et al., 2019). The CA glaciers are located in proximity to sources of desert dust, which typically form on abandoned agricultural land or dry lake and river beds (Nobakht et al., 2021). The glaciers are also close to large cities and industrial centres with poor air quality and high Black Carbon (BC) emissions (Shahgedanova, 2002b; Shahgedanova and Burt, 1994) as well as close to the extensive agricultural areas where fertilizers, pesticides and herbicides are used. The mineral dust and BC deposited on snow and glaciers are the light-absorbing impurities (LAI) which enhance snow and ice melt (Painter et al., 2012). They are also transport vectors for other pollutants (Kreutz and Sholkovitz, 2000; Aizen et al., 2004; Schmale et al., 2017). Pollutants accumulated in the glacial ice and snowpack have the potential to be released decades or centuries later (hence the term *legacy pollutants* is used here) with potential adverse impacts on the headwater streams which are typically characterized by low solute concentrations and, therefore, may be highly sensitive to change.

There is general agreement that the deposition of mineral dust defines the ionic composition of snow and ice in CA (Kang et al., 2019; Schmale et al., 2017; Kreutz and Sholkovitz, 2000, Zhao et al., 2011). The early studies of snow and ice chemistry of the Tuyuksy and Fedchenko glaciers in the Ile Alatau, northern Tien Shan and Pamir, respectively, showed that the chemistry was dominated by HCO_3^- and Ca^{2+} relative to SO_4^{2-}, Mg^{2+} and Cl^- due to the deposition of the calcite dust (Blinova, 1962). The predominance of Ca^{2+} and HCO_3^- was reported for the Inylchek glacier in the central Tien Shan (Aizen et al., 2004; Kreutz and Sholkovitz, 2000) and for the Abramov glacier in the Pamir-Alay (Hinkley et al., 1997) albeit at lower concentrations than in the Ile Alatau because of the higher elevation and more remote locations of these glaciers. Similarly in the eastern Tien Shan, the ionic composition of snow is enriched with crustal proxies such as Ca^{2+} and Mg^{2+} (Dong et al., 2009; Wake et al., 1990; You et al., 2015; Zhang et al., 2016). However, Na^+ concentrations in snow are high, and a significant correlation of Na^+ with Mg^{2+} and Cl^- suggests that the regional saline lakes are also a source of the deposited material (Dong et al., 2009).

Debate continues about the relative importance of anthropogenic and natural sources of sulphate. High SO_4^{2-} concentrations in the snowpack in the eastern Tien Shan have been attributed to industrial and urban sources rather than the gypsum-rich desert dust (Wake et al., 1990; Zhang et al., 2016) because there is a strong correlation between concentrations of sulphate, particulate matter and unsaturated hydrocarbons, all produced by coal burning (Lee et al., 2003). In contrast, in the same region, high sulphate concentrations in precipitation were associated with desert dust (Williams et al., 1992). Similarly high sulphate concentrations in snow in the Kunnes headwaters in the Balkhash-Alakol basin (Fig. 1) and on the Inylchek glacier were associated with desert soils, evaporate gypsum deposits and the dry lakes (Kreutz and Sholkovitz, 2000; Fengqing et al., 2002). Elevated snow nitrate (NO_3^-) and ammonium (NH_4^+) concentrations were measured on glaciers in the eastern Tien Shan, located close to populated areas (Zhang et al., 2016). The summer NH_4^+ concentration peaks in ice cores from the Inylchek glacier, and from a remote Muztaga glacier in the eastern Pamir, were reported and related to agricultural activities, particularly to fertilizer application (Kreutz and Sholkovitz, 2000; Aizen et al., 2004;

Zhao et al., 2011). An increase in SO_4^{2-} and NO_3^- in glacier ice, observed since the 1970 s, has been attributed to growing anthropogenic emissions in the Soviet Union in the 1970 s and in China in the 1990 s (Zhao et al., 2011).

Trace metals have been found in snow and ice. The trace elements (Mn, Ti, Sn, Cs) in dust deposited on the snowpack in the Ile Alatau near the city of Almaty (Fig. 1) (Glazovsky and Glazovsky, 1982) and Al and Fe in the Ürümqi Glacier N1 in the eastern Tien Shan (Zhongqin et al., 2007) are thought of lithogenic origin. Concentrations of other trace elements including Pb, Ni, Sn, Cr, Cd, Cu and Zn were measured in these and other glaciers and attributed to anthropogenic sources including industrial production and the use of leaded petrol. The Pb concentrations (averaging 2.4 ng g^{-1}), Cd and Zn measured in the Ürümqi Glacier N1 exceeded concentrations reported for the Himalayas and the European Alps by approximately a factor of 40 (Li et al., 2007). An increase in Cd, Sb, Bi, Tl, Sn and Pb concentrations has been observed since the 1950 s in the Miaoergou glacier in the eastern Tien Shan (Liu et al., 2011). Both glaciers are in relative proximity to urban sources. However, in the remote Muztaga glacier, Sb, Bi and Pb concentrations increased too between the 1950–1970 s and the 1990 s corresponding with growing industrial production in the Soviet Union and China, respectively (Li et al., 2006). The ice core measurements from the Inylchek glacier, extending from 1908 to 1995, also showed that Pb, Cd and Cu concentrations increased between the 1950 s and 1980 s in line with industrial growth in Kazakhstan and Uzbekistan. Following a decline in the early 1990 s, the concentrations began to increase again reflecting industrial growth in China and a widespread use of fertilizers, herbicides and fungicides, which contain Cu, in the Tarim basin (Grigholm et al., 2016).

The chemical composition of glacial melt depends upon natural factors including lithology, glacier morphology, climate, drainage pathways and biological activity (Tranter, 2003). The legacy pollutants, which are deposited on glaciers and preserved in ice, enter the hydrological system as glaciers retreat and can contaminate the aquatic systems if toxic metals (e.g. mercury) or persistent organic pollutants (POPs) are released (Bogdal et al., 2009). In melting glaciers, the leaching process is complex because meltwater percolation can be stopped by layers of superimposed ice leading to the preservation of ions which are removed by runoff only during intensive melt (Lee et al., 2003). There is evidence of water contamination by legacy pollutants in the European Alps (Bettinetti et al., 2008; Bogdal et al., 2009), Tibet (Chen et al., 2019), and Alaska (Miner et al., 2019), but there are very few studies in CA with which to draw comparison. Measurements at the Ürümqi Glacier N1 showed that trace metal concentrations in snow increased in winter with a secondary maximum in spring, when dust deposition peaks. The trace metals were leached from the melting snowpack in July and August (Li et al., 2007). Concentrations of Pb and Cd remained high for a relatively short period of time, but their rapid removal aided by elution implied that they were transported to the mountain streams with the onset of seasonal melt potentially affecting aquatic ecosystems. The removal of other elements form the melting snow and ice was studied to a limited extent too. You et al. (2015) showed that of all ions, NO_3^- was the most mobile followed by SO_4^{2-}, while other species including NH_4^+ had a higher residence time.

Overall, there is a good understanding of soluble chemistry of snow and ice, growing information about trace metals, but little data on how these chemicals enter the hydrological system and what impact they make on river HWQ. There is a notable lack of data on other pollutants such as POPs or emergent contaminants (e.g. microplastics).

3.2. *Stream water hydrochemistry: from the glacial headwaters to the mountain base*

The spatial variability of ion concentrations in the glacierized headwaters is primarily related to the predominant lithology. The relative contributions of snow and glacier melt to runoff are important but second-order factors (Dobroumov, 1973; Tranter, 2003; Anderson, 2007). The ion concentrations in the stream water at high elevations are usually low because of the low weathering rates of the resistant lithologies which form the mountain chains. The order of anions and cations is a function of the predominant lithology, weathering kinetics, and transport mechanisms. Calcium is the predominant cation in glacial melt due to its rapid dissolution kinetics, and carbonate dissolution and sulfide oxidation are the most typical chemical weathering mechanisms (Tranter et al., 2002; Tranter, 2003). Bicarbonates are often the predominant anions where basic rocks are present (Anderson, 2007). In the glacial headwater catchments of CA the orders (in terms of concentration) are: $HCO_3^- > SO_4^{2-} >> Cl^-$ and $Ca^{2+} > Mg^{2+} >> Na^+ > K^+$. These orders are observed in the Kishi and Ulken Almaty in Kazakhstan (Romanova et al., 2016), Chu, Talas (Dobroumov, 1973; Ma et al., 2020) and Naryn (Ma et al., 2019) rivers in Kyrgyzstan, and the Kafarnihon in Tajikistan (Finaev et al., 2017). Although the carbonate lithology dominates in the upstream Ile catchment in China, evaporate dissolution and carbonate weathering have an approximately equal effect (c. 40%) on the river water ionic composition (Zhu et al., 2013). In contrast, in the hyper-arid Tarim basin, evaporate dissolution dominates over carbonate weathering. Here, Na^+ and Cl^-, sourced from halite dissolution, and SO_4^{2-} can be high, even in the headwaters (Xiao et al., 2012).

In the glacierized catchments, weathering of suspended and dissolved solids is highest at the peak of meltwater production. The large runoff volumes ensure that glacial meltwater is usually very diluted and concentrations of chemicals are low. However, high flow (see Fig. S2) enables transportation of large loads and fluxes of solutes and sediment during the glacier melt period (Tranter, 2003). The literature on seasonal variations in the ion fluxes in stream water in CA is limited but in agreement: the fluxes are related to seasonal melt and the associated variations in discharge. In the catchments, where the contribution of glacier ice melt to runoff is high, ion discharge peaks in summer in line with the maximum in river discharge (Fig. S2). In the larger catchments, where glacierization is lower and snow melt dominates, a spring peak in ion discharge is typical suggesting a diffuse input of weathered material. For example, in the Kishi Almaty and Ulken Almaty rivers, which drain small catchments with high glacierization in the Ile Alatau (Shahgedanova et al., 2018), approximately 50% and 30% of the total annual solute flux are transported in summer and autumn, respectively, with a smaller proportion accounted for by the snow melt contribution in spring (Romanova et al., 2016). The ion flux in the middle courses of the River Talas peaks in June. In the River Chu, which has much larger catchment where snow melt dominates, the ion flux peaks in spring (60%) followed by winter (25%), summer (10%) and autumn (5%) (Dobroumov, 1973).

Despite the dominance of snow melt in runoff, glacier melt affects the stream hydrochemistry of the headwater catchments in specific ways. Glacial runoff is rich in fine sediment, known as glacier flour, which gives the runoff its clouded appearance. Glaciers are important exporters of dissolved organic carbon (DOC) and nitrogen (Milner et al., 2017). Mountain glaciers, especially those in the middle and low latitudes, are known to store and release organic carbon to streams and the export is expected to increase as glaciers melt and retreat (Hood et al., 2015). Carbon is leached from the till and from englacial and supraglacial ecosystems supported by cryoconite (Cook et al., 2016). Glacial melt keeps the downstream water temperature low which in turn reduces primary productivity and slows organic matter decay (Kneib et al., 2020). These effects were studied in the European Alps, North America and the Arctic (Anderson, 2007; Tranter, 2003) but there is little data on nitrogen and carbon cycling in CA. Recent studies published for the Chinese Tien Shan (Gao et al., 2020; Li et al., 2018; Liu et al., 2016) on carbon export show that area-weighted carbon fluxes are higher than in Alaska and European Alps (Li et al., 2018) and exceed previous estimates (Hood et al., 2015).

The melt of permafrost and sub-moraine and rock-glacier ice contributes to an increase in ion flux (Colombo et al., 2018). In other glacierized regions, solute leaching in permafrost areas has been observed to have two seasonal peaks: the first when acidic snowmelt flushes soil horizons and a second in late summer-early autumn when melt is released from deeper mineralized horizons as the ground warms (Colombo et al., 2018). Melting permafrost can increase inorganic N, P and Si export, as well as that of major ions (e.g. Ca^{2+}, Mg^{2+}, SO_4^{2-}) and trace elements (e.g. Ni, Mn, Al, Hg, Pb) (Colombo et al., 2018) and it has been suggested that Total Dissolved Solids (TDS) concentrations in the runoff from rock glaciers are higher than in glacial runoff. This is because the extensive mineral surface area-ice contact in rock glaciers promotes chemical weathering which, in turn, leads to solute-enrichment of water contained within and downstream rock glaciers (Jones et al., 2019). However, there are insufficient studies to draw firm conclusions anywhere and there are no studies of impacts of permafrost and rock glacier melt on hydrochemistry in CA.

Although industrial activities are usually limited at high elevations, gold mining at the Kumtor glacier in the Akshiirak massif, Kyrgyzstan gained notoriety (Horrocks-Taylor, 2018). Its impacts on the local surface water and HWQ of the river Naryn were found to increase concentrations of iron, aluminium, lead, and manganese in the local surface waters during the warm season when mining activities intensify (Abduvaliyev and Khudaybergenova, 2016). However, concentrations of pollutants in the Naryn itself remain low due to the high summer runoff and melt water dilution.

Currently, there are very few HWQ measurements in the mountains. There is knowledge about fluxes of major ions in river channels from the studies conducted in the 1970–1980 s. However, there is little or no information about changes in HWQ related to glacier melt and retreat (e.g. release of legacy pollutants), melt of rock glaciers and permafrost (notably in terms of carbon fluxes) and interactions between meltwater and groundwater HWQ.

3.3. *Stream water hydrochemistry: from the foothills to the lowland plains*

There is a consensus in the literature that in all studied catchments in CA, ion concentrations in stream water increase along the mountain to plains stream-continuum. The number of studies, whilst detailed in their analyses, is low and most are short-term. Moving downstream, inputs from industrial, urban and agricultural sources increase (Fig. 2) as does evaporation (Fig. S2d). In the lowlands, aridity and sparse vegetation lead to the high evaporation from soil and open water driving evapoconcentration (Yapiyev et al., 2017; Fig. S1). Thus the salinity of surface and groundwater, and land salinization are the major problems in CA (Hamidov et al., 2016).

Overall, the river water quality in CA is mostly within national and international standards (Table S2) but there are localised instances of poor water quality. The water pollution hot spots are attributed to the return of the agricultural wastewater, the practice of soil washing especially in the Aral Sea Basin and Chu-Talas catchment, and to urban and industrial sources (Chu-Talas Commission, 2018; Crosa et al., 2006a, 2006b; Groll et al., 2015). For example, the River Zerafshan flows for 870 km through predominantly natural landscapes in Tajikistan and then through farmland and industrial areas in Uzbekistan, where approximately 60% of the flow is used for irrigation ultimately limiting flow into the Amu Darya (Groll et al., 2015). Within the Zerafshan, the TDS concentrations range between 160 and 190 mg l^{-1} in the Tajik sector, increase to 240 mg l^{-1} at the Uzbek border and then to 1800 mg l^{-1} at the outflow, significantly exceeding national standards and the WHO threshold of water potability (Table S2; Groll et al., 2015, Olsson et al., 2013). Similarly, in the River Chu whose watercourse exceeds 1200 km, TDS concentrations increase from 30 mg l^{-1} in the mountains, to 900 mg l^{-1} in the middle course, and to 2500 mg l^{-1} in the lower reaches in the desert (Dobroumov, 1973). The return of irrigation water to the River Ile in the Balkhash-Alakol basin and its tributaries significantly increases the solute concentrations (Aidarov, 2006). Some crops (e.g. many vegetables and fruits) are sensitive to water salinity and have reduced yields when irrigated with water high in TDS. The irrigation water requirements for some crops for TDS may be lower than a common threshold for drinking water of 1 g l^{-1} (Ayers and Westcot, 1985).

The prevalence of sodium and sulphate in the stream water is typical of CA plains due to high evaporation (Fig. S2d). However, high sodium and sulphate concentrations in the Zerafshan are attributed to industrial and urban sources, and high chloride to the inflow of the returned irrigation water (Crosa et al., 2006b; Olsson et al., 2012, 2013). Very high nitrate and phosphate concentrations reaching 56 mg N l^{-1} and 57 mg P l^{-1}, respectively, were reported in the irrigation water returned to the Zerafshan (here and thereafter, values have been converted from NO_3^- and PO_4^{3-} are used; see Introduction for conversion factors). However, nitrate concentrations in its stream water were predominantly in the range of 5.65 – 11.30 mg NO^-_3-N l^{-1} only occasionally exceeding national and WHO thresholds (Groll et al., 2015; Table S2).

Since the 1990 s, there is evidence of some water quality improvements evidenced by declines in chloride, calcium, nitrate and phosphorous concentrations and in Chemical Oxygen Demand (COD) in the Zerafshan (Groll et al., 2015; Olsson et al., 2013), most likely due to decline of industrial and agricultural production and use of fertilizers in the last decade of the 1990 s especially in Tajikistan (Fig. S3). However, this observation is not ubiquitous in CA. In the Kazakhstani part of the Ile catchment, whilst nitrate concentrations are low (0.23–0.45 mg N l^{-1}), detectible concentrations of pesticides in returned irrigation water have been reported

(Aidarov, 2006). In the lower reaches of the Talas, (downstream of the town of Taraz), nitrate concentrations have increased from 0.01 to 1.13 mg NO_3^--N l^{-1} in the 1960–70 s to 1.58–2.94 mg NO_3^--N l^{-1} in 2000–2014 whilst phosphate concentrations did not exceed 0.12 P mg l^{-1} in the 1960–70 s with no data reported for 2000–2014 (Dobroumov, 1973; Chu-Talas Commission, 2018). In the Chu-Talas Basin, nitrate concentrations in river water have also increased since the 1960 s, though lower Biological Oxygen Demand (BOD) concentrations were reported suggesting an increase in fertiliser leaching and better sewage treatment (*ibid.*). It should be noted, however, that the data were generated by two measurement campaigns and inhomogeneity in the data can affect the comparison.

In the Amu Darya, phosphorus concentrations are higher in small towns upstream of the major agricultural areas, and are inversely related to discharge (Lobanova and Didovets, 2019). This suggests point source contamination with sewage. Conversely, there is a positive correlation between nitrate concentrations and flow at the same locations suggesting diffuse nitrogen inputs. The phosphorus concentrations in the Kazakhstani downstream section of the Syr Darya did not change significantly between the 1970 s and 2000 s (Amirgaliyev, 2007) with concentrations ranging from 0.001 to 0.009 mg P l^{-1} in the 1971–1978 period and from 0.002 to 0.012 mg P l^{-1} in the 1993–2000 period. Nitrate was reported to range from 0.07 to 4.1 mg N l^{-1} and from 2.3 to 6.0 mg N l^{-1} in the same periods. These concentrations are within the national water quality standards (Table S2) though there has been a gradual increase in nitrate and ammonium after 2000 following an increase in agricultural production (Amirgaliyev, 2007), (Fig. S3). Downstream from the urban and industrial centres such as Samarkand, Kattakurgan and Navoi in Uzbekistan, where water used for municipal and industrial needs is discharged, water in the Zerafshan is characterised by high COD indicating large amounts of organic waste consuming oxygen and increasing phosphorous inputs (Groll et al., 2015). In the Kazakhstani sector of the Balkhash-Alakol basin, municipal sources are important too as only approximately 20% of sewage is treated biologically (Aidarov, 2006). Municipal wastewater discharge in urban areas is considered as a major source of pollution in the Chu catchment together with irrigation and soil washing (Chu-Talas Commission, 2018). In contrast, the contribution of municipal sources to TDS in the Amu Darya water was insignificant relative to the impacts of irrigation activities (Crosa et al., 2006a).

Studies that examined seasonal variations in TDS, nitrate and phosphate concentrations report a minimum in summer and a maximum in January to March in the Zerafshan (Groll et al., 2015; Olsson et al., 2013) and a primary maximum in March-April and a secondary maximum in October-November in the Amu Darya and its other tributaries (Crosa et al. 2006a; Lobanova and Didovets, 2019). The extended periods of the elevated TDS concentrations observed in the lower reaches of these rivers were attributed to the return of the irrigation wastewater and to soil washing. Importantly, the low TDS concentrations, correlating with the summer peak in river discharge caused by the snow and ice melt in the headwaters, were reported for the lower reaches of the Amu Darya showing that the dilution effect extends along the course of this major CA river far from the glaciers (Crosa et al., 2006a). The TDS concentrations increased in years with low discharge, while in years of high discharge, caused by the enhanced melt in warmer summers, water quality improved through dilution in the Talas, Chu and Syr Darya (Amirgaliyev, 2007; Chu-Talas Commission, 2018; Lobanova and Didovets, 2019). The influence of the meltwater on the stream water quality in the lower reaches of the main channels was evident as well as the difference between the tributaries that do and do not drain glaciers.

To conclude, water quality remains mostly within national and WHO standards in the main river channels due to the dilution effect associated with snow and glacier melt. There are hot spots of pollution associated with soil washing, discharge of irrigation water, sewage and water used in industrial production although the latter is discussed to a lesser extent in literature. Perhaps the main identified gap is a lack of long-term measurements made using consistent methods supported by more frequent sampling to characterise extreme low and high concentrations and the corresponding flow conditions.

3.4. Lakes and reservoirs as buffers of water quality extremes and contaminant sinks

The HWQ of six major lakes is discussed in literature including the high-elevation lakes Issyk-Kul and Bosten and the low-elevation Aral Sea and lakes Balkhash, Alakol, and Sarygamysh, but not for the smaller lakes (Fig. 1). Artificial reservoirs are built both in the mountains for hydropower and on the plains to supply water for irrigation and municipal use. The HWQ of the former is not examined in the published literature. The information about the latter is limited although the lowland reservoirs are often used as fisheries and their water quality is subject to regulation. In general, reservoirs reduce both seasonal and interannual variability in ion concentrations (Burlibayev et al., 2007). For example, following the filling of the Kapshagay reservoir, Kazakhstan, in the 1980 s, the annual variation in TDS concentrations in the downstream section of the Ile declined from approximately 400 mg l^{-1} to 150 mg l^{-1}, and TDS concentrations became almost independent of the runoff (Burlibayev et al., 2007).

The Issyk-Kul is the largest high-altitude lake in CA (Fig. 1; Table S3) and the most researched. Both arable and pastoral farming are practiced in its catchment and, importantly, the Issyk-Kul is a major centre for recreation and tourism (Koronkevich, 2002). Glacial runoff accounts for 14% of the total runoff received by the Issyk-Kul (Sorg et al., 2012), however, rivers in the Issyk-Kul basin have higher TDS concentrations than the glacier-fed rivers elsewhere because of a considerable proportion of subsurface flow (Dobroumov, 1973; Lyons et al., 2001; Asankulov et al., 2019). During the high-flow period, TDS ranges between 75 and 200 mg l^{-1}, increasing to 100–300 mg l^{-1} in winter (Dobroumov, 1973). The Issyk-Kul itself is brackish with salinity of approximately 6 g l^{-1} (Asankulov et al., 2019; Lyons et al., 2001). The river chemistry is dominated by Ca^{2+} and HCO_3^- but the concentrations are low in the lake water which is strongly influenced by evapoconcentration and calcium precipitation from the water column saturated with carbonates (Asankulov et al., 2019; Kawabata et al., 2014; Lyons et al., 2001; Savvaitova and Petr, 1992). The ion composition of the Issyk-Kul water is similar to that of the Aral and Caspian Seas despite its high elevation. This is because all three lakes accumulate salts in a similar way through evapoconcentration, the groundwater inputs are high (approximately 40% of the inflow to the Issyk-Kul), the groundwater seepage is low and there is no surface outflow. The Issyk-Kul is oligotrophic and the vertical distribution of nutrients including nitrate, phosphate,

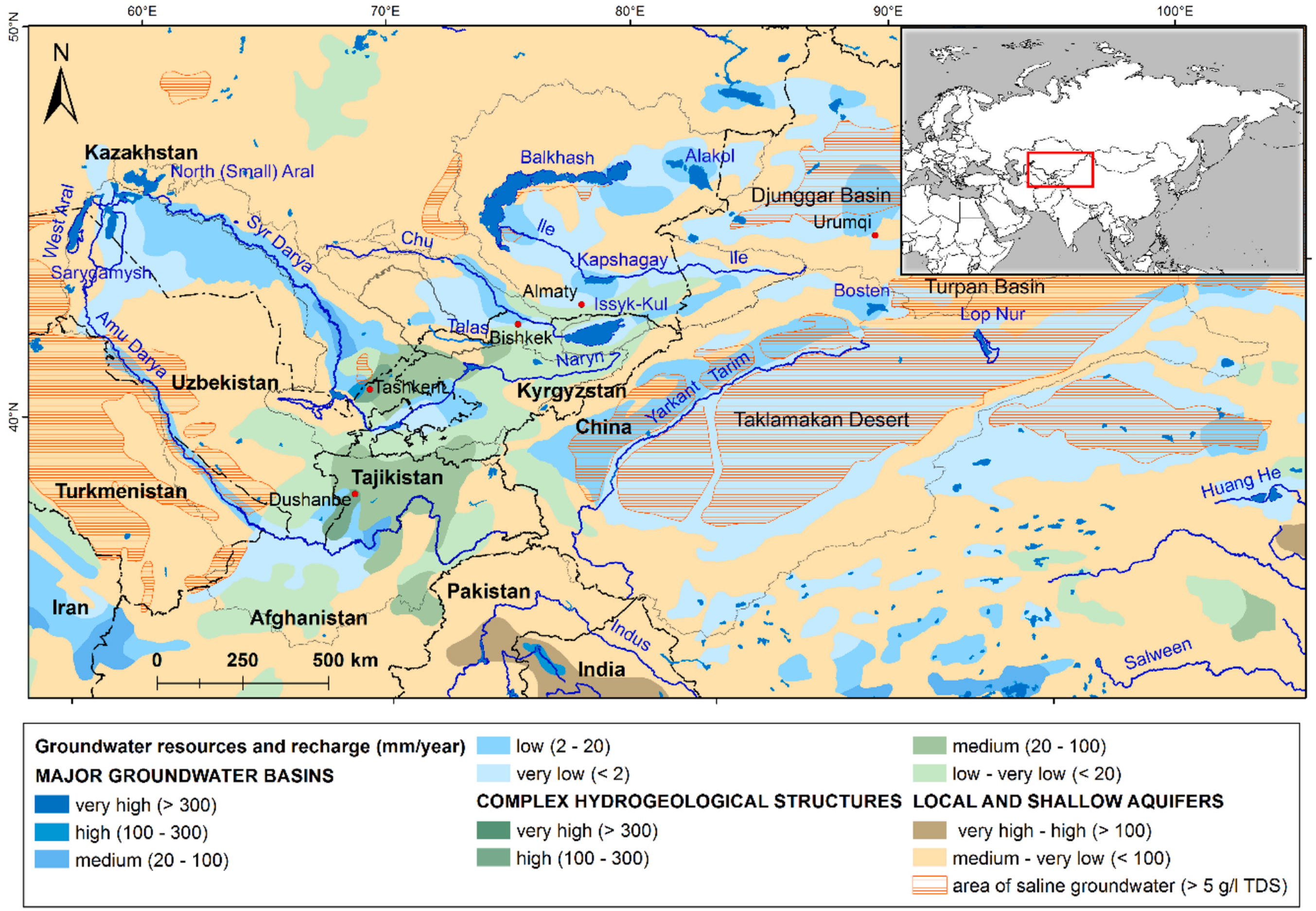

Fig. 3. Groundwater resources of CA (WGS-84-UTM42 projection).
The data are from Richts et al. (2011).

silicate and the major cations are uniform to the depth of approximately 80–90 m (Savvaitova and Petr, 1992; Kawabata et al., 2014). The lake water is well oxygenated with an alkaline pH of 7–9 (Asankulov et al., 2019; Dobroumov, 1973; Savvaitova and Petr, 1992). The lake water is enriched in some trace elements (V, Co, Cu, Mo, U, Sr, Sb, Cs, Br, F, and Li) in comparison with the stream water but all concentrations comply with the national and WHO standards (Lyons et al., 2001).

Lake Bosten is one of the largest freshwater lakes in China (Fig. 1; Table S3) (Xiao et al., 2015) receiving most of its inflow from the glacier-fed Kaidu River and losing water through evaporation and discharge to the Kongque River (Yao et al., 2018). Positioned at a lower elevation than the Issyk-Kul, it provides water for irrigation and industry. From 2003–2012, the lake level decreased by approximately 5 m but started to rise after 2013 (Yao et al., 2018). The TDS concentrations correlated inversely with water level changing from a minimum of 600 mg l^{-1}, characteristic of freshwater, in 1960–1900 mg l^{-1} in 1987 (Yao et al., 2018). The discharge of wastewater, used in irrigation and industrial production, contributed to increase in lake water salinity (Yao et al., 2018). Exceedances of the Chinese water quality standards in surface and groundwater for nitrate (10 mg N l^{-1}) and sulphate (250 mg l^{-1}) were reported (Xiao et al., 2015).

Water quality in warm and shallow lakes, located on the plains, is likely to be most vulnerable to climate change (Malmaeus et al., 2006). Lakes Balkhash and Alakol, fed by the rivers originating in the northern Tien Shan and Jetisu (Junggar) Alatau, are shallow and saline (Fig. 1; Table S3). In the Balkhash, salinity is higher in the east with TDS concentration of about 2–4 g l^{-1} and lower in the west where, prior to the construction of the Kapshagay reservoir, TDS values were approximately 1000–1500 mg l^{-1} (Petr, 1992; Propastin, 2012; Abuduwaili et al., 2019). This gradient is due to a division of the lake by the Sary-Isek peninsula and the Ile delivering most of the inflow in the west. Salinity of the lake increased in its western part following the construction of the Kapshagay reservoir, intercepting the Ile and disconnecting from glacial melt (Fig. 1), and now exceeds 2000 mg l^{-1} (Burlibayev et al., 2007; Mischke et al., 2020). Ion composition is dominated by Cl^-, SO_4^{2-}, Na^+ and K^+. The Balkhash is affected by the inflow of irrigation wastewater, discharged in the Ile, and pesticides, such as DDT metabolites, have been observed. Elevated concentrations of metals, particularly copper and zinc, and petroleum products were found in the lake water exceeding the national standards and attributed to the industrial facilities, including copper smelting, on its shores (Burlibayev et al., 2007).

The HWQ of the Alakol basin and its impacts on the health of the lake's ecosystem were systematically researched by Amirgaliyev et al. (2007) between 1988 and 2004. The mountain rivers flowing into Lake Alakol are characterized by strong seasonal variability in TDS with the sum of major ions ranging from 200 to 800 mg l^{-1} dominated by HCO_3^- and Ca^{2+} (Amirgaliyev et al., 2007). The water of the Alakol itself is brackish with mean long-term salinity of approximately 7.4 g l^{-1} and relatively small interannual variability of TDS. SO_4^{2-}, Na^+ and K^+ dominate the ionic composition (Amirgaliyev et al., 2007). The local rivers are contaminated by Ni, Co, Zn and Cu due to the agricultural activities. Concentrations of organochlorine pesticides, such as lindane and DDT-metabolites, peaked between 1991 and 1993, and although the use of pesticides declined afterwards, they are still detected in the water bodies, sediments and fish in the Alakol basin (Amirgaliyev et al., 2007).

Lake Sarygamysh (Fig. 1) has become progressively salinized though in the past the lake was fed by the Amu Darya and was fresh (Micklin et al., 2007; Orlovsky et al., 2012). In 1548, British travellers reported that water in "the lake from which the Uzboy originates was fresh and sweet" (Orlovsky et al., 2012). Later, the Sarygamsyh became progressively salinized following the migration of the Amu Darya channel towards the Aral Sea. In the 1950 s, the Sarygamysh nearly dried and consisted of several small lakes with water salinity reaching 300 g l^{-1} but was subsequently turned into a collector of wastewater used in irrigation and for soil washing (Severskiy, 2004; Orlovsky et al., 2012). Currently, water salinity is about 11 g l^{-1} and Cl^-, SO_4^{2-} and Na^+ dominate accounting for about 80% of TDS suggesting the strong impact of evapoconcentration (Orlovsky et al., 2012). Importantly, the absence of phosphates and low concentrations of nitrate were reported both in the lake water (about 0.68 mg N l^{-1}) and in irrigation discharge (0.68–1.58 mg N l^{-1}) (Orlovsky et al. 2012). However, pesticides, such as lindane and DDT, were found in the Sarygamysh water (Pavlovskaya, 1995). The dry exposed bed of the Sarygamysh is one of the main sources of desert dust in CA (Nobakht et al., 2021) and there is a danger that pollutants, contained in the sediments, may be transported to the regional glaciers.

The Aral Sea is the largest internal lake in CA and degradation of its environment has been discussed in multiple publications (Micklin, 2007; Middleton, 2002; Severskiy, 2004). The withdrawal of water for irrigation, primarily for growing cotton, during the Soviet period, resulted in a decline of the Amu Darya and Sur Darya runoff to the Aral from 56 km^3 in the 1960 s to 5 km^3 in 1980 s (Micklin, 2016) leading to the desiccation of the Aral. Its area declined from 67,499 km^2 in 1960–39,734 km^2 in 1989 (Micklin, 2016). Currently, the Aral consists of two main residual basins: the Large (South) Aral and the Small (North) Aral (Fig. 1) which have different physical, chemical, and biological characteristics (Izhitskiy et al., 2016). The Small (North) Aral, located in Kazakhstan is, in fact, a reservoir regulated by the Kok-Aral dam built in 2005 (Micklin, 2016). Its hydrological and hydrochemical characteristics are similar to those of the former Aral before desiccation with salinity about 12 g kg^{-1} allowing some ecological restoration. The highest salinity of about 130 g kg^{-1} is observed in the western part of the Large (South) Aral which its largest and hypersaline residual basin (Izhitskiy et al., 2016). Rzymski et al., (2019) reported that concentrations of arsenic exceed the WHO threshold for drinking water (Table S2) in the Small Aral and in the lower reaches of the Syr Darya. The high As content in the water bodies of the Aral Sea region is attributed to both, natural underground leaching (see Fig. 3) and anthropogenic contamination (Podgorski and Berg, 2020; Rzymski et al., 2019; Törnqvist et al., 2011). Concentrations of copper, nickel and lead exceed the WHO recommendations in the lower reaches of the Amu Darya delta and the adjacent part of the Large Aral (Törnqvist et al., 2011). Analysis of lacustrine sediment cores from the Small Aral showed that increase in concentrations of these and other (e.g. Cr, Co, Cd) metals increased dramatically around 1970 implicating human activities (W. Liu et al., 2020a) similarly to the sedimentary records obtained from lakes Ebinur (Ma et al., 2016), Bosten (W. Liu et al., 2020b) and Chaiwapu (Ma et al., 2013) in north-western China. The measured concentrations, however, suggest that these pollutants represent medium risk to the Aral Sea ecosystem except for Cd which represents a significant risk (W. Liu et al., 2020a). This issue is explored further in Section 5.3.

Intermittent water quality measurements were reported for the two main lowland reservoirs, the Kapshagay in the Balkhash-Alakol basin and the Shardara on the Syr Darya, Kazakhstan (Fig. 1). In the Shardara, nutrient concentrations were found to be low but the presence of the organochlorine pesticides and concentrations of Zn, Cd, Cu, Pb, exceeding the national water quality standards for fisheries (Table S2), were reported for 2015 (Barinova et al., 2017; Snow et al., 2020).

To conclude, lake water quality varies being, understandably, worse in the terminal lakes which receive industrial and irrigation wastewater and where water abstraction is high. Data are available predominantly for large lakes and lowland reservoirs while little is published about HWQ of small lakes and mountain reservoirs despite the fact that construction of reservoirs is expanding, predominantly in China but also in the post-Soviet CA. This is an important gap in knowledge because pesticides and heavy metals may accumulate in these water bodies and HWQ in lowland lakes, where evapoconcentration dominates, can deteriorate quickly if river flow declines either due to glacier recession or water abstraction.

4. Groundwater – surface water interaction and pollution

In CA, major groundwater basins, which are often transboundary, occur along the alluvial valleys of the rivers (Fig. 3). The mountains are the main groundwater recharge areas and are characterized by a complex hydrogeology (Gafurov et al., 2019, Liu et al., 2020; Fig. 3). In the arid lowlands, local and shallow aquifers predominate often with saline groundwater (Fig. 3). The hyper-arid Tarim, and adjacent Junggar and Turpan, are sedimentary basins with saline groundwater (Fig. 1; 3). Although average population density is relatively low (Table S1), settlements (including many large cities) are located on aquifers in the foothills and oases increasing population density locally (Fig. 3). The use of groundwater for potable water supply considerably increases pressure on water resources. Bishkek depends on groundwater almost fully (Morris et al., 2006), while Almaty and Dushanbe obtain 60% and 50% of their drinking water from this source, respectively (Finaev et al., 2017; VOXPOPULI, 2019). In the Soviet Union, groundwater was considered a strategic resource and its use for drinking and irrigation was limited (Gafurov et al., 2019) but more recently, the groundwater use has increased in CA especially during dry years (Y. Liu et al., 2020).

The groundwater chemistry is different from that of the surface waters in several ways. Firstly, the aquifers filter the turbid river water, characterized by high sediment load, improving its quality. Secondly, the groundwater is typically enriched in solutes depending on the regional lithology relative to the surface waters. Thirdly, the groundwater tends to accumulate higher contaminant concentrations in urban areas, in particular nitrate. Concentrations of nitrate reach and sometimes exceed national and WHO threshold of 10–11.3 mg NO_3^- l^{-1} (Table S2) in local shallow groundwater wells in Dushanbe and Bishkek in summer months (Yapiyev et al., 2020).

Snow and glacier melt ensures high groundwater flow and flushes the aquifers to some extent particularly in the upstream sections (Morris et al., 2006; Somers and McKenzie, 2020) although interactions between snow and glacier melt, aquifer recharge and quality of groundwater were not studied in CA. Changes in the groundwater HWQ with elevation resemble those of the surface water. In the lowlands, salinity is a major problem (Fig. 3) (Gafurov et al., 2019; Y. Liu et al., 2020). In the Aral Sea Basin, better groundwater quality was reported in the upper than in the downstream sections of the Amu Darya and Syr Darya catchments (Gafurov et al., 2019).

Table 1
Availability of information about hydrochemistry and water quality in the glacierized catchments of Central Asia.

Elevation zone	Available	Required
Glaciers and perennial snow pack	Ionic composition and concentrations of metals in snow and ice	The relative contributions of natural and anthropogenic sources to deposition are not fully understood Concentrations of legacy pollutants and emerging contaminants (e.g. microplastics) have not been quantified
Glacier headwaters to mountain base	Ionic composition of streamflow as measured in the 1970–1980 s and its relation to predominant lithology	Pathways of pollutants from snow ice to the aquatic systems are not well understood HWQ of discharge from rock glaciers and permafrost has not been quantified Carbon fluxes from the retreating glaciers, rock glaciers and permafrost have not been quantified There is little contemporary data on HWQ of mountain rivers Groundwater quality is not quantified
Foothills to lowlands	Concentrations of TDS, COD, N, P and metals measured at low temporal resolution (monthly) in main river channels in Kazakhstan and Uzbekistan	Lack of water quality measurements in Tajikistan Groundwater quality is not well quantified Water quality in tributaries is not well quantified Water quality measurements at higher temporal resolution are required Lack of water quality modelling studies under the current conditions and under future climate scenarios
Lakes and reservoirs	Concentrations of TDS, COD, N, P and metals measured at low temporal resolution (monthly) or at irregular intervals in the large terminal lakes (the Aral Sea, Issyk-Kul, Alakol, Balkhash, Bosten) and several reservoirs.	HWQ of mountain lakes and reservoirs is not quantified HWQ of small lakes and reservoirs on the plains is poorly quantified

In the upstream catchments, the ionic composition of groundwater was dominated by carbonates and calcium ions similar to the surface waters, while closer to the Aral Sea, the groundwater was saline with elevated chloride and sulphate concentrations (Fig. 3). Rakhmatullaev et al. (2009) and Gafurov et al. (2019) related salinity of groundwater to salinization of soils: while less than 10% of land in the upper Amu Darya basin is saline, 95% of soils are saline or very saline in its lower reaches. Changes in irrigation practices, e.g. switching for furrow to drip irrigation, can help not only save water but also reduce salinization of soils, surface and underground water. The extent of soil contamination by potential toxic elements and POPs is not well researched but it may impact both surface and groundwater quality. A recently published study on potential toxic elements in soils in Kazakhstan by Guney et al. (2020) identified elevated As, Cd, Ni in two points in Chu and Talas basins.

Overall, groundwater chemistry and quality is one of the major knowledge gaps in CA and, in particular, very little is known about groundwater HWQ in the mountains.

5. A perspective on future hydrochemistry and water quality research requirements in Central Asia

5.1. The current state of knowledge and the identified gaps

In this paper, we have reviewed the current knowledge about the HWQ along the mountain to lowland continuum in CA. The amount and quality of the information and level of understanding vary between issues, regions and elevation zones. The available knowledge and the main gaps are summarized in Table 1. However, the largest gap is the lack understanding of cycling of pollutants and changes in the HWQ along the whole elevation continuum from the glacierized source regions to sinks in the arid lowlands (Fig. 2).

The best researched aspect of the HWQ is the solute chemistry of mountain snow and ice. Multiple studies are in agreement about its relationship to the atmospheric deposition and the important role of desert dust. There is growing information about concentrations of sulphate, nitrate, ammonium, and metals, but no consensus on how these relate to dust sources and emissions from the combustion of fossil fuel and agriculture. The use of pesticides and herbicides in CA was, and in some regions still is, widespread (Tang et al., 2021). The major sources of mineral dust in CA are associated with the abandoned arable land and sinks of water used in agriculture (Nobakht et al., 2021). The atmospheric transport of POP with mineral dust entrained from these areas and its accumulation in the high-elevation zone is implied (e.g. Snow et al., 2020) but never proven as POP measurements in the uplands are unavailable. It is widely known that glaciers can support microbial food webs and that they store organic carbon from local and distant sources and release it in the downstream environments as they melt (Hood et al., 2015; Wadham et al., 2019). The microbial food webs have not been researched in the region. There are very few studies of carbon export possibly because the CA basins are not connected to the world ocean although they do support lacustrine environments (Li et al., 2017). Overall, there are only a few studies considering how any chemicals enter the hydrological system following snow and glacier melt (e.g. You et al., 2015; Zhongqin et al., 2007) and there are no assessments of their impacts on stream water HWQ. There is no understanding of biogeochemical cycling between the glacierized, aquatic and terrestrial lowland ecosystems. There is also no consideration of whether glacier retreat and permafrost and rock glacier melt will promote solute leaching. Since the 1990 s, most studies on snow and ice chemistry have been conducted by international teams in collaboration with regional scientists and glacier and hydrometeorological monitoring have been reinstated in the region (Barandun et al., 2020; Hoelzle et al., 2019). Therefore, there is strong potential to address these challenges.

Downstream, the gaps in knowledge are due to the lack of access to the long-term HWQ data and contemporary higher-frequency measurements (Table 1). In the post-Soviet CA, monitoring of a large range of chemicals in surface water (Table S2), which began in the 1960 s, is now performed by the national Hydrometeorological Agencies (United Nations Economic Commission for Europe, 2018). Although the monitoring networks declined in the 1990 s, samples are collected once per month from permanent sites and methods are consistent across the region. In Kazakhstan and Uzbekistan, the monitoring networks are more extensive and analyses are conducted in certified laboratories. In Kyrgyzstan and especially in Tajikistan, these are less advanced due to the funding constrains (United Nations Economic Commission for Europe, 2018). Despite the long monitoring history, until recently, data access was limited and water quality was at best reported as exceedance of national standards, the so-called Maximum Allowable Concentrations (Table S2), constraining scientific analysis. Most of the post-1990 literature is based on the data obtained in the short-term projects with few studies analyzing changes in HWQ over time and larger basins (Amirgaliyev, 2007; Crosa et al., 2006a, 2006b; Groll et al., 2015; Lobanova and Didovets, 2019; Olsson et al., 2013). As a result, many local studies report conflicting findings and their independent evaluation is challenging because of the limited information about data quality. Recently, actual data on concentrations of selected pollutants became publicly available from the state agencies in Kazakhstan (Kazhydromet, 2020) and Kyrgyzstan (KyrgyzHydroMet, 2020) albeit almost entirely for the plains.

Data on the groundwater quality are not publicly available and are treated as classified (restricted) information (Y. Liu et al., 2020). This is a significant limitation providing that while the use of this resource is increasing including the provision of potable water, contamination of the shallow ground water (Bekturganov et al., 2016; Bosch et al., 2007; Morris et al., 2006; Nurtazin et al., 2020; Törnqvist et al., 2011; Yapiyev et al., 2020) and salinization (Gafurov et al., 2019; Liu et al., 2020; Rakhmatullaev et al., 2009) are reported by the few available studies. Further work is needed to better understand groundwater recharge rates and the surface water-groundwater interactions that control the replenishment and flushing of the shallow aquifers around the cities used for drinking water, and to understand the relative importance of groundwater and melt water contributions to lowland river flow, water use and quality (Buytaert et al., 2017).

Multiple dams and reservoirs, in the mountains and on the plains, are a characteristic feature of CA. Reservoirs modify runoff and work as bioreactors which store and transform sediments, nutrients and contaminants travelling from upstream locations. Globally reservoirs have been observed to promote eutrophication and bury organic matter in sediments, emitting nitrogen by denitrification processes (Maavara et al., 2020; Fig. 2). The impacts of dams and reservoirs on the regional HWQ are one of the biggest gaps in knowledge, especially taking into account the extensive reservoir construction in China which already causes concerns about water quality in the Ile basin because of the observed and predicted increase in water abstraction which, in combination with a projected decline in glacial meltwater input (Kogutenko et al., 2019), may result in a reduced dilution effect (Stone, 2012). There is a significant potential for reservoir expansion in the mountains of Kyrgyzstan and Tajikistan to adapt to the continuing deglacierization (Farinotti et al., 2019) while there is very little information in the published literature about HWQ of the upland reservoirs.

5.2. *Water quality at present and after the peak flow*

CA strongly depends on water provision from the mountains (Viviroli et al., 2020) and more than any other region, on glacier melt (Kaser et al., 2010). Currently, high air temperatures and low precipitation in summer do not imply a lack of river flow because of the meltwater contribution and in many headwater catchments an increase in streamflow has been observed due to the intensifying glacier melt (Huss et al., 2017, Shahgedanova et al., 2018). Although the trends are often different in the downstream catchments affected by water abstraction (Grill et al., 2019; Immerzeel et al., 2012; Severskiy, 2004), both snow and glacial melt maintain the dilution effect which peaks in the early and late summer, respectively. This ecosystem service sustains the acceptable water quality even in the lower reaches of large rivers such as the Amu Darya (Crosa et al. 2006a, Lobanova and Didovets, 2019) despite a low proportion of the total catchment area occupied by glaciers and a large extent of agricultural land (Table S1). The decline in the use of fertilisers in the post-Soviet Central Asia, especially in Kazakhstan and Tajikistan, in the 1990 s (Fig. S3) has helped to reduce nitrogen and phosphorus concentrations in the lowland farmed areas. Most studies point at the water pollution hotspots, often associated with the degradation of sewage treatment systems (Bekturganov et al., 2016), rather than persistent and widespread exceedance of the national and international standards.

The emphasis on pollution hotspots is an interesting contrast with the recent perspectives on the downstream impacts of glacier shrinkage which describe cascades of effects (Milner et al., 2017; Rasul and Molden, 2019). It was suggested that such cascades may affect various HWQ variables, for example, dissolved organic carbon whereby carbon fluxes from montane sources (e.g. retreating glaciers) add to the inputs from lowland farmland and sewage. However, inputs from montane sources may be localised and subsequently diluted (or, by contrast, concentrated) when mixed with inputs from multiple tributaries, especially in the lowlands, whose hydrochemistry is very different from that of the mountains. Further work is needed to quantify the combined effects of multiple tributaries with different characteristics on the downstream HWQ.

The peak of non-renewable water released by the melt of glacier ice is expected in CA in the 2040–2050 s followed by a decline in glacier runoff (Huss and Hock, 2018) and streamflow (Immerzeel et al., 2012; Shahgedanova et al., 2020). In the 2010 s, the use of nitrogen fertilizers reached and exceeded its 1992 level in Kazakhstan and Uzbekistan, respectively, and the application of phosphates began to increase in all countries (Fig. S3). Given the ongoing economic recovery of the region, the observed growth in the use of fertilisers is expected to continue especially in Uzbekistan. The juxtaposition of these trends is likely to have negative implications for HWQ. Extensive effort in water quality modelling under the present and future climates is required to quantify the effects of the projected climatic and hydrological changes on the HWQ of both surface and groundwater after the peak water. There are no studies in CA in the absence of the long-term reliable data of water quality in the glacierized catchments. A recent systematic review of the literature on adaptation to impacts of climate change in the mountain catchments of CA, published between 2013 and 2020, showed that none focused on water quality (Saidaliyeva et al., 2021).

5.3. *Implications for human health and ecosystems*

The need for knowledge about HWQ is based on its importance for human and ecosystem health. The Aral Sea crisis has put this issue on the national and international environmental agendas (Micklin, 2007) but only limited understanding has been achieved for the region as a whole. Research focused primarily on the presence of POP and pathogenic microbes in the Amu Darya and its tributaries and in drinking water in the Aral Sea region. Water pollution in the Amu Darya delta was considered a low risk to health (see Section 3.4) although concentrations of the potentially toxic substances such as arsenic and pesticides exceeded the WHO guidelines in potable water from the ground wells (Törnqvist et al., 2011). This was not the case in the Aralsk region in Kazakhstan although in this region pathogenic microbes were present in potable groundwater (Bosch et al., 2007). Conflicting results on the quality of potable groundwater were provided for the Balkhash region. Bekturganov et al. (2016) reported an increase in water-borne diseases due to the poor drinking water treatment, contamination during distribution, and a frequent use of shallow groundwater which is often polluted by sewage. However, an extensive survey of drinking water quality in the rural area between the Kapshagay reservoir and Lake Balkhash reported that, overall, potable water met national standards though microbial contamination was detected in wells (Nurtazin et al., 2020). Importantly, the effects of water quality on human health depend on exposure and pathways of pollutants to human bodies. Research in the Aral Sea Basin suggested that drinking water quality did not threaten human health directly. Rather, pollutants, including pesticides and toxic elements, had different pathways, e.g. through the consumption of food which did not comply with the health standards and inhalation of contaminated desert dust (O'Hara et al., 2000; Jensen et al., 1997; Muntean et al., 2003; Crighton et al., 2011). Therefore, a holistic approach to research of water quality on human health is required including different types of exposure and multiple pathways.

The deltas of large rivers in CA such as Amu Darya, Syr Darya, and Ile are occupied by the vast wetlands connecting rivers to endorheic lakes. The wetlands are biodiversity hotspots. It is known that they are affected by salinization (Tesch and Thevs, 2020). However, impacts of pollution, caused by the discharge of water used for irrigation and municipal needs upstream, on the wetland ecosystem have not been characterised (Mischke et al., 2020).

The montane rivers and lakes of CA, characterised by low water temperatures, low channel stability and low solute concentrations (but high sediment flux during the high flow period), have low productivity and apparent low biological diversity (Mitrofanov and Petr, 1999; Savvaitova and Petr, 1999). There is little data about the aquatic ecology in the high mountains and, therefore, the true biodiversity is poorly described as well as the ways in which it can be affected by changes in climate, glaciers and HWQ. In comparison to the aquatic ecosystems elsewhere, the aquatic organisms likely to be present are predominantly benthic biofilms, bryophytes and invertebrates. These are likely sensitive to change in water temperature and flow regime (Brown et al., 2015; Meyer et al., 1999; Wilhelm et al., 2013; Woodward et al., 2010), water acidity, and solute concentrations (Loayza-Muro et al., 2014; Milner et al., 2017). Overall, the effects of deglaciation on aquatic biodiversity may be secondary to the detrimental impacts caused by the introduction of new species, construction of reservoirs and other catchment modifications, and, downstream, by the return of saline irrigation water (Mitrofanov and Petr, 1999; Savvaitova and Petr, 1999). However, in the high-elevation environments, such as the cold-water lakes in the Pamir which provide refuge for the endemic species, the impacts of deglaciation are likely of primary importance. Further data on aquatic biodiversity across all trophic levels is needed to better understand biogeochemical cycling and the effects of hydrological changes caused by deglaciation.

6. Concluding remarks

This paper reviewed the state of knowledge and the main challenges in research on the HWQ in CA related to the present state of the glacierized catchments. The identified questions can be resolved if the HWQ and the processes regulating it are understood along the elevation continuum from glaciers to the arid plains. At present, the state of water quality in CA appears to comply with the national and international standards except the shallow groundwater and specific pollution hotspots. These areas are related to the discharge of water used in irrigation and poor sewage treatment, although there is often a discrepancy between studies.

It is not clear if the status quo can be maintained in the future when peak water passes and glaciers become unable to sustain river flow at its current rate. Currently, there are no reliable studies answering this question. Water quality modelling can provide future scenarios and inform adaptation but water quality data are required and this is either lacking or not accessible.

There are significant differences in levels of economic development and in river protection strategies between the CA countries. Water quality problems appear to be more pressing in Uzbekistan due to the large-scale agricultural production but national expertise and involvement in international projects are substantial and improvements can be achieved through national projects strengthened by international collaboration. Water quality in the upstream Tajikistan benefits more than in any other country from the effect of snow and glacier melt but restoration of monitoring network, capacity building, and improvements in sanitation are urgently needed. Importantly, all considered basins are transboundary. The International institutions lament on the lack of cooperation on water quality in CA (Evans et al., 2012; Rahaman and Varis, 2008) although recently there have been positive developments such as the establishment of the transboundary commissions concerned with water quality among other issues. Water quality is another dimension of transboundary water-sharing in CA, and is under explored. Not only the enhancement of national but joint bilateral and international monitoring and research leading to measures to improve water quality are recommended for CA.

CRediT authorship contribution statement

V. Yapiyev: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization. **A. Wade:** Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition. **M. Shahgedanova:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Z. Saidaliyeva:**: Investigation, Visualization. **I. Seveskiy:**: Conceptualization. **A. Madibekov:**: Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100960.

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