



Cryosphere and land cover influence on stream water quality in Central Asia's glacierized catchments

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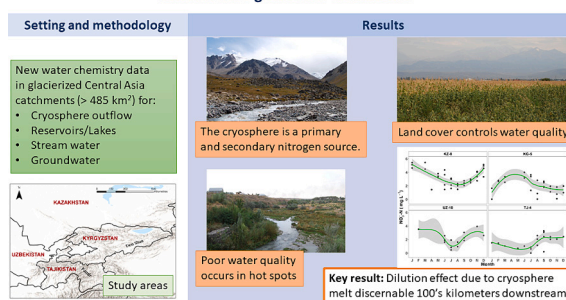
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HIGHLIGHTS

- The water quality of glacierized Central Asia catchments (>485 km²) is assessed.
- The cryosphere is a primary and secondary nitrogen source.
- Poor water quality occurs in hot spots rather than being uniformly good or bad.
- Shallow urban groundwater is contaminated by sewage.
- A dilution effect due to the cryosphere was discernible 100's km downstream.

GRAPHICAL ABSTRACT

Influence of cryosphere outflow and land cover on stream water quality in Central Asia's glacierized catchments



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ABSTRACT

This work helps address recent calls for systematic water quality assessment in Central Asia and considers how nutrient and salinity sources, and transport, affect water quality along the continuum from the cryosphere to the lowland plains. Spatial and, for the first time, temporal variations in stream water pH, temperature, electrical

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conductivity, and nitrate and phosphate concentrations are presented for four catchments (485–13,500 km²), all with glaciers and major urban areas. The catchments studied were: Kaskelen (Kazakhstan), Ala-Archa (Kyrgyzstan), Chirchik (Uzbekistan) and the Kofarnihon (Tajikistan). Measurements were made in cryosphere, stream water, groundwater, reservoir and lake samples over a 22-month period at fortnightly intervals from 35 sites. The results highlight that glacier, permafrost and rock glacier outflows were primary and secondary nitrate sources (>1 mg N L⁻¹) to the headwaters, and there were major increases in salinity and nitrate concentrations where rivers receive inputs from agriculture and settlements. Overall, the water quality complied with national and World Health Organization standards, however there were pollution hot-spots with shallow urban groundwaters contaminated with nitrate (>11 mg N L⁻¹) and stream electrical conductivity above 800 µS cm⁻¹ in some agricultural areas indicative of high salinity. Phosphate concentrations were generally low (<0.06 mg P L⁻¹) throughout the catchments, though elevated (>0.2 mg P L⁻¹) in urban areas due to effluent contamination. A melt water dilution effect along the main river channels was discernible, in the electrical conductivity and nitrate concentration seasonal dynamics, 100 s of km from the headwaters. Thus, the input of relatively clean water from the cryosphere is an important regulator of main channel water quality in the urban and farmed lowland plains adjacent to the Tien Shan and Pamir. Improved sewage treatment is needed in urban areas.

1. Introduction

Over the past 50 years, glacier retreat has been observed and attributed to climate change, with this trend projected to continue for the next 70 to 100 years (Hock et al., 2019). Worldwide, approximately 1.9 billion people depend on the water supplied by glaciers for domestic and commercial consumption, irrigation and hydropower, and therefore the assessment of current and future mountain water resources is important (Hock et al., 2019). Outside North America and Europe, relatively little attention has been given to water quality assessment in glacier-fed catchments, to the relationship with freshwater ecosystems and to the provision of clean water for downstream use. In part, this lack of attention on water quality arises because of the practical difficulties and expense of sustained sample collection in remote locations. When done, water chemistry studies of glacierized catchments tend to focus on the spatial and temporal variations in the hydrochemistry with emphasis on water isotopes and the major ions to quantify source water contributions to stream flow, and to assess weathering and the release of potentially toxic elements (Brighenti et al., 2023; Brighenti et al., 2021; Cable et al., 2011; Crespo et al., 2020; Engel et al., 2019; Tranter, 2003). Downstream changes in salinity and nutrient concentrations and the seasonal dynamics remain poorly quantified and understood (Brighenti et al., 2019b; Milner et al., 2017).

Central Asia (CA) is a largely arid region dependent on mountain snow and glacier melt for water supply (Kaser et al., 2010; Viviroli et al., 2020). Model-based estimates of climate-change impacts suggest a glacier-mass reduction, but that glacier remnants will remain (Farinotti et al., 2015; Hock et al., 2019; Shahgedanova et al., 2020; Shannon et al., 2019; Van Tricht and Huybrechts, 2023). The mass reduction has increased summer flows due to increased melt, however this increase is likely to be followed by a summer flow reduction as the melt water declines though the precise timing of 'peak water' remains uncertain (Duethmann et al., 2015; Hagg et al., 2013; Huss and Hock, 2018; Kriegel et al., 2013; Shahgedanova et al., 2020; Shahgedanova et al., 2018).

The headwaters provide water that may both dilute downstream contaminant concentrations yet also increase the headwater contaminant flux (Brighenti et al., 2023; Brighenti et al., 2019a; Crespo et al., 2020; Salerno et al., 2016). Thus, it is important to assess the salinity and nutrient concentrations from the cryosphere to the plains to assess potable and irrigation water provision, and eutrophication, along the river continuum. As the high mountain cryosphere melts and thaws, headwater solute concentrations in the vicinity of the glacier terminus will likely be affected by: trace element leaching from the exposed substrate due to weathering; nutrient leaching from microbial processes, and the release, in meltwater, of legacy pollutants stored in glacier ice, rock glaciers, permafrost and snow (Bogdal et al., 2009; Colombo et al., 2018; Liu et al., 2021). Shifts in the timing of ice and snow melt to earlier in spring and a change in precipitation form, from snow to rainfall, are

anticipated, as are changes in snow accumulation and duration, and possibly precipitation patterns (Beniston et al., 2018; Milner et al., 2017). All these hydrological changes will likely change solute release, including nitrate and phosphate, and stream temperatures (Brahney et al., 2021; Brighenti et al., 2019a).

Headwater aquatic ecosystems are sensitive to small changes in melt water hydrochemistry and temperature because of the low stream water concentrations and temperatures. Phosphate, for example, typically has very low stream water concentrations in mountain areas as it is rapidly assimilated by the cryosphere (e.g., cryoconite) and soil and stream biota, and therefore increased concentrations could increase stream and lake productivity (Bettinetti et al., 2008; Bogdal et al., 2009; Brighenti et al., 2019b; Colombo et al., 2018; Milner et al., 2017; Miner et al., 2019). Freshly comminuted glacier flour can contain high ion concentrations that can lead to high fluxes with the ion composition dependent on the bedrock. Nutrient limitation in proglacial streams and lakes is complex, variable and dependent on the organism considered, with nitrogen and phosphorus co-limitation of stream biofilms and phosphorus limitation of consumers identified (Ren et al., 2019).

Downstream, there has been little consideration of the water quality of lakes and reservoirs used to supply drinking water and of stream water used for irrigation. The mixing of surface and groundwater has been established as important in the lowland plains around Bishkek, with the city almost entirely dependent on an unconfined aquifer fed by precipitation and melt water for drinking water (Morris et al., 2006). Work is therefore needed to assess aquifer water quality especially given the surface-groundwater interaction.

A recent review of the hydrochemistry and water quality (HWQ) in glacierized CA mountain catchments showed that river water quality mostly complies with national and World Health Organization (WHO) standards, however studies are limited and not all are based on reliable data (Yapiyev et al., 2021). Most publications on CA water quality focus on the middle and lower reaches of the Amu Darya (Crosa et al., 2006; Hao et al., 2023) and its main tributary, the Zeravshan (Groll et al., 2015; Olsson et al., 2012). The studies found that melt water dilutes pollutants released from urban areas and farmland and regulates endorheic lake salinity (Jones and Deocampo, 2003; Orlovsky et al., 2014; Wurtsbaugh et al., 2017). The review also noted that almost no information about hydrochemistry and water quality in CA montane catchments was published after the 1980s and, whilst the solute chemistry of ice and snow is understood relatively well, only one study was found that described how solutes enter the hydrological system following glacier ice and snow melt (You et al., 2015). A further recent study assessed nitrogen and phosphorus inputs to the Aral Sea Basin and found that cropland diffuse sources made the greatest contribution to the lower reaches based on two longitudinal sampling campaigns in April and July 2019 (Leng et al., 2021). Thus, there is a need to build on these works to quantify the extent, dynamics and severity of freshwater contamination in the lowland tributaries draining urban and

agricultural areas in CA in different water types, with an emphasis on the importance of the seasonal melt water dilution effect. Recent papers have highlighted the need for the systematic measurement of contaminants, including nutrients, in CA catchments (Leng et al., 2021; Liu et al., 2021).

The aim of this work is to quantify the cryosphere influence on the downstream water quality along the elevation gradient, in lakes and reservoirs in the arid lowlands, and on groundwater in large catchments with major urban centers. Three objectives were considered to achieve the aim:

1. To investigate the water quality of the cryosphere components, including the release of nitrate and phosphate.
2. To investigate how the cryosphere and land use influence water quality when moving downstream, accounting for the summer dilution effect from melt water.
3. To identify polluted areas along the continuum from the cryosphere to the lowlands.

To address the three objectives and achieve the overall aim, fortnightly measurements of pH, water temperature, salinity (assessed using electrical conductivity which is strongly correlated with total dissolved

ions), and nutrient (nitrate, NO_3^- -N and phosphate, PO_4^{3-} -P) concentrations were made in surface waters and groundwaters along the elevation continuum between 2019 and 2021 in the Kaskelen (Kazakhstan, KZ), Ala-Archa (Kyrgyzstan, KG), Chirchik (Uzbekistan, UZ) and Varzob/Kafornihon (Tajikistan, TJ).

2. Material and methods

2.1. Study region

The Kishi Almaty and Ulken Almaty (KZ) are tributaries of the Kaskelen river (Fig. 1; Table 1). The Kaskelen also flows into the Kapshagay reservoir which the Ile river flows into and from. The other three catchments are also the headwaters of major rivers: the Ala-Archa (KG) – of the River Chu; the Chirchik (UZ) – of the Syr Darya, and the Kofarnihon and its tributary, the Varzob (TJ) – of the Amu Darya. All rivers drain large ($> 485 \text{ km}^2$) areas and have a glacial-nival regime, and the relative glacial area ranges from 0.4 to 4.5 % of the catchment area (Table 1). The Kaskelen, Ala-Archa and Chirchik drain from the Tien Shan mountains and the Kofarnihon and Varzob from the Pamir. The Chirchik and Kofarnihon are an order of magnitude larger than the Kaskelen and Ala-Archa, and longer.

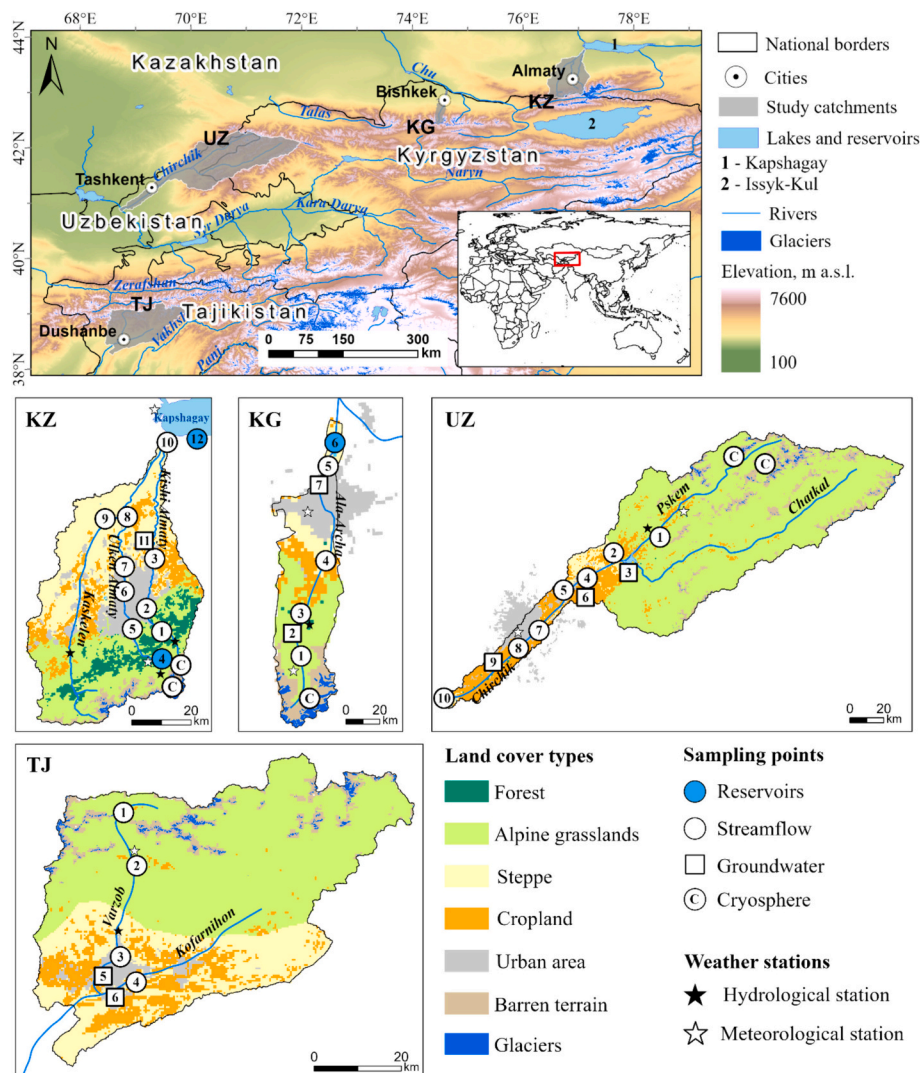


Fig. 1. The study catchments showing the land cover, sample site and weather station locations. The glacierized area shown was derived from the Global Land Ice Measurements from Space (GLIMS) database (RGI Consortium; Raup et al., 2007). Here and in the subsequent figures: KZ – Kazakhstan, KG – Kyrgyzstan, TJ – Tajikistan, and UZ – Uzbekistan.

Table 1
Study area characteristics. The potential evapotranspiration (PET) is from the Climate Research Unit CRU TS 4.01 data set (Harris et al., 2020). The glacierized area was calculated for the following years: 2011 (Varzob/Kofarnihon), 2014 (Chirchik), 2017 (all Kazakhstan catchments), 2018 (Ala-Archa). The proportion of the glacierized area is expressed as a percentage of the total catchment area (measured at the highest elevation gauging station, Fig. 1). *The catchment area, glacierized area, elevation range and mean of the Kaskelen catchment includes the Kaskelen River, Ulken Almaty and Kishi Almaty basins. Discharge is given to two significant figures.

Catchment	Area (gauging station area)	PET (1991–2010)	Catchment elevation min – max (mean)	Glacial area	Gauging site	Gauging site Lat., Long., (elevation)	Discharge (years)	Specific discharge	Major city (population)
	km ²	mm year ⁻¹	m.a.s.l.	km ² (%)		Decimal degrees (m.a.s.l.)	m ³ s ⁻¹	m ³ s ⁻¹ km ⁻²	million
Kishi Almaty (KZ)	1048 (43)	900	447–4361 (1051)	4.5 (0.4)	Below Sarysai inflow	43.1396; 77.0684, (1942)	1.5 (2005–2013)	0.03	
Ulken Almaty (KZ)	485 (74)		547–4355 (2033)	13.8 (2.8)	Upstream of Big Almaty Lake	43.0389; 76.9947, (2559)	2.3 (2000–2013)	0.03	Almaty (1.78)
Kaskelen (KZ)*	3792 (294)		447–4361 (1360)	34.0 (0.9)	Kaskelen town Kaskelen downstream	43.134260, 76.612036, (1129)	4.0 (2001–2013)	0.01	
						43.7219, 77.0716, (502)	10 (2000–2013)	NA	
Ala-Archa (KG)	701 (238)	887	608–4746 (1940)	31.5 (4.5)	Bat'yk	42.647609 74.495405, (1560)	5.5 (1990–2015)	0.02	Bishkek (0.98)
Chirchik (UZ)	13,464 (2506)	1129	226–4455 (2251)	142.9 (1.1)	Mullala Chinaz	41.771928, 70.190761, (925)	77 (1980–2010)	0.03	Tashkent (2.52)
						40.909312, 68.7593287, (253)	120 (2004–2010)	0.01	
Varzob/Kofarnihon (TJ)	7536 (1275)	1056	673–4835 (2170)	98.8 (1.3)	Dagana	38.702, 68.79, (1056)	51 (1990–2011)	0.04	Dushanbe (0.92)

All rivers flow through irrigated farmland and cities, with populations of 0.9–2.5 million, which rely on river flow, typically stored in mountain reservoirs, for water supply (Table 1). Exceptions are Bishkek, in the Ala-Archa basin, relying on groundwater almost entirely (Morris et al., 2006), and Dushanbe (TJ) with an approximately even ratio of abstraction from ground and surface water (Finaev et al., 2017). The regional geology and hydrogeology are described in detail elsewhere (Gao et al., 2009; Koronovsky, 2003; Li et al., 2019). In brief, the Tien Shan mountains are comprised of granitoids mainly, and the downstream plains of cropland and dry steppe in the Kaskelen, Ala-Archa and Chirchik are primarily on Quaternary deposits on Meso-Cenozoic sedimentary rocks. The Kofarnihon and Varzob rivers drain from the Devonian volcanic rocks and Carboniferous conglomerates and sandstones of the Pamir, and then also cross Quaternary deposits on Meso-Cenozoic sedimentary rocks. The soils in the four catchments are thin Leptosols in the mountains, and Calcisols around the cities at the mountain base in Kaskelen, Ala-Archa and Chirchik which are characterized by calcium carbonate accumulation. Gleysols occur around Kapchagay in Kaskelen where the soils are wet, and Anthrosols occur in the lowest reaches of the Chirchik near Tashkent modified by farming. In TJ, there are Cambisols in mountain base which are weakly to moderately developed soils, and Anthrosols in the lowest reaches downstream of Dushanbe where the Varzob flows into the Kofarnihon (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

Along all the rivers, the predominant land cover changes from barren, mountain terrain with glaciers to alpine grassland and forest and then to cropland and dry grassland steppe (Fig. 1, Table S4). In the Ala-Archa, Bishkek is located on the steppe, downstream of cropland. The Kaskelen is different as Almaty is located at the mountain base and upstream of the cropland and steppe, whilst Tashkent in the Chirchik and Dushanbe in the Kofarnihon are surrounded by cropland.

All catchments have large altitudinal gradients in air temperature and precipitation, and distinct seasonal precipitation with a spring maximum (Fig. 2a, b). In the KZ and KG catchments in the north of the region, and in the high mountains, the Köppen climate classification is subarctic and tundra with a humid-continental climate on the lower slopes that transitions to semi-arid grassland steppe (Fig. 1). In UZ and TJ, to the south, the Köppen climate classification changes from subarctic in the high mountains to humid-continental and then to a Mediterranean climate as the altitude decreases to semi-arid grasslands and desert. Discharge is an order of magnitude higher in the Chirchik and Varzob which have larger headwater areas than the Ulken Almaty, Kishi Almaty and Ala-Archa though the specific discharge is similar in the Ulken Almaty, Kishi Almaty, Chirchik and Varzob (Table 1). The discharge peaks in summer (JJA) in all catchments in the middle mountain sites (Fig. 2c), and the maximum occurs in June in the south and west (Chirchik, Varzob). In the north and north-east catchments (Kaskelen, Ulken Almaty, Kishi Almaty and Ala-Archa), the maximum occurs in July where seasonal snow melt dominates over the runoff from glaciers (Fig. 2c). During winter, in November through to February, stream and river flows are at a minimum at all the middle mountain sites (Fig. 2c). In the lowlands, the stream flow is modified, with the flows in the lower Kaskelen affected by reservoir storage in the Ulken Almaty, and the flows in the lower Chirchik by irrigation abstractions (Fig. 2d).

In this article, ‘upland’ or ‘high-elevation’ refers to those sites above the transition from forest and alpine grassland to cropland and dry grassland steppe in each catchment (Fig. 1), and ‘lowland’ or ‘low-elevation’ to the areas downstream of this transition point. ‘High-flow’ refers to the surface water flows augmented by glacier and snow melt in JJA (MJJA in Chirchik and Varzob) and ‘low-flow’ to the baseflow dominated winter. Physical and chemical weathering and the microbial processing of organic material at the glacial ice-rock interface, are considered a *primary* source of ions, whilst legacy ion release from glacial ice and snow is considered a *secondary* source with, in this case, the primary source distant and the material transported to the cryosphere through the atmosphere and deposited (Chen et al., 2022; Painter

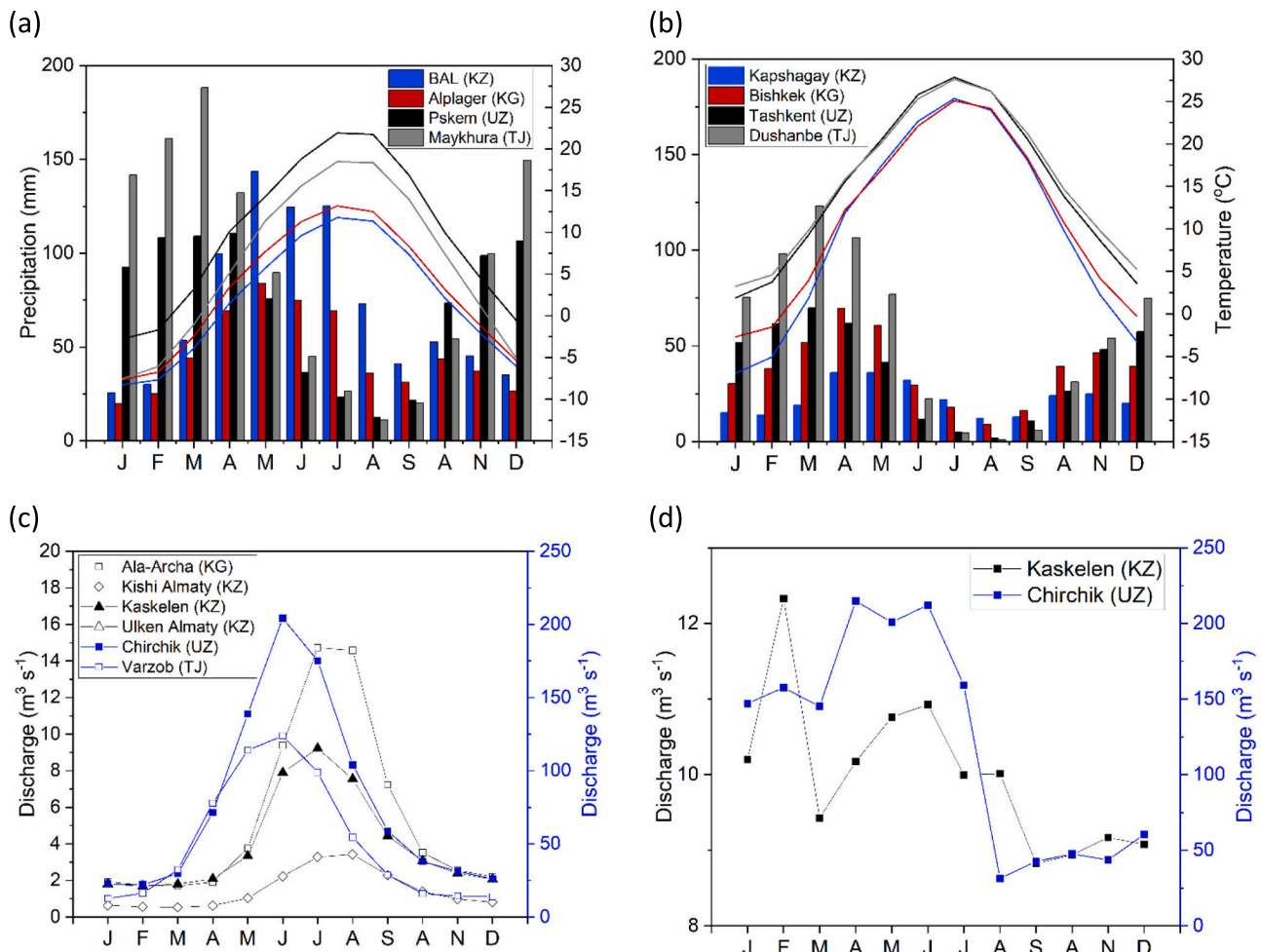


Fig. 2. Air temperature and precipitation at the (a) middle mountain (1200–2500 m a.s.l.) and (b) plains and foothill (500–800 m a.s.l.) stations, and stream flow in the (c) middle mountains and on the (d) plains. The blue lines show the catchments in the south and west (UZ, TJ) and the black lines those in the north and north-east (KZ, KG) and the difference between the timing of the peak flow (June in the south and west, July and August in the north and north-east). The meteorological and stream flow gauging site locations are shown in Fig. 1. The meteorological data are for the 1980–2020 period if not indicated otherwise and the station elevations are: Big Almaty Lake (BAL, 2500 m a.s.l.), Alplager (2100 m a.s.l., 1992–2010), Pskem (1256 m a.s.l.), Maykhura (1921 m a.s.l.), Kapshagay (492 m a.s.l., 1971–2000), Bishkek (828 m a.s.l., 1980–2000), Tashkent (488 m a.s.l.), Dushanbe (803 m a.s.l.). The coordinates and elevation of the stream gauging sites and observation period are in Tables 1 and S1.

et al., 2012).

2.2. Surface and groundwater samples

Once every two weeks for 22 months, water samples were collected at fixed locations along the main channel from 10 to 20 km downstream of the headwaters to the lowlands and from large tributaries. In addition, samples were taken from five wells, three deep and two artesian, and three springs to characterize the groundwater water chemistry (Fig. 1, Tables S1, S2a and b). All water samples were analyzed for NO_3^- -N (mg N L^{-1}), and PO_4^{3-} -P (mg P L^{-1}) (Section 2.4). Sample collection started between April and July 2019 and ended between October 2020 and January 2021 dependent on the country (Table S1). The water was sampled using a plastic syringe and filtered through a $0.45 \mu\text{m}$ syringe filter (Fisher Scientific, part No. 15216869) in the field into a 30 ml universal plastic screw cap tube. The samples were stored in a portable fridge and analyzed in a laboratory within 24 h at room temperature. Water temperature ($^{\circ}\text{C}$), electrical conductivity (EC, $\mu\text{S cm}^{-1}$) and pH were measured in the field using a hand-held field meter (Hanna Instruments Inc., model HI 9812-5) and combination probe (Hanna Instruments Inc., model HI 1285-5). The portable meters were calibrated before each day of sampling. The sampling locations were chosen to

represent different land uses, the headwater to lowland continuum, and the main water sources: glacial headwaters, main channel and tributaries, groundwater, lakes and reservoirs (Fig. 1; Tables S1, S2a and b).

2.3. Cryosphere samples

Snow and glacial melt water samples were collected during the summers of 2019, 2020 and 2021 at the Tuyuksu (KZ) glacier, in 2019 and 2020 at the Golubin (KG) glacier, and at the Barkrak and Tekesh glaciers (UZ) in 2020 (see Table S3 for detailed cryosphere sampling sites information, Fig. 1). Sampling in TJ in 2020 was prevented by Covid-19 travel restrictions. The snow samples were collected from snow pits using plastic scoops, placed in plastic bags, melted at room temperature, and filtered and stored with the other water samples. The snow pit sampling was most extensive in KZ where, in 2019, samples were collected from 6 cm layers from the top to the bottom of the snow pit (Tables S1 and S3). In 2020, the snow pit was divided into three equal vertical layers of the overall depth of 162 cm and one sample was taken from each layer. In Kyrgyzstan, the cryosphere samples (snow, glacial ice and glacial melt) were collected in 2019 and 2020. In Uzbekistan, 13 samples were collected from the Tekesh and Barkrak glaciers in June and July 2020. In Kazakhstan, at least three water samples were

collected in immediate proximity of the Tuyuksu glacier terminus. Water samples were also collected from the outflow of Gorodetskiy and Morenniy rock glaciers and the meltwater from the permafrost active layer in the Ulken and Kishi Almaty headwaters. In total, cryosphere samples were taken at 39 unique locations, and the pH, EC and water temperature were measured in situ except were samples required melting, and NO_3^- -N and PO_4^{3-} -P was measured on return to the laboratory. Not all analytes could be measured in every sample (see Table S3 for details and data). Given the glacier samples include ice melt, subglacial waters, and waters emerging at the glacier snout then these data were collectively labelled 'glacier outflow'. Proglacial streams in all study areas were sampled separately further downstream and labelled 'proglacial streams'. The rock glacier samples include melt, spring and stream flow from rock glacier areas, and in combination, these were labelled 'rock glacier outflow'. The permafrost samples were taken from springs and streams in the permafrost areas and collectively labelled 'permafrost outflow'.

2.4. Laboratory analysis

Nitrate and phosphate concentrations were measured using a laboratory spectrophotometer (Hach Lange Ltd., model DR3900) and the manufacturer's reagent kits: nitrate cuvette test (part Nr. LCK 339) and phosphate ortho/total cuvette test (part Nr. LCK 349). Calibration of the spectrophotometer was checked using manufacturer standards (part Nr. LCA 721) before each analysis using a one-point calibration. Every two months, a set of three standard solutions for each analyte was prepared to check calibration drift with a $\pm 10\%$ deviation considered acceptable. Nitrate and phosphate concentrations were reported in mg L^{-1} of NO_3^- -N and PO_4^{3-} -P. The detection limits were 0.23 mg N L^{-1} and 0.05 mg P L^{-1} .

2.5. Land cover, glacial area and potential evapotranspiration

The Moderate Resolution Imaging Spectroradiometer (MODIS) Land cover product (MCD12Q1, Type 1) was used for land cover classification of the study catchments with a 500 m pixel resolution (Friedl and Sulla-Menashe, 2019). The product, using 2018 imagery, identifies 17 land

cover classes of which 13 were present and merged as follows for use in this study: forest (class 1–9); grasslands (10–11), and croplands (12 and 14) (see Table S4). Grasslands were divided into alpine grasslands and steppe based on elevation. Land cover area was calculated for each sub-catchment using the 'Calculate geometry' function in ArcGIS Pro, and the sub-catchment boundary was delineated using the Spatial Analyst Hydrology tool using the sampling point as the pour point. Glacier extent and barren terrain were delineated using the semi-automated glacier mapping method using Landsat 5 and 8 TM and Sentinel 1 and 2 imagery (Narama et al., 2010; Severskiy et al., 2016). CRU potential evapotranspiration (PET) data were obtained for 1991–2010 (grid resolution 0.5° ; CRU TS v. 4.03) (Harris et al., 2020).

2.6. Statistical methods

The differences between cryosphere measurements for each catchment were visualized using stacked box and whisker diagrams (Fig. 3) with one-way ANOVA done on the means using parametric (Welch) and non-parametric (Kruskal-Wallis) tests (R package: ggstatplot, Supplementary material, Fig. S1). The spatial variations in the surface water and groundwater quality mean values were plotted with the land cover as a background for visual inspection (Figs. 4 and 5) and summary statistics calculated for each site (Table S2a and b). The differences between the upland and lowland surface water and groundwater for each catchment were also visualized using stacked box and whisker diagrams (Fig. S2) with one-way ANOVA done using the same methods as for the cryosphere measurements (Fig. S3). Paired scatterplots were drawn and the Spearman's correlation co-efficient and the associated significance calculated to determine the correlation between analytes and with land cover using all stream and reservoir/lake data (Fig. 6), then grouped by catchment (Fig. S4) and then grouped by water type: stream and reservoir/lake (Fig. S5). No groundwater sites were included in the correlation analysis. Some sample sites were located on the same channels with the data autocorrelated and dependent. For this reason, no regression analysis was done. Only three land cover types were shown in the correlation analysis: cryosphere, cropland and urban. Cropland and urban had a high, negative correlation with the other land covers associated with the uplands: barren terrain, forest and alpine

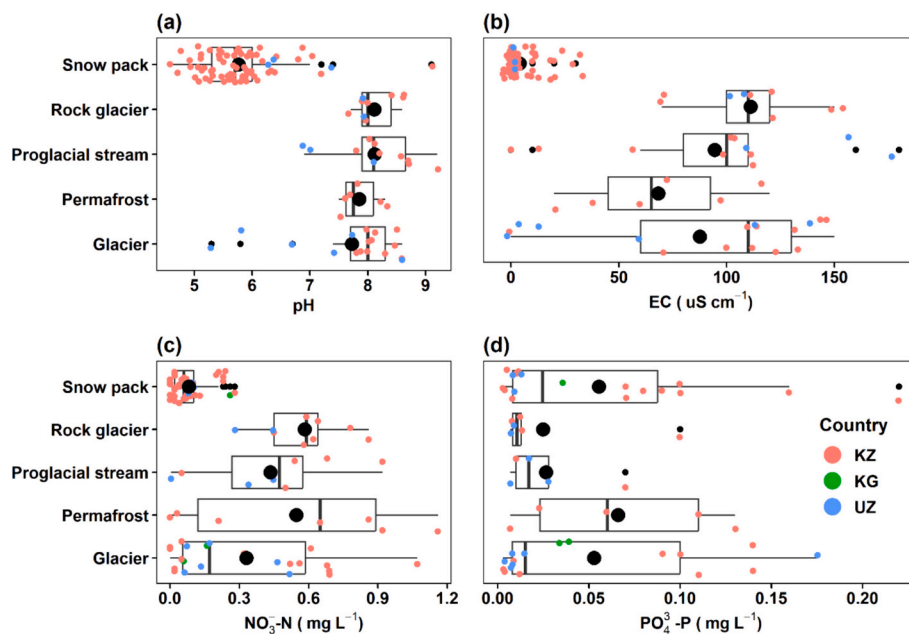


Fig. 3. Cryosphere water quality: (a) pH, (b) EC, (c) NO_3^- -N and (d) PO_4^{3-} -P in glacier, rock glacier and permafrost outflow, proglacial streams, and snowpack melt. The large black points are mean values and the small black points highlight outliers >1.5 times the inter-quartile range. Parametric and non-parametric ANOVA tests are presented in the Supplementary Material (Fig. S1).

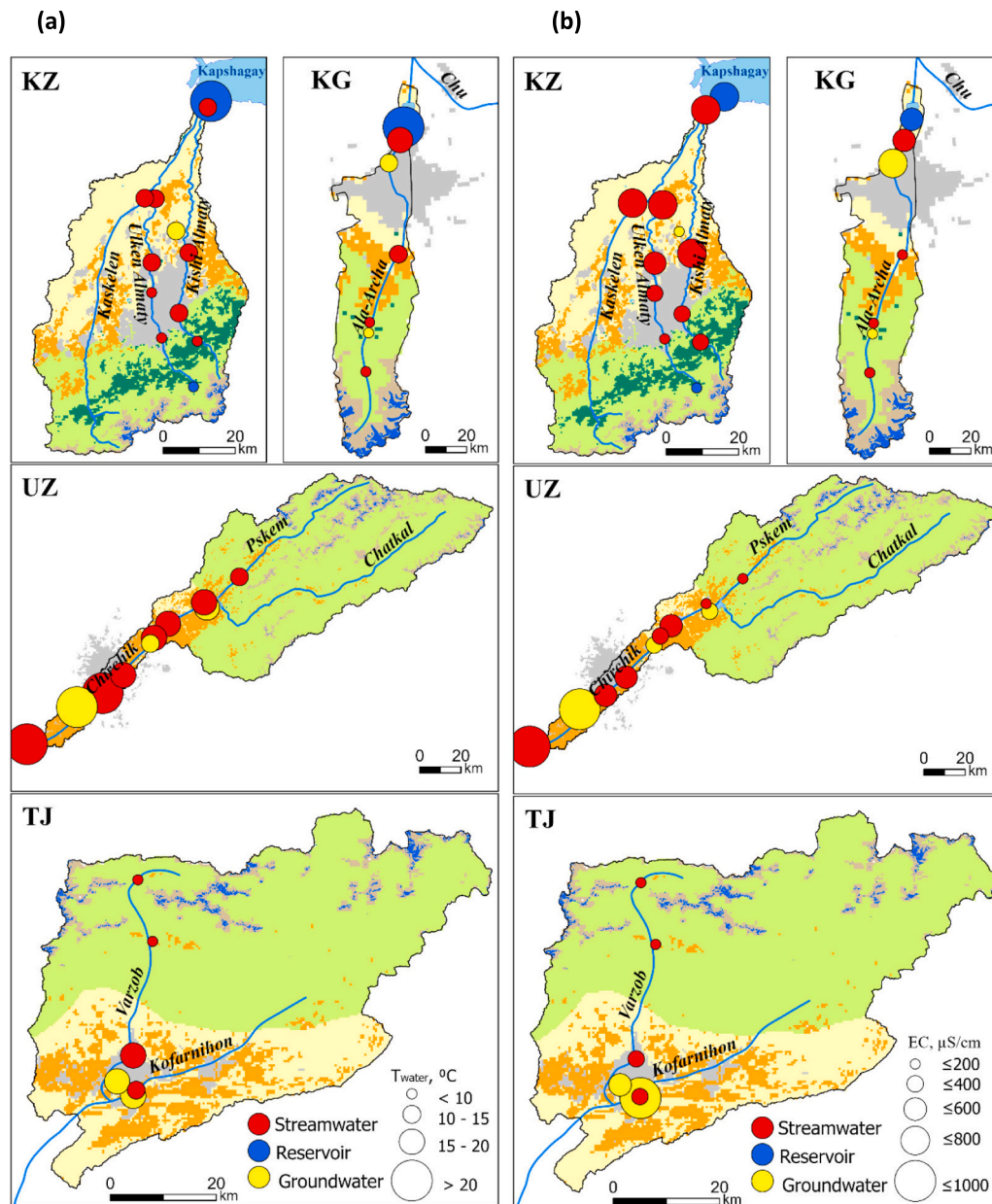


Fig. 4. Stream water, reservoir and groundwater mean (a) water temperature and (b) EC concentrations. The background shading shows the land cover classes as defined in Fig. 1.

grassland. The seasonal water-quality variations are presented in Fig. 6 with LOESS curves drawn, using the function *loess* from the core *r stats* package version 4.3.0 (R Core Team, 2020), to highlight the temporal patterns.

3. Results

3.1. Cryosphere water quality

The mountain snow-pack melt was acidic with a mean pH of 5.8, which was significantly lower than the mean pH for the glacier, permafrost and rock glacier outflows and proglacial streams (Fig. 3a, Welch, $p < 0.001$, see Supplementary materials Fig. S1a for full details). Three glacial outflow samples were acidic also, at approximately pH 5.4.

The EC of the cryosphere samples was lowest for the mountain snowpack ($n = 73$) with a mean of approximately $4 \mu\text{S cm}^{-1}$ and varied most in glacier outflow ($n = 17$) from zero to $150 \mu\text{S cm}^{-1}$ (with mean

and median values of 90 and $120 \mu\text{S cm}^{-1}$) (Fig. 3b). In comparison, the rock glacier ($n = 9$) and permafrost ($n = 6$) outflows were relatively high in dissolved ions with a mean EC of approximately 110 and $70 \mu\text{S cm}^{-1}$, respectively.

Mountain snowpack nitrate concentrations were lowest among all the cryosphere samples with a mean value of 0.1 mg N L^{-1} . The nitrate concentrations measured in the glacier and permafrost outflows and the proglacial streams were all highly variable, and only the mean nitrate concentrations in the rock glacier outflows were significantly higher ($p < 0.01$) than those in the snow melt assessed using the Welch test. However, using Kruskal-Wallis, the glacier, rock glacier, permafrost, and proglacial stream nitrate concentrations were all significantly higher ($p \leq 0.05$) than those in snow melt (Fig. S1f). The rock glacier and permafrost outflows had higher mean nitrate concentrations (c. 0.5 – 0.6 mg N L^{-1}) compared to that of the glacier outflow. The glacier outflow nitrate concentrations ranged from below detection to 1.16 mg N L^{-1} , and spanned the range of nitrate concentrations measured in rock

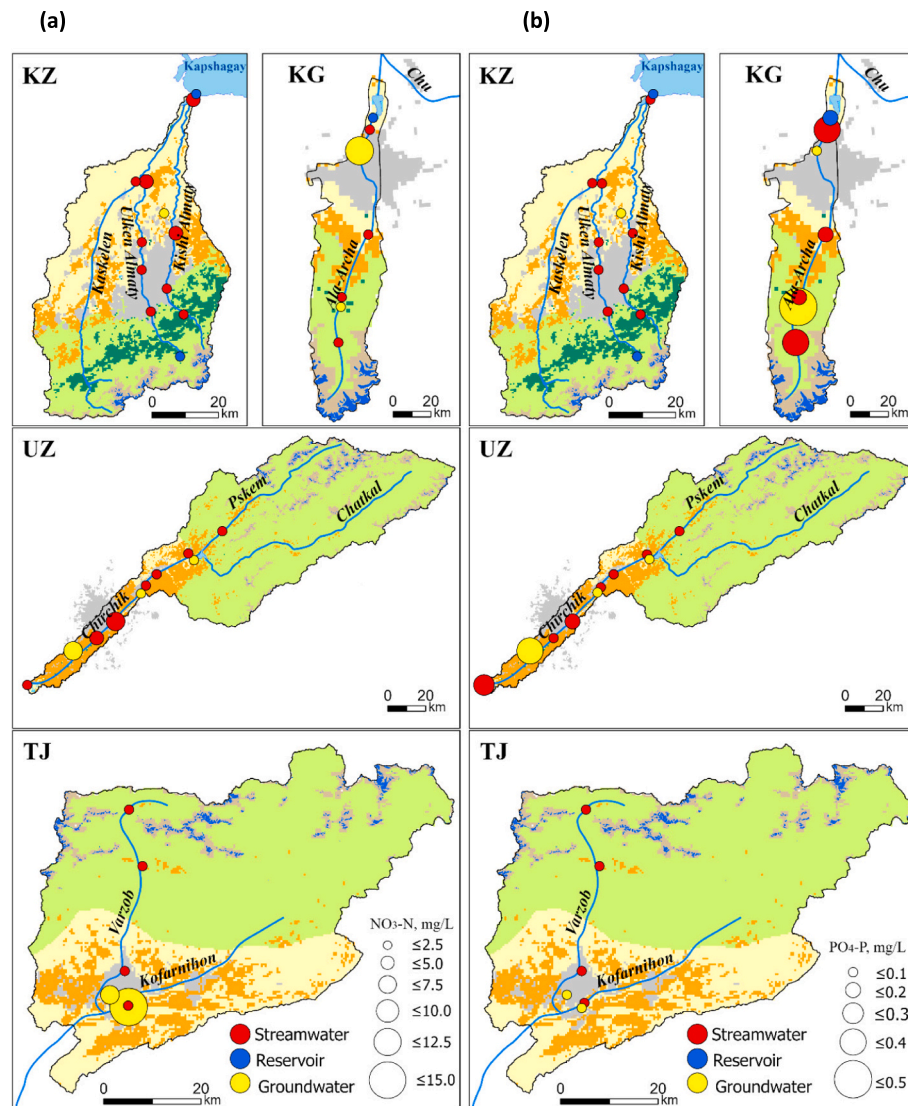


Fig. 5. Stream water, reservoir and groundwater mean (a) $\text{NO}_3\text{-N}$ and (b) $\text{PO}_4^{3-}\text{-P}$ concentrations. The background shading shows the land cover classes as defined in Fig. 1.

glacier outflows, permafrost outflows, proglacial streams and snow melt (Fig. 3c).

The cryosphere sample phosphate concentrations were all low with means of approximately $0.05 \pm 0.03 \text{ mg P L}^{-1}$ which was close to the detection limit. The highest phosphate concentrations, measured in the cryosphere samples, were found in the mountain snowpack and glacier outflows, with a maximum concentration of 0.22 mg P L^{-1} in the Tuyuksu snow melt (Fig. 3d). No significant differences between the glacier, rock glacier, permafrost, proglacial stream and snow melt group means were identified (Fig. S1g and h).

3.2. Spatial variations in surface water and groundwater quality

The elevation range that equates to the transition in land cover from upland (i.e., cryosphere, alpine grassland and forest) to lowland (i.e., cropland, urban) was found to vary between catchments and occurred in the following ranges: Ulken Almaty (800–1000 m.a.s.l.), Ala-Archa (1100–1800 m.a.s.l.), Chirchik (1400–2000 m.a.s.l.) and Kofarnihon (1300–2400 m.a.s.l.). The percentages of the three land cover types, cryosphere, cropland and urban were correlated with elevation and there was a steep increase in the cropland and urban percentages in each subcatchment below 1300–1500 m.a.s.l. (Figs. 4, 5 and 6).

3.2.1. pH

The pH data showed little variation either between stream water sites or with season and were generally within the range 7 to 8.6 (Figs. 4 and 7, Table S2a and b) suggesting any pH differences between cryosphere sources were eliminated as waters mix. There were two notable outliers. The first was the Kapshagay reservoir where the pH reached 9. The second was an urban well in Dushanbe where the pH was slightly acidic with a minimum pH of 6.4.

3.2.2. Water temperature

The mean stream water temperature increased downstream in all catchments moving from the glaciers to the plains, reflecting the decreasing influence of meltwater and the increasing air temperatures at lower elevations (Figs. 4a, 6, S4, S5, Table S2a and b). Approximately 10–20 km downstream of the glaciers, in the Kaskelen, Ala-Archa and Kofarnihon catchments, the mean water temperatures were approximately 5–7 °C and the water temperature remained in this range in these catchments until the forest and alpine grassland transition to cropland and steppe when the water temperatures increased markedly to 10–15 °C (Fig. 6).

In Kaskelen and Ala-Archa, the urban groundwater temperatures were in a similar range to the surface water temperatures with a mean of

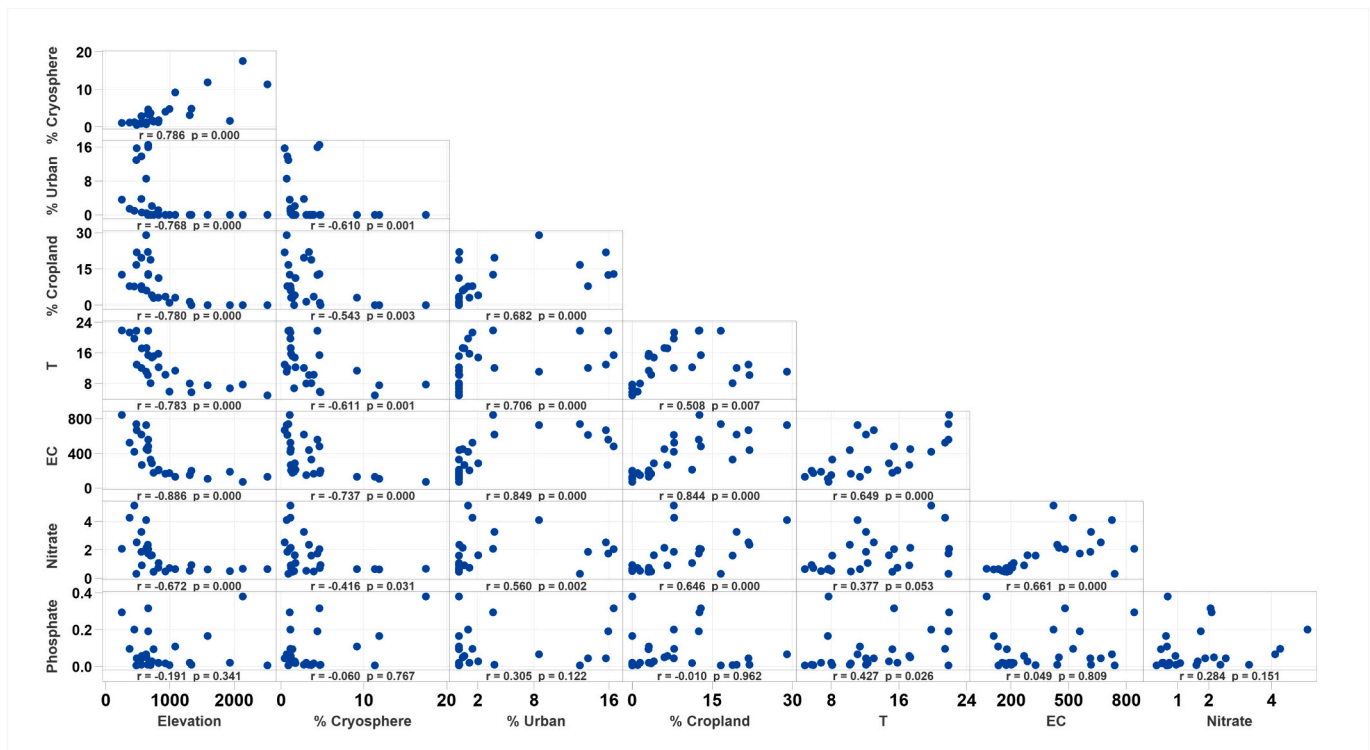


Fig. 6. Matrix scatterplot of mean water quality values across all four catchments with Spearman's correlation co-efficient values and *p*-values shown. The units are cryosphere, urban and cropland (% catchment area), elevation (m.a.s.l), mean air temperature (*T*, °C), mean electrical conductivity (EC, $\mu\text{S cm}^{-1}$), mean nitrate (mg N L^{-1}), and mean phosphate (mg P L^{-1}). No groundwater sites are included.

approximately 13 °C. In Tashkent and downstream, the surface water and groundwater temperatures of the Chirchik were similar to each other, but higher than in Kaskelen and Ala-Archa (median c. 22 °C).

The highest water temperatures were found in the two reservoirs, Kapshagay and Ala-Archa, with mean water temperatures of approximately 22 °C and summer maximums of 29 °C (Table S2b). These mean and maximum temperatures were approximately equal to those at the lowest measurement points on the Kaskelen at Arna village and the Ala-Archa at the main road bridge north of Bishkek, which were immediately upstream of the reservoir inflows. The Chirchik water temperatures were generally higher than in the other catchments because the catchment area is much larger, and the highest water quality sampling point at Mulala was further away from the glacial headwaters than elsewhere, and the lowest reaches of the Chirchik were located furthest (80–160 km) into the cropland and steppe (Fig. 4).

3.2.3. Electrical conductivity (EC)

Stream water EC, a measurement of salinity, increased downstream in all catchments and was correlated with water temperature and the percentage of cropland and urban area, which all increased downstream (Figs. 4b, 6, S4 and S5, Table S2a and b). In Kaskelen, the EC increased from approximately 130–200 $\mu\text{S cm}^{-1}$ in Big Almaty Lake (KZ-4), a reservoir formed from a proglacial lake, to approximately 500–700 $\mu\text{S cm}^{-1}$ downstream in the Kishi Almaty, Ulken Almaty and Kaskelen rivers and the Kapshagay reservoir. High ($>800 \mu\text{S cm}^{-1}$) EC concentrations were observed at Kosozen (KZ-8) on the Ulken Almaty, Arna on the Kaskelen (KZ-10), downstream of Bishkek on the Ala-Archa, and on the Chirchik near the inflow to the Syr Darya (UZ-10); however these were lower than the World Health Organization TDS standard of 1000 mg L^{-1} (approximately equivalent to 1564 $\mu\text{S cm}^{-1}$) (World Health Organization, 2011). The mean EC concentrations in the Kaskelen at Arna Village and the Kapshagay reservoir were both approximately 700 $\mu\text{S cm}^{-1}$ and in the Ala-Archa at the bridge and the Ala-Archa reservoir approximately 500 $\mu\text{S cm}^{-1}$ (Fig. 4b).

3.2.4. Nitrate

Mean surface-water nitrate concentrations ranged from 0 to 1.25 mg N L^{-1} at the high-elevation stream water sites in all four study catchments, and between 0 and 6 mg N L^{-1} at the sample locations in, and downstream of, the major cities (Figs. 5a, S2, S3e and f). Stream water nitrate concentrations were correlated with EC ($r = 0.6$, $p < 0.001$; Figs. 6, S4 and S5). The greatest spatial variability was observed in the Chirchik catchment with concentrations ranging from 0.5 mg N L^{-1} in the headwaters (UZ-1) to over 5 mg N L^{-1} near Tashkent (UZ-7). There was a strong correlation between cropland area and stream water nitrate concentration in all catchments ($r = 0.65$, $p < 0.001$, Fig. 6), and a correlation between stream water nitrate concentrations and urban area also ($r = 0.56$, $p < 0.01$, Fig. 6). The highest nitrate concentrations were measured in shallow well-water samples in Bishkek (approximately 11 mg N L^{-1}) and Dushanbe (approximately 13 mg N L^{-1}). In the croplands upstream of Bishkek and Dushanbe, lower nitrate concentrations were observed in springs, and an artesian well, which suggests lower pollution from farming compared to urban areas (Fig. S2). The stream water nitrate concentrations were lower than those in the urban groundwater also (Welch, $p < 0.001$, Fig. S3e).

Overall, the mean electrical conductivity, water temperature and stream water nitrate concentrations at stream and lake/reservoir sites were all correlated and increased with decreasing elevation starting from approximately 1300–1500 m.a.s.l., depending on the catchment (Fig. 6). This elevation range broadly equates to the transition in land cover from upland cryosphere, alpine grassland and forest to cropland and urban area (Section 3.2).

3.2.5. Phosphate

The river and groundwater phosphate concentrations were low upstream of the urban centers, with mean stream water concentrations below the detection limit of 0.05 mg P L^{-1} . Downstream of the urban areas the concentrations increase to approximately 0.2 mg P L^{-1} indicating effluent inputs to the lower reaches (Figs. 5b and S2d, Table S2a

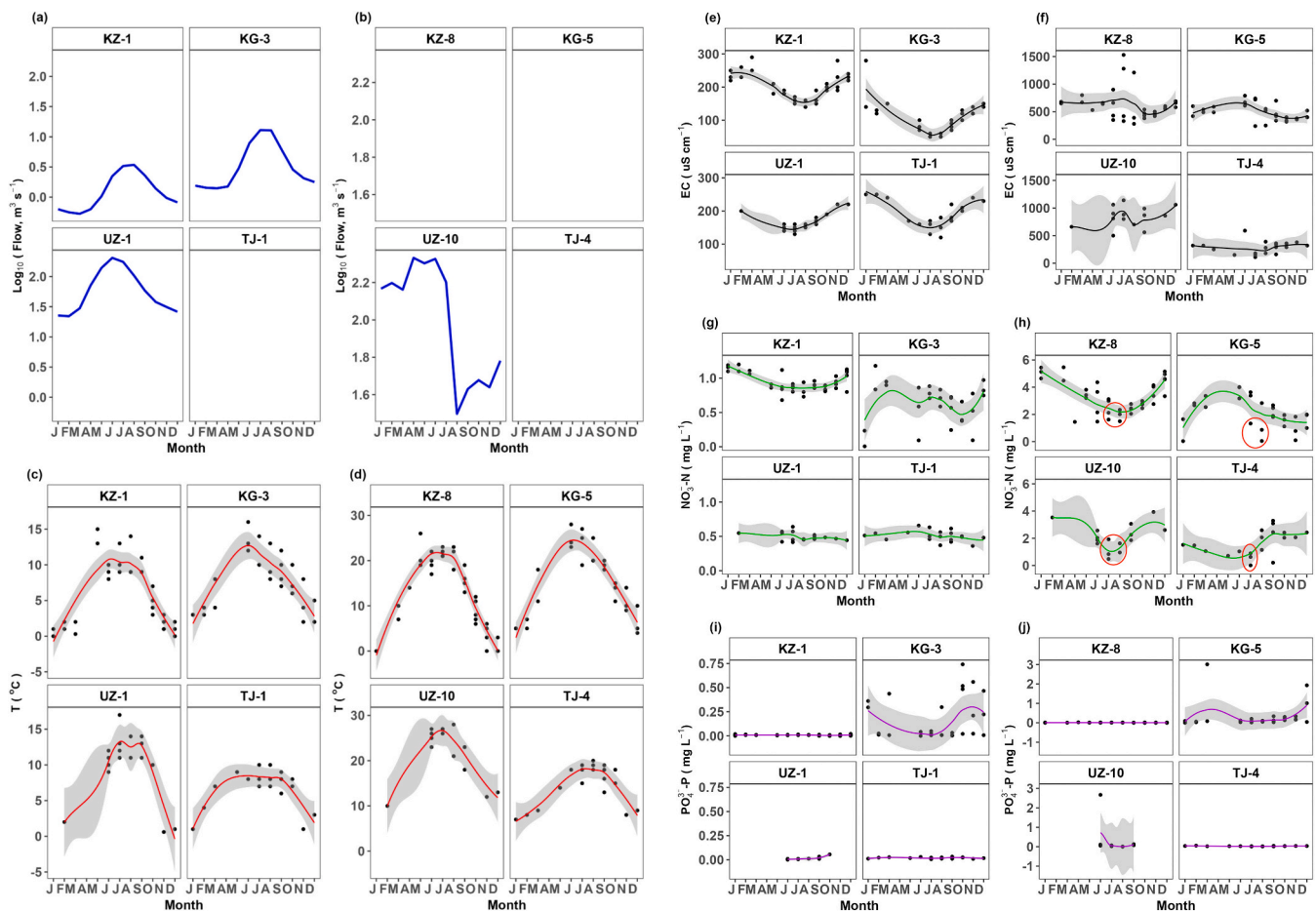


Fig. 7. Seasonal (a) flow – high elevation, (b) flow – low elevation (from Fig. 1), (c) stream water temperature – high elevation, (d) stream water temperature – low elevation in selected upstream and downstream points in each catchment (see also Fig. 1). The water quality measurements were made in 2019–2020. Seasonal (e) EC – high elevation, (f) EC – low elevation, (g) $\text{NO}_3\text{-N}$ – high elevation, (h) $\text{NO}_3\text{-N}$ – low elevation, and (i) $\text{PO}_4\text{-P}$ – high elevation, (j) $\text{PO}_4\text{-P}$ – low elevation in selected upstream and downstream points in each catchment (see also Fig. 1). The water quality measurements were made in 2019–2020. The red circles highlight the low nitrate concentrations at the lowland sites during July and August.

and b). High phosphate concentrations were measured throughout the Ala-Archa catchment with mean and maximum phosphate concentrations of 0.38 and 2.7 mg P L^{-1} (KG-1) respectively, upstream of Bishkek, and with a measurement of 1.8 mg P L^{-1} in a headwater groundwater spring (KG-2; Figs. 5b and S2, Table S2a and b). The corresponding EC concentrations were variable with some high EC values equating to high phosphate concentrations and with some samples having low EC but high phosphate (Fig. 6). Large spikes, as high as 3 mg P L^{-1} , were also measured in the phosphate concentrations in Bishkek (KG-5; Figs. 5b and S2d, Table S2a and S2b). Relatively high phosphate concentrations of approximately 0.3 mg P L^{-1} were also observed in an urban well (UZ-9) in the Chirchik catchment and at the surface water sampling point immediately downstream of Tashkent (UZ-10; Figs. 5b and S2d, Table S2a and S2b). Overall, the stream water phosphate concentrations were only weakly correlated with urban area ($r = 0.3$, not significant) and not correlated with cropland ($r = 0.0$), and there was little correlation with stream water nitrate concentration ($r = 0.28$).

3.3. Seasonal water quality dynamics

3.3.1. Stream flow

The seasonal variations in stream flow are described in Section 2 and are drawn in Fig. 7 to allow comparison with the observed water quality dynamics. The stream measurement locations on the Kishi Almaty (KZ-1), Ala-Archa (KG-3) and Chirchik (UZ-1 and UZ-10) were co-located with the stream water sampling points.

3.3.2. Water temperature

Stream water temperatures at the upland and lowland sites have a strong seasonal pattern with temperature maximums in summer (JJA) and minimums in winter (NDJF). In the uplands of the Kishi Almaty (KZ-1), Ala-Archa (KG-3) and Chirchik (UZ-1), the maximums were in the range of 10 to 15°C . These were higher when compared to the Maykhura River which is a headwater tributary of the Varzob where the maximum water temperatures were between 5 and 10°C but the elevation was higher (Fig. 7c). This difference was evident in the lowland reaches also with the summer stream water maximum temperatures between 20 and 30°C in the Kaskelen, Ala-Archa and Chirchik, but approximately 18°C in the Kofarnihon (Fig. 7d).

3.3.3. Electrical conductivity

Seasonal changes in electrical conductivity (EC) were evident with EC lower under the summer high flow conditions at all upstream sites suggesting solute dilution (KG-3, KZ-1, TJ-1 and UZ-1, Fig. 7a and e). The lowest EC concentrations occurred one month after peak flow, indicating a dilution effect due to the input of water with relatively low EC from glacier outflow and snow melt (see Section 3.1). At the downstream-lowland locations, the meltwater inputs reduced the mean EC at all sites in July and August relative to the June values commensurate with an increased input of melt water (Fig. 7a, b and f). In the snowmelt dominated Kofarnihon River at Dushanbe (TJ-4), the EC seasonal variation was low with a mean value of $285 \mu\text{S cm}^{-1}$ demonstrating a sustained dilution even at the most downstream site below a

large urban area (Fig. 7a, b and f, Table S2a and b).

Variations in EC were evident around the mean EC values in all catchments and, in the downstream-lowlands of Ala-Archa (KG-5), the EC peaked at approximately $800 \mu\text{S cm}^{-1}$ in July and August (Fig. 7f). A large annual variation in EC was observed at the lowest sample site on the Ulken Almaty (KZ-8), downstream of Almaty, and was probably dependent on the amount of summer glacier and snow melt, and altered hydrological connections between soil leaching and the main river, during the summer months in 2019 and 2020 (Fig. 7f). In the Ulken Almaty at Kosozen (KZ-8), the summer EC varied from 300 to $1600 \mu\text{S cm}^{-1}$ in July due to differences in discharge between 2019 and 2020. In 2019, the summer discharge was high and associated with an EC of $300 \mu\text{S cm}^{-1}$. In 2020, delayed melt due to cloudy conditions and lower air temperatures resulted in lower summer discharge and an EC of $1600 \mu\text{S cm}^{-1}$.

3.3.4. Nitrate

In the Kishi Almaty (KZ-1) and Ala-Archa rivers (KG-3) at high-elevation, there is some evidence that nitrate was higher during the winter low-flow period and lower during the summer melt period, though little seasonal variability in nitrate concentrations was observed for the Chirchik (UZ-1) and Varzob (TJ-1) rivers (Fig. 7g). The nitrate concentrations of all the cryosphere samples range from 0 to 1.2 mg N L^{-1} (Section 3.1), which were close to the values observed in the upstream stream water sites and this suggests complex mixing from the range of water sources.

Seasonal variations in the lowland nitrate concentrations were larger and the patterns complex. In the lowlands, nitrate concentration minima were observed in the Ulken Almaty (KZ-8) in August, in Chirchik (UZ-10) in July and August, and in the Kofarnihon (TJ-4) in July (Fig. 7h). In Ala-Archa (KG-5), the nitrate concentrations decrease after June to a minimum in December and January. Thus, there is evidence that the lowest nitrate concentrations corresponded with the periods of highest cryosphere melt water inputs (Fig. 7h, red circle highlight).

3.3.5. Phosphate

Both high- and low-elevation phosphate concentrations exhibited little seasonal variation (Fig. 7i and j), though concentration spikes were evident. There was some evidence for meltwater dilution or summer uptake of phosphate in the high-elevation Ala-Archa (KG-3) and phosphate concentration spikes were measured in March (3 mg P L^{-1}) and December (1.9 mg P L^{-1}) at the downstream Ala-Archa site (KG-5). High phosphate concentrations were also measured in the Chirchik (UZ-10) in June with maximum values of 0.97 and 2.7 mg P L^{-1} for UZ-9 and UZ-10 respectively suggesting an agricultural or urban source (Fig. 7j, Table S2a and b).

4. Discussion

For the first time, an extensive spatial and temporal dataset describing key water quality parameters has been created for four glaciated catchments in Central Asia. Whilst some data were available for KZ and UZ, this study extends water quality measurement to KG and TJ, increases the measurement frequency from monthly to fortnightly to better capture seasonal variations, links the cryosphere to the downstream stream water, and includes groundwater and high mountain and lowland reservoirs. Thus, the work begins to address recent calls for better systematic and consistent quantification of contaminants in the catchments of Central Asia through the initiation of a water quality monitoring network (Beard et al., 2022a; Beard et al., 2022b; Leng et al., 2021; Liu et al., 2021).

4.1. Cryosphere water quality

We observed snow to have the lowest pH values. This likely reflects the interaction between precipitation and atmospheric carbon dioxide to

form weak carbonic acid, with further absorption of carbon dioxide during snow melt (Sharp and Tranter, 2017). Interactions, in the atmosphere, between the precipitation and sulphur and nitrogen oxides to form weak sulphuric and nitric acids are also possible. In contrast, glacier, rock glacier and permafrost outflows and proglacial stream waters were neutral or slightly alkaline. These neutral and slightly alkaline pH values indicate greater contact of the outflow with soil and bedrock, which likely contain carbonates mostly as CaCO_3 (Fig. 3a) (Yapiyev et al., 2021). The three instances of low pH (5.3–6.7) in outflow from the Barkrak glacier (UZ), occurred in August 2020 and were attributed to snow melt, though sulphide oxidation in the subglacial drainage system cannot be excluded (Li et al., 2022; Tranter et al., 1997).

The higher EC concentrations in the permafrost and rock glacier outflows, when compared to glacier and snow melt EC concentrations, were likely due to greater rock: water ratios and rock-water contact times. The EC measured at the upland stream water sites, 10–20 km downstream of the cryosphere, had a similar range to the glacier outflow (0 – $200 \mu\text{S cm}^{-1}$, Section 3.1; Table S2a and b); This similarity suggests few additional solute inputs and instream processing until the transition from the forest and alpine grassland to cropland and steppe.

Our data show that nitrate can be present in significant concentrations in mountain cryosphere streams, particularly in the Ulken Almaty headwaters which contained over $1 \text{ mg NO}_3\text{-N L}^{-1}$. This result concurs with Slemmons et al. (2013) who also note that nitrate enriched melt can lead upland lakes to shift from N and P co-limitation to P-limitation. The nitrate concentrations were especially high in rock glacier and permafrost outflows. Therefore, the subsequent contribution of permafrost and rock glaciers is a concern for downstream fluxes to streams and lakes (Fegel et al., 2016).

Given the proglacial stream nitrate concentrations were found to be significantly lower than those in rock glacier and permafrost outflows and significantly higher than those in the snowpack melt, then the proglacial stream water nitrate seems likely derived from a mixture of sources. These sources were both primary, namely from basal debris with the nitrate transported with subglacial flow, rock glacier springs and permafrost outflows, and secondary, with the nitrate derived from the release, during melt, of legacy wet and dry nitrogen deposition stored in snow. The primary nitrate sources were likely microbial ammonification of organic nitrogen with subsequent nitrification (Wynn et al., 2007), supplemented by rock weathering (Montross et al., 2013). Further work is required to confirm this.

In 1999, Vilesov and Uvarov (2001) measured elevated nitrate concentrations (up to 3.9 mg L^{-1} of $\text{NO}_3\text{-N}$) in Tyuksu glacier melt samples, and these were linked to the air pollution of Almaty from fossil fuel combustion. We did not find concentrations as high and more detailed study is required to better understand the relative contribution of nitrate to proglacial streams from atmospheric deposition, especially as air pollution of large cities in Central Asia is a growing concern (Tursumbayeva et al., 2023). The relative contributions of supraglacial, englacial and subglacial melt, including snow and firn melt, also require further measurement to confirm if the nitrate is derived from a mix of primary and secondary sources (Sharp and Tranter, 2017). Further, to develop a more complete understanding of nitrate sources and dynamics, investigation is required also of the relative seasonal nitrate inputs from soil and groundwater (Colombo et al., 2019; Williams et al., 2007), as well as the importance of nitrification following substrate exposure after glacier and rock glacier thaw, and permafrost thaw (Barnes et al., 2014; Baron et al., 2009; Clark et al., 2021).

The glacier, rock glacier and permafrost outflow, proglacial stream and snowpack mean phosphate concentrations were not significantly different. This result demonstrates less distinction between the phosphate concentrations in wet and dry deposition and those derived from water contact with rock and basal debris. The phosphate concentrations in the cryosphere samples were also low. Together, these results suggest low phosphate inputs from weathering and deposition, or that any

available phosphorus was rapidly assimilated by the glacier, soil or stream biota. Whilst glacier flour was not an important source of phosphate, the possibility remains of phosphorus weathering release in a particulate form (Darcy and Schmidt, 2016; Hodson et al., 2004; McCutcheon et al., 2021; Ren et al., 2019; Tranter, 2003).

4.2. Cryosphere and land use influence on water quality

In all four catchments, land cover was correlated with elevation, and there was a marked transition in water quality in the elevation range where the land cover changed from forest and alpine grassland to cropland, urban and grassland steppe. There was strong evidence that land cover explained the spatial variations in the water temperature, EC and nitrate concentrations as there was significant correlation between these and the percentage of cryosphere, cropland and urban area (Fig. 6). Thus, land cover is the predominant control on the spatial variations in water quality.

The observed longitudinal variations in stream water nitrate and phosphate concentrations were found to be similar to other regional studies, being low close to the glaciers, and higher in urban and cropland areas (<0.23 to 6 mg N L^{-1} ; <0.05 to 3 mg P L^{-1}) (Leng et al., 2021; Yapiyev et al., 2021). The elevated phosphate concentrations with a mean of 0.43 mg P L^{-1} and a maximum of 1.86 mg P L^{-1} measured in an upland spring in the Ala-Archa (KG-2) but distant ($>10 \text{ km}$) from the cryosphere are difficult to explain. The concentrations may be due to small, localised sewage inputs, or a geological source. Further measurements of the spring water and local geochemistry are required for resolution.

Whilst EC and $\text{NO}_3\text{-N}$ concentrations were correlated, the increase in stream water $\text{NO}_3\text{-N}$ concentrations at the land cover transition was less marked than for EC. This may reflect that nitrogen inputs from agriculture remain low even following economic recovery in the post-Soviet era, or that farms and farmland are managed to maintain a balance between nitrogen inputs and outputs. World Bank fertilizer application data suggest the former, with fertilizer-application rates generally low except in Uzbekistan which may explain partly the higher stream water $\text{NO}_3\text{-N}$ concentrations observed in the Chirchik (Yapiyev et al., 2021).

If the groundwater and surface water EC and nitrate concentrations measured in proximity were similar, then this would suggest mixing. The EC and nitrate concentrations in the urban groundwater were all significantly higher than those in the surface waters, both upstream and downstream of the cities. Therefore, there was no evidence of surface-groundwater mixing diluting groundwater EC, nitrate and phosphate concentrations. Instead, the higher nitrate and phosphate ($>0.2 \text{ mg P L}^{-1}$) concentrations observed in urban wells indicate the contamination of urban groundwater with sewage effluent. Leng et al. (2021) modelled high total dissolved phosphorus inputs in urban locations from effluent discharges which concurs with our findings. Further investigation is required, using stable water and nitrogen isotopes, to determine if the groundwater is distinct from the surface water in all the urban areas sampled, especially in Bishkek where groundwater and surface water mixing has been observed to occur (Morris et al., 2006).

The high pH measured in Kapshagay reservoir was likely due to the wash-in of the adjacent Calcisols enriched in calcium carbonate and bicarbonate. The finding that the mean and maximum temperatures and EC concentrations were approximately equal in the Kapshagay reservoir and at the lowest measurement point on Kaskelen at Arna village, and in the Ala-Archa reservoir and the upstream river sample point at the main road bridge north of Bishkek, demonstrates the influence of the rivers on the reservoir water quality close to the inflow.

In the mountains, seasonal dynamics in the water temperatures and EC were evident in all four catchments indicating ion dilution during the summer (JJA) melt. At the most downstream sites on the main river channels, a dilution effect was discernible with lower EC and $\text{NO}_3\text{-N}$ concentrations during JJA even when the land cover was dominated by cropland and urban areas. However, though the stream water EC and

nitrate concentrations were lower during the high flows in the summer, the total flux of ions including nitrate, could be higher due to the increased flow. Observations of glacier and snow melt within Kaskelen and Ala-Archa, suggest stream flows are dominated by snow melt from April to mid to late June, and this is followed by glacier melt from July until mid to late October. This suggests that the in Ala-Archa and Kishi Almaty headwaters, the nitrate flux was dominated by a steady, supply of nitrate from the glacier, rock glacier and permafrost outflow, which was diluted by summer snow melt to begin, however as the minimum monthly concentrations were observed in August, this suggests that glacier melt was a contributing factor to dilution also.

Overall, we find that land cover was the predominant control on the spatial variations in water quality, with a seasonal dilution effect evident in the river nitrate and EC concentrations even at the most downstream locations some 100 s km from the headwaters. The melt water dilution effect was difficult to quantify with the data collected because of the integration of sources, pathways, and instream processes including evapoconcentration, nitrification and denitrification, which may amplify or diminish the summer ion concentrations and cause a positive correlation between discharge and stream water nitrate concentration close to glaciers and rock glaciers. The nearest flow measurement locations were at least 10 km from the glaciers. To confirm the importance of melt water dilution in the lowlands, further work is needed to measure flow and concentrations simultaneously at multiple sites along the continuum to enhance understanding and quantification of the wash-in of contaminants from the cryosphere, croplands and urban groundwater, biogeochemical cycling and the dilution effects of inter and intra-year variations in snow and ice melt. Ideally these measurements should be supplemented with water isotope measurements to track cryosphere contributions and nitrogen isotope experiments to help quantify instream nitrogen processing. Further assessment should include also the effects of higher air temperatures, an early melt season, greater spring precipitation and controlled water release from lakes and reservoirs (Mueller et al., 2016).

4.3. Water pollution

The general downstream increase in EC was likely caused by pollutant inputs from cropland and urban areas, higher evapoconcentration resultant from higher water temperatures, longer water residence times, and probably inflows of irrigation return water and soil leaching. Downstream of the land cover transition, contamination hot-spots were evident. The stream water EC remained within accepted standards for good quality drinking and irrigation water though higher ($>1000 \text{ }\mu\text{S cm}^{-1}$) values occurred near the river mouths, lowland reservoirs and groundwaters but still below levels that become problematic for human and livestock consumption (i.e., c. $1500 \text{ }\mu\text{S cm}^{-1}$) (World Health Organization, 2011). The groundwater had higher EC than the surface waters likely due to higher dissolved solutes and urban pollution, however it was also lower than $1500 \text{ }\mu\text{S cm}^{-1}$.

Along the continuum from the source to the plains, the stream water nitrate concentrations in all four catchments complied with the national drinking water standards of 10 mg N L^{-1} adopted in KZ, KG and TJ and 9 mg N L^{-1} adopted in UZ, and the 11.3 mg N L^{-1} set by the World Health Organization (Yapiyev et al., 2021). The high urban groundwater nitrate concentrations indicate pollution with concentrations measured above the national drinking water standards.

The surface water phosphate concentrations generally do not breach national drinking water standards; however, they are a concern for eutrophication in the lower river reaches with concentrations measured above nutrient thresholds for eutrophication ($\text{TP} > 0.1 \text{ mg P L}^{-1}$ and $\text{TN} > 1 \text{ mg N L}^{-1}$) (Figs. 4b and 5, Table 2a and b) (Bowes et al., 2012; Poikane et al., 2022). The high groundwater phosphate concentrations in Bishkek, Tashkent and Dushanbe suggest likely microbial contamination given the lack of sewage treatment and this is important to remedy given the millions of people potentially effected (Table 1).

The water stored in upland lakes and reservoirs was clean in terms of the analytes measured and of apparent high quality for drinking when transferred to the cities downstream. There was neither evidence of lake or reservoir acidification nor eutrophication. Based on field observations, the cold water-temperatures in the mountains, typically <6 °C, combined with the turbulent, often turbid, stream flows, appear to keep primary productivity low in streams and limited to biofilm and microbial growth, which is similar to other high mountain ecosystems (Milner et al., 2017; Slemmons et al., 2013). However, the productivity of the lakes and reservoirs requires a more complete assessment to determine eutrophication risk.

4.4. Next steps: extending the range of water quality measurements

Given projected population growth in the region and the reliance on glacier and snow melt water for irrigation and drinking, and transboundary contaminant transport in both the atmosphere and water, then continued regional collaboration is required to maintain and expand the monitoring network established. The transport and release from ice and snow of persistent organic pollutants, for example organochlorine pesticides, including DDT (e.g. *p,p'*-DDT and its chief metabolite *p,p'*-DDE) and the Hexachlorocyclohexane isomers (e.g. α and γ -HCH), PAHs and PFAS, and potentially toxic elements (e.g., Pb, Cd and As) and radionuclides, now need to be considered given projected increases in dust storms in the region and the legacy pollution identified (Banks et al., 2022; Nobakht et al., 2021). This assessment should include measurement of sediment transport and the associated contamination (Guney et al., 2020; Liu et al., 2021). Our data showed that there is likely a substantial nitrate flux from the cryosphere melt given the relatively high concentrations measured, however, concurrent flow and concentration measurements are required to determine accurate flux estimates for a range of solutes and particulates. Enhanced primary productivity depends on residence time, light and water temperature, and further work is needed to assess these in the proglacial streams, downstream lakes and the lower river reaches to better assess eutrophication with consideration of organic and particulate forms of nitrogen, phosphorus and carbon.

5. Conclusion

The first dataset to describe the water quality in four catchments in Central Asia in a systematic way is presented. Our key findings are that land cover is the predominant control on the spatial variations in water quality, and that water derived from the cryosphere is an important control on downstream water quality in the main river channel; A summer dilution effect is discernible 100 s of km from the glacial headwaters. Overall, the water quality is good upstream and downstream of the transition point in land cover from alpine grassland and forest to cropland and steppe when compared with national and World Health Organization standards. However, melting ice and snow in the cryosphere appears to be a source of nitrate, likely from both microbial processing and weathering, and the release of nitrogen deposition. Shallow urban groundwater is contaminated by nitrate and phosphate, most probably from urban sewage, and these pollution hot spots are a primary concern given the use of groundwater for drinking in Bishkek and Dushanbe. The data provide a baseline against which to assess future changes in spatial and seasonal concentrations, and the newly established network of environmental research institutes in Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan provides a basis for further systematic, water quality measurement across the region. Whilst a melt water dilution effect is discernable in the seasonal data even at the lowest monitoring points close to the river mouths, an exact quantification of the dilution effect is required, probably using stable water and nitrogen isotopes and modelling, to determine the melt water contribution along the continuum and the implications of a reduced future melt water input on water quality.

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CRediT authorship contribution statement

Andrew J. Wade: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Vadim Yapiyev:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Shahgedanova:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Zarina Saidaliyeva:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis, Data curation. **Azamat Madibekov:** Validation, Supervision, Resources, Methodology, Investigation. **Vassiliy Kapitsa:** Investigation. **Nikolay Kasatkin:** Investigation. **Laura Ismukhanova:** Investigation. **Roza Kulbekova:** Investigation. **Botakoz Sultanbekova:** Investigation. **Igor Severskiy:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mukhammed Esenaman:** Investigation. **Olga Kalashnikova:** Investigation. **Ryskul Usabaliyev:** Supervision, Project administration, Funding acquisition. **Fakhriddin Akbarov:** Investigation. **Gulomjon Umirzakov:** Writing – review & editing, Investigation. **Maksim Petrov:** Supervision, Project administration, Funding acquisition. **Ilkhomiddin Rakhimov:** Validation, Investigation. **Dilorom Kayumova:** Investigation. **Abdulhamid Kayumov:** Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Andrew J Wade reports financial support and article publishing charges were provided by UK Research and Innovation. Maria Shahgedanova reports financial support and article publishing charges were provided by UK Research and Innovation. Andrew J Wade reports a relationship with UK Research and Innovation that includes: funding grants. Maria Shahgedanova reports a relationship with UK Research and Innovation that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Research shared in open Mendeley Data Repository

[Data for: Influence of cryosphere outflow and land cover on stream water quality in Central Asia's glacierized catchments \(Original data\) \(Mendeley Data\)](#)

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