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Exploration of the driving factors and distribution of fecal coliform in rivers under a traditional agro-pastoral economy in Kyrgyzstan, Central Asia

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HIGHLIGHTS

- The fecal coliform (FC) concentration in surface water of Kyrgyzstan ranged from 0 to 23 MPN/mL.
- The FC concentration in high river flow period and in lowlands was higher.
- Animal husbandry contributed for little to FC in Kyrgyzstan.
- Population and human modification of terrestrial systems strongly correlated with FC.

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ABSTRACT

Fecal coliform (FC) in river water is one of the threats to human health. To explore the pollution status of FC in rivers of Kyrgyzstan, a mountainous country with traditional agro-pastoral economy, 184 water samples from the rivers of Kyrgyzstan in low and high river flow period were analyzed. Spatial autocorrelation and classical statistical methods were used to analyze the spatiotemporal distribution and driving factors of FC. The results showed that the surface water quality of Kyrgyz rivers was good, and the concentration range of FC was 0–23 MPN/100 mL. Temporally, the maximum FC concentration was 4 MPN/100 mL in low river flow period, while in the period of high river flow, the highest value reached to 23 MPN/100 mL. Spatially, the concentration of FC in high altitude areas was low, while that in the lowland areas was relatively high, which indicated that animal husbandry in high altitude areas contributed little to FC in rivers, and urban domestic sewage and agricultural activities in lowlands were the main pollution sources of FC in rivers. There was no correlation between FC and hardness, electrical conductivity (EC), pH and total organic carbon (TOC) in river water of Kyrgyzstan, and the distribution of FC in high river flow period was mainly driven by population and human modification of terrestrial systems. The results can provide a basis for the prevention and control of surface water FC pollution and related diseases in Kyrgyzstan.

1. Introduction

With the growth of populations and the transformation of terrestrial ecosystems, microbial pollution in water has become a major threat to human health (Kongprajug et al., 2019; Roșca et al., 2020). To date, outbreaks of gastrointestinal, eye, ear, skin and respiratory diseases caused by exposure to contaminated water (swimming or bathing) or direct consumption of contaminated water have been reported worldwide (Eregno et al., 2016; Florini et al., 2020; Viau et al., 2011). In particular, for Central Asia, due to the lack of proper sanitation and safe drinking water supply facilities, most of the population obtains drinking water from open water sources, such as irrigation channels, rivers and

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unprotected wells (Bekturganov et al., 2016; Liu et al., 2020). In recent years, parasitic diseases and pathogenic microbial infections caused by poor health habits and unsafe drinking water have become considerable public health problems in Central Asia (Bekturganov et al., 2016). Kyrgyzstan is located in the center of Central Asia, where glaciers are widely developed and water resources are abundant. Therefore, Kyrgyzstan is referred to as the "water tower" of the five Central Asian countries (Li et al., 2010). The quality of river water in Kyrgyzstan is very important not only for its aquatic ecosystem and associated human health implications but also due to its impact on other Central Asian countries downstream of the rivers. However, the surface water quality researches carried out in Kyrgyzstan mainly focuses on physical and chemical pollutants, and the research areas have been limited to river basins or restricted regions (Corcho Alvarado et al., 2014; Kulenbekov et al., 2012; Liu et al., 2020; Ma et al. 2019, 2020). Therefore, it is of practical significance to study the microbial pollution of surface water in Kyrgyzstan.

The concentration of fecal indicator bacteria (FIB) is usually used to evaluate microbial pollution in water (Zhang et al., 2020). Fecal coliform (FC), as one of the most practical FIB, has been widely used in water microbial pollution assessments worldwide (Choi and Seo, 2018; Neufeld et al., 2020; Ramos-Ramírez et al., 2020; St Laurent and Mazumder, 2014). Differing from other physical or chemical pollutants, the state and concentration of FC with biological activity in rivers changes dynamically in time and space due to various climate conditions, water environmental factors and human activities (Zhang et al., 2020). Macroscopically, FC usually shows seasonal or temporal distribution variability under the influence of various climate factors, such as precipitation (Cho et al., 2010; Jokinen et al., 2019; Park et al., 2018), precipitation events (Lalancette et al., 2014), accumulated rainfall (Vijayashanthar et al., 2018), temperature and wind speed (Pang et al., 2018). Simultaneously, the physical and chemical properties of water affect the survival, decay or growth rate of FC. However, the specific mechanism of this effect has not been uniformly confirmed across different water bodies or regions with different FC pollution sources. Previous studies have shown that some physical and chemical water parameters, such as pH, turbidity, ammonia nitrogen, chloride ions, dissolved oxygen and NO_3^-, in water were significantly correlated with FC concentrations (Draper et al., 2016; Mitra et al., 2018; Mustapha et al., 2013). However, some studies have found no significant correlation between the distribution of FC concentrations and aquatic environment factors in areas where human activities were the main influencing factors (Vesga et al., 2019). In addition, in the tidal system of Tamsui River Estuary, Taiwan, the concentration distribution of FC was found to be influenced by the settling velocity of suspended sediment, partition coefficient, darkness decay rate and FC concentration in the sediment bed (Chen and Liu, 2017). Similarly, the anthropogenic factors influencing dynamic changes in FC concentrations, such as urbanization, land use change, population density, road density and the proportion of tertiary industry in GDP, also vary across different regions and water bodies (Avigliano and Schenone, 2015; Hong et al., 2010; Vitro et al., 2017; Wang et al., 2017). In addition, relevant scholars have also conducted a lot of researches on FC concentration level, transport pattern, spatiotemporal variability or key influencing factors of the regions with different human activities degrees. For example, in rural-suburban-urban watershed with multiple land uses (Zhang et al., 2020), tropical urban watershed (Chow et al., 2013), cold climate region (Meshesha et al., 2020), large tropical river (Yadav et al., 2019), and Atlantic rainforest without city influence (Avigliano and Schenone, 2015), etc. In Central Asia, under the condition of the traditional agro-pastoral economy, animal husbandry in high mountain areas and agricultural activities in lowland areas that use livestock manure as organic fertilizer are potential sources of FC contamination in rivers. However, knowledge of concentrations, spatial and temporal distribution characteristics and driving factors of FC pollution are still poor understood in typical mountainous country with traditional agro-pastoral economy, and need to be further studied.

The objectives of this study were to 1) investigate the concentration of FC in the river water of Kyrgyzstan, which is a traditional country with an agro-pastoral economy in Central Asia; 2) reveal the spatial and temporal distribution of the FC concentration in the river water of Kyrgyzstan; and 3) explore the main driving factors of the FC concentration. Therefore, water samples were collected from the major rivers and their tributaries in Kyrgyzstan during low and high river flow periods in 2017, and the samples and data were analyzed by means of experimental analyses, spatial autocorrelation analyses and classical statistical methods in this study. The research results can provide a scientific basis for the evaluation of water quality in rivers and regions across Kyrgyzstan and other Central Asian countries and formulation of seasonal control measures of microbial pollution.

2. Geographical setting

Kyrgyzstan is located in northeastern Central Asia (Fig. 1a), bordering Kazakhstan in the north, Tajikistan in the south, Uzbekistan in the southwest, and China in the southeast and east. Kyrgyzstan is approximately 925 km long from east to west and 454 km long from north to south, covering a land area of 199,900 km^2 (Omurakunova et al., 2020). In Kyrgyzstan, there are seven states (provinces): Chuy, Talas, Osh, Jalal-Abad, Naryn, Ysykt and Batken (Fig. 1b). There are over 2.5×10^4 rivers, 1923 lakes and well-developed glacier resources in Kyrgyzstan, which all contribute to its rich river water resources (Miao et al., 2011). Kyrgyzstan is a mountainous country, with mountains accounting for approximately 94 % of the total land area (Hoppe et al., 2016), and the lowlands are mainly distributed in the Fergana Basin in the southwest and the Talas River Valley in the north. As a result, the large areas consisting of natural seasonal pastures and grasslands, animal husbandry have become important pillars of Kyrgyz agriculture and key areas of the Kyrgyz economy. Among them, grass and livestock species are important parts of the country's animal husbandry practices, with cattle, wool sheep, goats and horse feed accounting for the vast majority of the produced animal husbandry varieties, while pigs and chickens account for a relatively small proportion (Datkaiym, 2020). The economy in Kyrgyzstan is dominated by traditional agro-pastoral production, with the agriculture-related population accounting for more than 60 % of the total population, and its industrial base is weak (Ai, 2018).

3. Materials and methods

3.1. Sampling and analysis

Systematic sampling of river water in Kyrgyzstan was carried out in May (low river flow period) and July–August (high river flow period) of 2017. The locations of the sampling points are shown in Fig. 1c. Ninety-two samples were collected in each period for a total of 184 samples (Table S1 and Table S2). Water chemical parameters such as pH and electrical conductivity (EC), were measured in situ by an HI 9828 multiparameter water quality meter (HI 9828, Hanna instruments, Limena, Italy). The total organic carbon (TOC) content was measured by a total organic carbon analyzer (Multi N/C 2100, Analytic Jena AG, Jena, Germany), which has a detection limit of 800 ppb. FCs were analyzed in a laboratory in the Central Asian Center for Ecological and Environmental Research (Bishkek, Kyrgyzstan). First, a certain amount of each water sample was placed into a lactose peptone culture medium for the preliminary fermentation test. After incubation at 37 °C in an incubator for 24 h, the strains from the fermentation tubes that produced acid, gas and only acid were inoculated on an eosin methylene blue medium or a fuchsin sodium sulfite medium and cultured in a 37 °C incubator for 24 h; then, the colonies that met the characteristics were selected for Gram staining smear microscopic examination. Finally, according to the results of smear microscopic examination, a

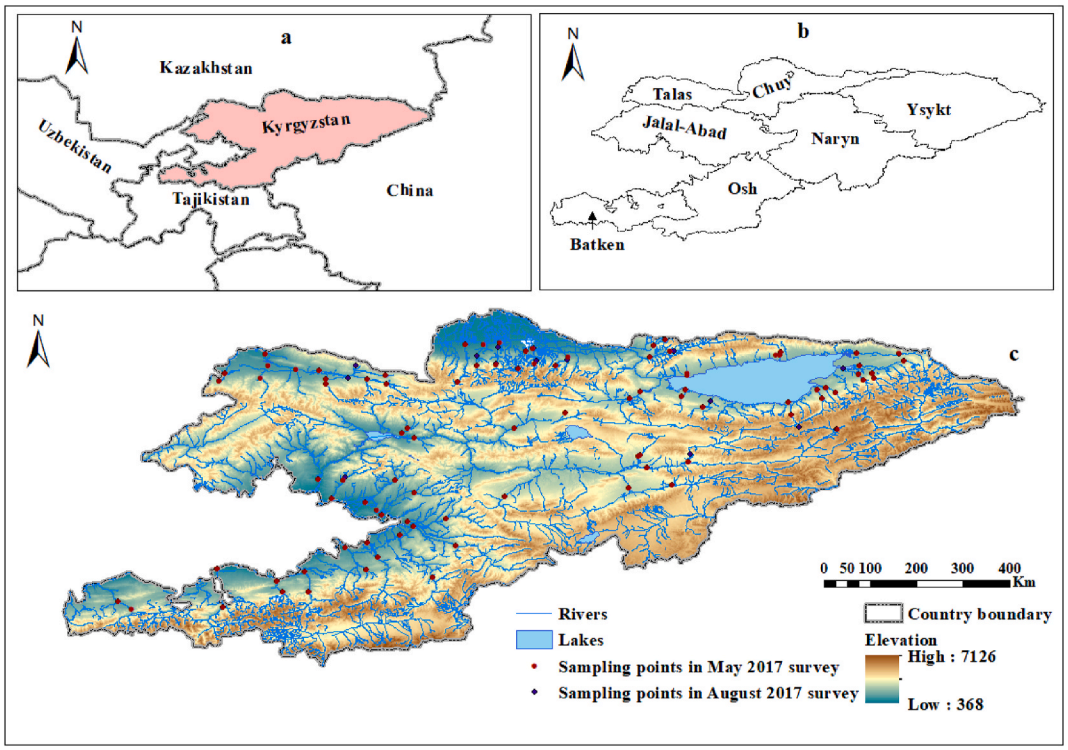

Fig. 1. Location map of Kyrgyzstan (a), state administrative division (b) and the distribution of the river water samples (c).

refermentation experiment was carried out. The gram-negative non-spore bacteria detected by microscopy were inoculated into test tubes containing lactose peptone culture medium at ordinary concentrations and then cultured at 37 °C incubator for 24 h. The presence of coliform groups was determined by acid and gas production. According to the number of fermentation tubes at each dilution, the most probable number (MPN) table was checked to obtain the coliform number per 100 mL or per liter of water.

3.2. Geographic data sources

The basic geographic data applied in this study included records of the national, state and county divisions of Kyrgyzstan, roads, rivers, lakes and socioeconomic central cities, etc. The data were collected from the Global Aviation Data Management website (https://www.gadm.org/) and China Resource and Environment Science and Data Center (http://www.resdc.cn/data). DEM (digital elevation model) data with a 90 m × 90 m resolution in the study area were collected from the Geospatial Data Cloud website (http://www.gscloud.cn/). The 1 km × 1 km resolution population data and human modification of terrestrial systems data of Kyrgyzstan were collected from the Social Economic Data and Applications Center (SEDAC) of NASA (https://beta.sedac.ciesin.columbia.edu/).

3.3. Data analysis method

3.3.1. Spatial autocorrelation analysis

The spatial autocorrelation analysis method is usually used to evaluate the clustering, randomness or fragmentation degree of spatial patterns (Zhao et al., 2020). At present, the spatial autocorrelation analysis method has been widely used in the spatial distribution analysis of water pollution factors in rivers (Crosby et al., 2019; Islam et al., 2020; McManus et al., 2016; Wang et al., 2019). Spatial autocorrelation includes global and local autocorrelations. Global autocorrelation describes the overall distribution and determines whether a contaminant has aggregation characteristics within a specific region, while local autocorrelation can indicate where significant aggregation occurs (Zhao et al., 2019). Moran's I is a common index used in spatial autocorrelation analyses, and can be divided into global Moran's I and local Moran's I. The global Moran's I index was proposed by Australian statistician Park Moran, and the specific calculation equation is as follows (Fan and Xue, 2020):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

where n is the number of spatial sample data; x_i and x_j are the attribute values of spatial objects in region i and j, respectively; $\overline{x}$ is the mean value of all spatial data; and w_{ij} is the element of the spatial weight matrix, which is a generally symmetric matrix, where $w_{ij} = 0$. In general, the standard statistic $Z(I)$ is used to test the significance level of the spatial autocorrelation of variables, and $Z(I)$ is calculated as follows:

$$Z(I) = \frac{I - E(I)}{\sqrt{Var(I)}} \tag{2}$$

where $E(I)$ and Var(I) are the theoretical expectations and theoretical variance of Moran's I index respectively. When $|Z|>1.96$, the original hypothesis is rejected, i.e., spatial autocorrelation exists in the spatial variables with a 95 % probability. The global Moran's I is between −1 and 1. A global Moran's I value > 0 indicates spatial correlation, a global Moran's I value < 0 indicates spatial heterogeneity, and a global Moran's I value = 0 indicates a random distribution of variables, i.e., there is no spatial correlation.

In 1995, Professor Luc Anselin proposed the local Moran's I index (Anselin, 1995) on the basis of global Moran's I, which can be used to analyze the internal structure of a global space and the dependence of the local space by combining it with a local spatial autocorrelation clustering graph (LISA). The local Moran's I index is calculated as follows (Tepanosyan et al., 2019):

$$I_i = \frac{n(x_i - \bar{x}) \sum_{j=1}^{n} w_{ij}(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (3)$$

At a given significance level, a local Moran's I value > 0 indicates that the attribute values of the observation area are similar to those of the adjacent region, i.e., high-high or low-low cluster; in contrast, a local Moran's I value < 0 indicates that the attribute values of the observation area are different from those of the adjacent region, i.e., low-high or high-low outlier.

3.3.2. Statistical analysis

All statistical analyses in this study were completed using Excel and SPSS software. The correlation coefficient method was used to analyze the correlation between the FC concentration in river water and its driving factors. The spatial autocorrelation analysis of the FC concentration was completed using OpenGeoDa software to reveal the spatial distribution characteristics. The collection and calculation of distance to the roads (DR) and distance to the social-economic center (DSE) data were realized using ArcGIS software.

4. Results

4.1. Hydrochemical characteristics of river water

The descriptive statistics of the hydrochemical parameters of the river water samples collected in Kyrgyzstan are shown in Table 1. Table 1 shows that the pH range of river water sampled in Kyrgyzstan during the low river flow period was 7.76–8.61, with an average value of 8.05; the pH range of river water sampled during the high river flow period was 7.68–8.5, with an average value of 8.08, indicating that the river water in Kyrgyzstan was weakly alkaline overall. The World Health Organization (WHO) does not provide specific guidelines for the pH value of drinking water (Ahmad et al., 2020), however most developed countries in the world stipulate that the pH value of drinking water should be 6.5–9.0. Therefore, all river water samples in Kyrgyzstan met the pH requirements for drinking water. The variation range of EC during the low river flow period was 60–570 μs/cm, with an average value of 246.29 μs/cm; during the high river flow period, the variation range of EC was 36–573 μs/cm, with an average value of 247.47 μs/cm. These results suggest that the total dissolved ion content in the river water of Kyrgyzstan experiences little change between the high and low river flow periods. The variability of river water hardness during the low (641.05 mg/L) and high river flow (352.89 mg/L) periods was quite different. According to the water hardness classification standard of the Water Quality Association (WQA) in the United States, more than 85 % of the river water samples in Kyrgyzstan collected during the high and low river flow periods in 2017 belonged to the "medium hard", "hard" and "very hard" water grades, indicating that river water hardness in Kyrgyzstan needs to be further controlled (Table S3). The total organic carbon (TOC)and ammonia nitrogen (NH_3N) contents in the river water varied little in space (variance less than 1) remaining within in a low range.

4.2. FC pollution in the river water of Kyrgyzstan

The distribution of FC in the river water sampled during low and high river flow periods in Kyrgyzstan is shown in Fig. 2. It can be seen from the figure that the concentration of FC in the river water of Kyrgyzstan during the low river flow period was relatively small, and the maximum FC concentration was 4 MPN/100 mL, which appeared in the Talas state. In 91.30 % of the samples, the FC concentration in the river water was <2 MPN/100 mL, i.e., the detection limit was not reached. The FC concentration of the river water during the high river flow period was higher than that during the low river flow period. FC was detected in 42.39 % of the samples, among which the FC concentration of 20.88 % of the river water samples exceeded 4 MPN/100 mL (Fig. S1). The concentration of FC in the two sampling sites exceeded 20 MPN/100 mL during the high river flow period at 22 MPN/100 mL in Bishkek city and 23 MPN/100 mL in Issyk−Kul Lake scenic area. According to the World Health Organization drinking water quality guidelines (Fourth Edition), human drinking water should not contain fecal indicator microorganisms such as FC. Therefore, from the perspective of FC pollution, 91.30 % and 57.61 % of river water samples collected during the high and low river flow periods can be directly used as drinking water (Fig. S2), and the river water from the rest of the sampled areas needs further treatment before drinking.

4.3. Spatial autocorrelation of FC concentration

To analyze the spatial distribution characteristics of FC in the river water of Kyrgyzstan, the study area was divided into 44 research units

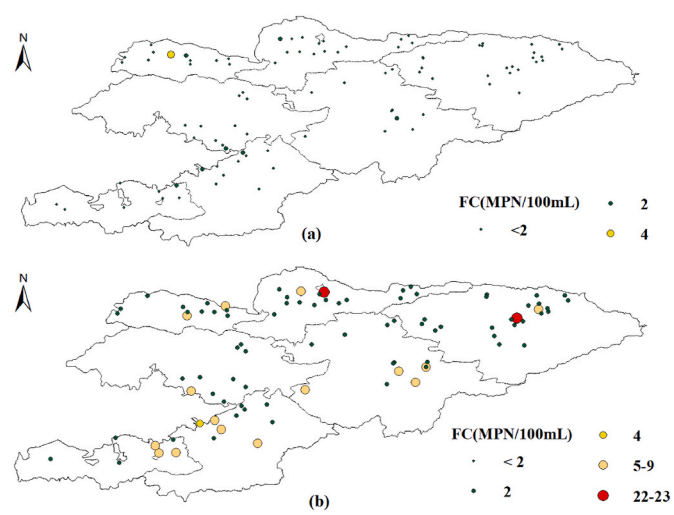

Fig. 2. Distribution of the FC concentration in Kyrgyzstan during the (a) low and (b) high river flow periods.

Table 1
Hydrochemical parameters of the river water samples collected during the low river flow period (L) and high river flow period (H).

Period	Parameters	Range	Minimum	Maximum	Mean	Standard Deviation	Variance
L	Hardness (mg/L)	641.05	31.41	672.46	118.64	75.11	5640.78
	EC (μS/cm)	510	60	570	246.29	134.48	18,085.12
	pH	0.85	7.76	8.61	8.05	0.16	0.02
	TOC (mg/L)	4.52	1.54	6.06	2.81	0.75	0.56
	NH_3N (mg/L)	1.43	0.04	1.47	0.68	0.19	0.04
H	Hardness (mg/L)	352.89	27.22	380.11	117.34	59.04	3486.06
	EC (μS/cm)	537	36	573	247.47	143.68	20,643.51
	pH	0.82	7.68	8.5	8.08	0.18	0.03
	TOC (mg/L)	3.77	1.79	5.56	2.40	0.53	0.28
	NH_3N (mg/L)	1.42	0.43	1.85	0.66	0.15	0.02

(42 counties and 2 water areas) according to county-level divisions. The spatial autocorrelation of FC concentrations in the river water during low and high river flow periods was tested using GeoDa software, and a Moran's *I* scatter diagram was obtained, as shown in Fig. 3. Fig. 3 shows that under a significance level of $P < 0.05$, the global Moran's *I* index of FC concentrations in the low and high river flow periods were greater than zero, which were 0.116 and 0.257, respectively, indicating that there was a spatial correlation with the FC concentrations in the river water samples, and it was more obvious during the high river flow period than during low river flow period.

The four quadrants of the Moran's *I* scatter plot represent the high-high (HH) cluster, low-high (LH) outliers, low-low (LL) cluster and high-low (HL) outliers. Fig. 4 shows that the number of points in the first and third quadrants was significantly greater than that in the second and fourth quadrants; counties containing "low-low" and "high-high" clusters were more abundant than those with "high-low" and "low-high" outliers, indicating that counties with low (high) FC concentrations were more likely to gather in space. From the perspective of variability, it can also be seen that the spatial variability of the FC concentrations in the river water of Kyrgyzstan was small.

Although the global Moran's *I* index can represent the global spatial correlation of FC, it cannot judge whether the spatial correlation types of the FC concentrations were statistically significant, and the specific spatial cluster area cannot be intuitively understood. Therefore, this study performed a Lisa clustering analysis on the FC concentrations observed during the low and high river flow periods using GeoDa software (all kinds of clustered counties passed the significance test at the 0.05 level), and the results are shown in Fig. 4.

It can be seen from the figure that the FC concentrations observed during the low river flow period showed an uneven distribution pattern. Among the 44 counties, five counties, namely Tüp County, Kochkor County, Naryn County, Ak-sun County and Ysyk-köl County, belonged to the low-low cluster area, and two counties, Talas County and Kara-Buura County, belonged to the high-high cluster area, which indicated that the FC concentration in the river water of Kyrgyzstan exhibited a strong spatial dependence within the local range. Topographically, the low-low cluster patterns of FC concentrations were concentrated in northeastern high-altitude areas, while the high-high cluster patterns were relatively distributed in low altitude areas, which may have been related to the different ice and snow covers and melting tendencies present at different altitudes during the low river flow period, leading to the varied intensities of human activities. During the high river flow period, only low-low cluster areas were found in Jumgal County and Kochkor County in the northern Naryn state, and the concentration clusters or outliers in the other counties were not significant, which indicated that FC clusters only existed in these two counties during the high river flow period, but the distribution variability across the other areas was large.

5. Discussion

5.1. Comparison of FC concentration with other countries or regions

To compare the differences in FC concentrations in river water between Kyrgyzstan and other countries or geographical locations, the FC concentrations of some countries or regions are listed in Table 2. It can be seen from the table that, the FC concentration of surface water in Kyrgyzstan was lower than that of various water bodies in other countries which were mainly polluted by domestic waste, indicating that the FC pollution degree of rivers in Kyrgyzstan was relatively low under the condition of a traditional agro-pastoral economy. For example, the peak concentration in Beiyun watershed in Beijing, China reached 2.4×10^6 MPN/100 mL, and in canal water of Tha klong sub-district, Thailand reached 1.6×10^6 MPN/100 mL, which were several orders of magnitude higher than that in this study (Table 2). Avigliano and Schenone also proved that the surface water in the urban area of Argentina was more polluted by FC than that in the Atlantic rainforest, which was almost not affected by the city (Avigliano and Schenone, 2015). However, compared with Tokyo Bay River in Japan and Batang arau River in Indonesia, there is still a gap in the pollution control of FC in Kyrgyzstan. Generally, the FC pollution of the river water in Kyrgyzstan was not severe, but the harm of FC to human health still needs to be considered within individual areas.

5.2. Spatial and temporal distribution differences in FC concentration

According to the difference of FC concentration distribution in the low and high river flow periods of Kyrgyzstan mentioned in section 4.2, the concentration of in the river water of Kyrgyzstan during the high river flow period was higher than that measured during the low river flow period. And the FC concentration was significantly affected by runoff formation time and conditions, which indicates that FC in the river water in Kyrgyzstan mainly came from nonpoint source pollution. Although many studies have found that the increase in runoff caused by precipitation dilutes the concentration of various pollutants in the river (Pramanik et al., 2020), the magnitude of this dilution effect is affected

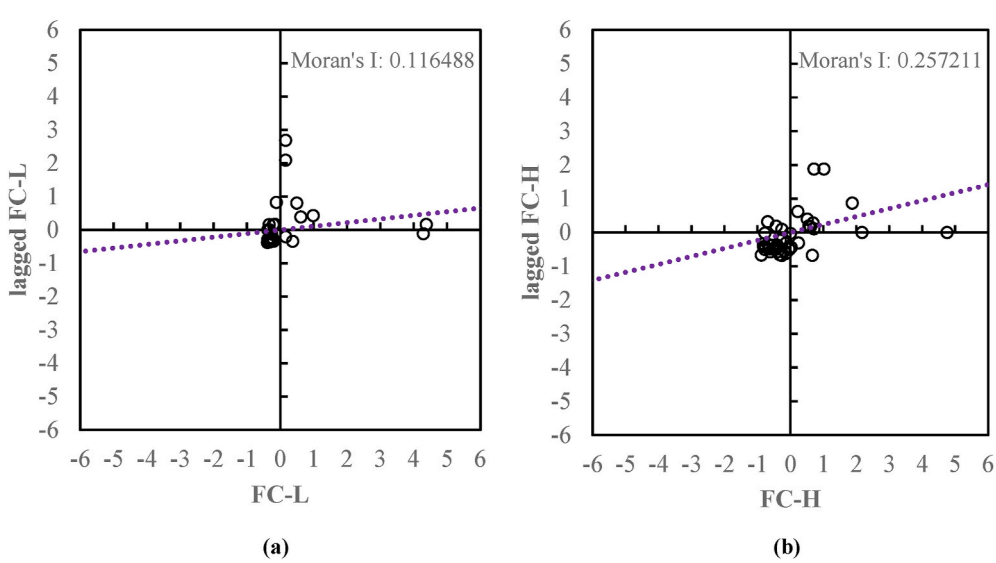

Fig. 3. Global Moran's I scatter plot of river water FC concentration in Kyrgyzstan during the (a) low (L) and (b) high river flow (H) periods.

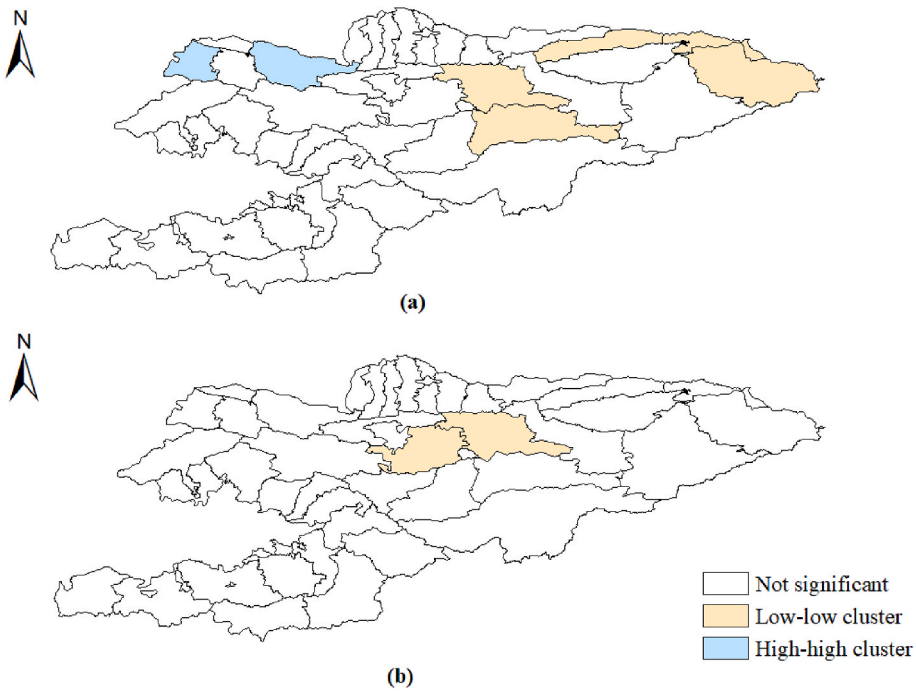

Fig. 4. Lisa concentration map of river water FC concentrations in Kyrgyzstan during the (a) low and (b) high river flow periods.

by the rainfall intensity, rainfall duration and pollution source. Therefore, some research conclusions were consistent with this study. For example, Mitra et al. (2018) concluded from the differences in FC concentrations between the premonsoon period (March–June) and monsoon period (July–October) that domestic sewage mixed into runoff was higher in the rainy season when river runoff was large (Mitra et al., 2018); Tian et al. (2019) also found that the river water quality in the flood season (August) was the worst compared with other seasons (Tian et al., 2019). Combined with the actual situation in Kyrgyzstan, the possible nonpoint source pollution sources of high-concentration FC in the river water of Kyrgyzstan in the high river flow period include domestic sewage from residential areas, livestock manure bioorganic fertilizer in irrigated agricultural areas and livestock and poultry excreta from alpine pastures. These pollution sources enter river runoff under the leaching and scouring of a large amount of rainwater, resulting in the high FC concentration of the high river flow period.

Spatially, the spatial heterogeneity of FC concentrations showed that the low-low cluster areas of FC were distributed in high mountains or high-altitude areas during the low and high river flow periods, while the high-high cluster areas were distributed in the low altitude areas of the Talas state during the low river flow season. These results showed that the FC produced by cattle and sheep excreta in the mountain pastures was not the main source of FC in the river water of Kyrgyzstan, and other pollution sources (such as surface runoff carrying, leakage or discharge from septic tanks and sewage treatment facilities, etc.) besides animal husbandry were the main pollution sources. Although some studies have shown that forests and grasslands can provide sites for animal husbandry, there may be a positive correlation between forest and grassland land use types and FC concentrations (Smith et al., 2001). However, most studies have concluded that there is a negative correlation between the land use ratio of grasslands and forests and FC concentrations (Tong and Chen, 2002; Zhang et al., 2020), which may be related to the difficulty of forming surface runoff on grassland and forest covers. There were no high-high cluster FC areas observed during the high river flow period, which indicated that the high concentration of FC in the river water was randomly distributed during the high river flow period, and its spatial distribution was only affected by the characteristics of specific areas.

5.3. Factors influencing FC distribution

5.3.1. Water environment parameters

The dynamic changes in FC states and concentrations in water bodies are closely related to the environment, but the environmental factors affecting FC concentration in different regions and water bodies are different. To understand the relationship between FC concentrations and hydrochemical parameters in the water of the Kyrgyzstan River, Pearson's, Tau-b Kendall's and Spearman's correlation coefficient methods were used for analysis, and the results are shown in Table 3. It can be seen from the table that there was no significant correlation between the FC concentration and the hardness, conductivity, pH and TOC in river water of Kyrgyzstan, indicating that the distribution of FC concentrations in the river water had no relationship with the water quality parameters and was mainly driven by other external factors.

5.3.2. Anthropogenic factors

Previous studies have shown that FC abundance is significantly correlated with the population of an area and the proportion of developed land within a region, i.e., the percentage of impervious surface coverage (Mallin et al., 2000); in addition, the law of FC released to the environment in urban and rural areas is also different (Tong et al., 2016). Therefore, to explore the anthropogenic driving factors of FC concentrations in the water of the Kyrgyz River, the distance to the roads (DR), distance to the socioeconomic center (DSE), population (P) and human modification of terrestrial systems rate (HM) were selected as the driving factors of the spatial distribution of FC concentrations in this study, and the correlation between the FC concentration and the four factors measured during low and high river flow periods is shown in Fig. 5.

As shown in Fig. 5, there was a nonsignificant negative correlation between the measured FC concentrations and DR, P and HM in the river water of Kyrgyzstan during the low river flow period, but a nonsignificant positive correlation with DSE; during the high river flow period, the correlation between the FC concentrations and four driving factors was different; there was no significant negative correlation observed with DR and DSE, but it highly positively correlated with P and HM. The results showed that the four factors of DR, DSE, P and HM had little effect on the

Table 2
Comparison of FC concentrations in river water of some countries or regions.

Water body	Country	Area type	FC	Reference
Beiyun watershed	China	Watershed	2–2.4 × 10^6 MPN/100 mL	Zhang et al. (2021)
Tha Klong sub-district	Thailand	Canal	80–1.6 × 10^6 MPN/100 mL	Yajima and Koottatep (2010)
Białka Czarny River, Dunajec River, Biały Dunajec River	Poland	Watershed	Mean = 158–11,800 CFU/100 mL (Three catchments)	Lenart-Boron et al. (2017)
Sergipe River	Brazil	Tropical estuary	0–7500 CFU/100 mL	Frena et al. (2019)
Cuitzmala River	Mexico	–	Mean = 163–7033 CFU/100 mL (2010–2016)	Antonio Tapia-Palacios et al. (2018)
Hooghly River	India	Estuary	5615 ± 584 MPN/100 mL (during monsoon)	Mitra et al. (2018)
Mártires Rive	Argentina	Urban	0–4300 CFU/100 mL (mean = 1540)	Avigliano and Schenone (2015)
Surface water	Nigeria	Rural Community	0–3000 CFU/100 mL	Oladipo et al. (2020)
Nile River	Egypt	Damietta branch	40–2800 MPN/100 mL	(M Haroon et al., 2020)
North Carolina streams	America	–	0.66–1220 CFU/100 mL	Vitro et al. (2017)
Pepirí Guazú	Argentina	Atlantic Rainforest	0–930 CFU/100 mL (mean = 64)	Avigliano and Schenone (2015)
River water in Miyazaki City	Japan	Urban	37 (±5) CFU/100 mL	Suzuki et al. (2018)
Batang Arau River	Indonesia	–	2.48–4.79 log10number/100 mL	Helard et al. (2019)
Sumida River, Furu River, Meguro River	Japan	Bay City	1–2.66 MPN/100 mL	Poopipattana et al. (2018)
Rivers in the country	Kyrgyzstan	–	0–23 MPN/100 mL	Present study

FC concentration of the river water during the low river flow period, while the FC concentration of the river water was mainly affected by P and HM during the high river flow period; the FC concentration was higher in areas with more population and more intensive human modifications of the terrestrial system. This result was also a good explanation for the phenomenon that the high concentration FC of the river water sampling points in Kyrgyzstan were distributed in Bishkek and the Issyk-Kul Lake scenic area during the high river flow period (Fig. 2b), while low-low cluster areas (Fig. 4b) appeared in some counties of Naryn. Bishkek is the capital of Kyrgyzstan and acts as the political, economic, cultural and scientific and technological center of the country, with a fixed population of over one million; tourism products in the Issyk−Kul Lake area are an important part of Kyrgyzstan's service export. Combined with the analysis of the factors driving the FC concentration, the distribution of high FC concentrations in Kyrgyzstan was, respectively related to the urban domestic sewage discharge in Bishkek and the population flow density in the Issyk-Kul Lake scenic area (Kozhokulov et al., 2019); Naryn is the state with the lowest population density among the seven states in Kyrgyzstan, so a low-low FC concentration cluster appeared during the high river flow period.

6. Conclusions

The hydrochemical characteristics and FC levels of river water samples collected in Kyrgyzstan were analyzed in this study, and the spatial and temporal distribution differences in FC and its main driving factors were compared. The following conclusions were drawn:

a) The quality of river water in Kyrgyzstan was considered good (excluding that of water hardness), and the concentration range of FC was 0–23 MPN/100 mL. Compared with other countries or regions in the world, the level of FC pollution in the river water of Kyrgyzstan, a traditional country with an agro-pastoral economy in Central Asia, was relatively low, but the FC pollution in some specific areas still need to be controlled during high river flow periods.
b) Temporally, the concentration of FC in the river water of Kyrgyzstan varied between the low and high river flow periods, and the overall performance was higher during the high river flow period than the low river flow period. Spatially, a high-high cluster of FCs appeared in high altitude or high mountain areas, while low-low cluster areas appeared in low altitude or basinal areas, which indicated that animal husbandry in high mountain area of Kyrgyzstan is not the main factor causing river FC pollution but is rather sourced by other factors such as urban domestic sewage and agricultural activities in lowlands.
c) The distribution of FC in the river water of Kyrgyzstan was not related to hydrochemical parameters but was only related to human activities, among which P and HM had a greater influence on the FC distribution observed during the high river flow period.

According to the above research conclusions, it is suggested that Kyrgyzstan, a traditional country with an agro-pastoral economy in Central Asia, should focus on areas with severe urbanization and dense populations in the treatment of river water FC. The contribution of mountain pasture animal husbandry to river water FC is relatively small due to its unique underlying surface conditions. Therefore, proper FC control and monitoring can be adopted for mountainous areas.

Table 3
Correlation coefficient between some hydrochemical parameters and FC.

Parameter		Pearson		Tau-b Kendall		Spearman	
		correlation coefficient	Sig. (bilateral)	correlation coefficient	Sig. (bilateral)	correlation coefficient	Sig. (bilateral)
Hardness	L	0.007	0.950	0.079	0.357	0.096	0.363
	H	−0.066	0.535	−0.036	0.655	−0.048	0.649
EC	L	−0.001	0.991	0.107	0.210	0.130	0.217
	H	−0.083	0.430	−0.085	0.290	−0.112	0.287
pH	L	−0.069	0.516	−0.064	0.463	−0.770	0.465
	H	0.145	0.168	0.112	0.166	0.152	0.148
TOC	L	−0.009	0.934	0.025	0.769	0.030	0.778
	H	−0.126	0.233	−0.144	0.074	−0.202	0.053

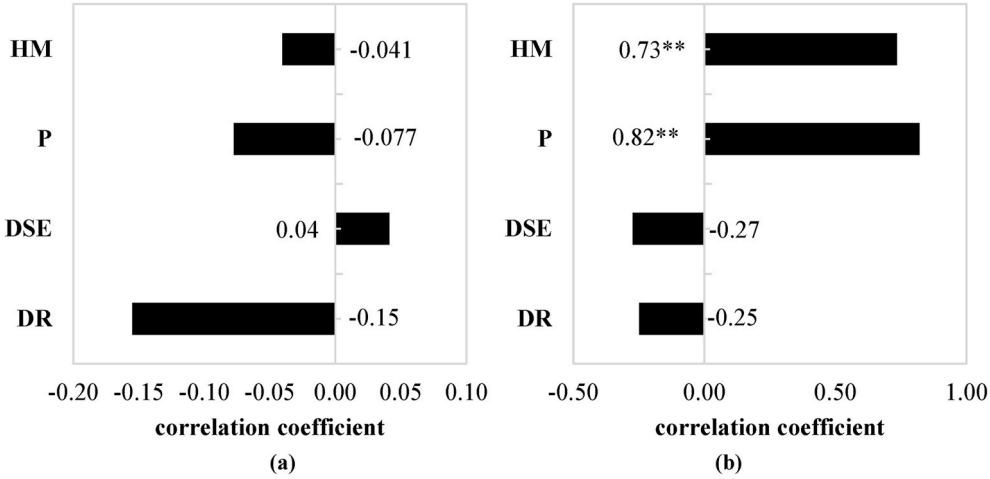

Fig. 5. Correlation coefficient of FC concentrations during the (a) low and(b) and high river flow periods and the influential anthropogenic factors ("**" means at the level of 0.01, the correlation is significant).

Author contributions

Yizhen Li: Writing - Original Draft, Conceptualization, Methodology. **Long Ma**: Writing - Review & Editing, Conceptualization, Formal analysis. **Yaoming Li**: Data Curation, Resources, Investigation. **Salamat Abdyzhapar uulu**: Data Curation, Resources, Investigation. **Jilili Abuduwaili**: Supervision, Project administration, Funding acquisition.

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. Supplementary data

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