Hydrology Research

Hydrology Research Vol 54 No 11, 1420 doi: 10.2166/nh.2023.305

Study of temporal changes in the hydrographic network of small mountain rivers in the Ile Alatau, Kazakhstan

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ABSTRACT

The article presents the outcomes of an assessment of hydrographic network changes within the Almaty city, utilizing geographic information system (GIS) technology and Earth remote sensing data. Two gauge stations were selected along the main rivers within the Almaty city. To identify distinctive alterations in these rivers, hydrological data series encompassing the maximum runoff from 1970 to 2021 were collected and subjected to statistical analysis. Differential integral curves were constructed to pinpoint periods corresponding to peak and trough runoff levels. For each of these identified periods, the processing of satellite imagery allowed for the computation of meandering coefficients for the river channels. Additionally, refinements were made to the slope values of the rivers during these same timeframes, and connectivity graphs were established to elucidate the relationship between slope and liquid runoff for each period. The analysis encompassed an assessment of the impact of anthropogenic factors on both artificial and natural bodies of water while also considering shifts in the boundaries of the Almaty city. The findings derived from this study have practical applications in the planning and design of water supply systems and in the implementation of measures aimed at mitigating the adverse effects of anthropogenic factors on water bodies.

Key words: anthropogenic factor, geoinformation systems, hydrographic network, space images, urban area

HIGHLIGHTS

- The changes in the hydrographic network of Almaty city in Kazakhstan were assessed.
- Hydrological time-series and differential integral curves were analyzed.
- The changes in channel outlines were identified and the riverbed modifications over decades were assessed.
- The influence of anthropogenic factors on artificial and natural water bodies was analyzed.
- The obtained results can be used to support the development of sustainable water management.

1. INTRODUCTION

The hydrographic network within a specific region encompasses a collection of rivers, streams, lakes, swamps, and reservoirs, some of which maintain perennial or intermittent flows (Tursyngali 2021). The assessment of the impact of both natural and anthropogenic factors on water bodies in urban areas is an exceedingly complex and pressing concern that has not yet received adequate attention. Its resolution holds significant scientific, social, and practical significance (Duskayev *et al.* 2021).

The examination of topographic maps created at different time points is a pivotal method for assessing alterations in the hydrographic network within the study area. This approach has been thoroughly elucidated in recent research (Grzywna & Niescioruk 2016; Miesiak-Wojcik 2021; Raduca *et al.* 2021).

Almaty, the largest city in Kazakhstan, finds itself surrounded by a diverse hydrological landscape. The city's hydrology is primarily shaped by the presence of the Ili River and the adjacent Tien Shan Mountain range. The Ili River holds a pivotal role as a crucial water source for Almaty, catering to a range of needs including drinking water, irrigation, and industrial usage. This river originates from glaciers within the Tien Shan Mountains, guaranteeing a consistent flow of water throughout the entire year. Furthermore, the mountain range enriches Almaty's hydrology with its numerous rivers and streams, thus providing supplementary water resources and contributing to the overall drainage system of the region. Nevertheless, Almaty confronts hydrological challenges, such as water scarcity during arid periods, necessitating the implementation of effective water management strategies to ensure the sustainable utilization of the available resources.

The modern hydrographic network of the city of Almaty has changed in accordance with the changes in the city's borders, as Almaty is a relatively young city that was founded in 1854 as the Verny Fortress. Since then, the city's borders have undergone a number of changes and its area has expanded from 3 to 704 km^2 (Chigrinets *et al.* 2021; Duskayev *et al.* 2021). The study area is situated within the mountainous and foothill regions of the northern slope of the central part of Ile Alatau, and this geographical setting significantly influences the alteration of the hydrographic network. Various exogenous processes like landslides, mudflows, avalanches, and rockfalls have the potential to modify the morphology of mountain river channels, thereby impacting the hydrographic network within a specific area. Noteworthy changes in this context have been documented since the mid-20th century, and these changes can be attributed to the heightened intensity of natural events in recent years, partly due to global warming. Furthermore, the construction of hydraulic structures designed to mitigate the effects of these hazards also results in modifications to the hydrographic network. Human economic activities play a pivotal role in this process, sometimes even surpassing the influence of natural factors.

The primary objective of this research is to assess alterations in the hydrographic network through the utilization of time-series observations of runoff, remote sensing data, and GIS technology. This endeavor aims to support local and regional authorities in formulating sustainable management strategies for both human activities and the natural environment within the city of Almaty.

2. STUDY AREA AND DATA

2.1. Study area

Almaty city is situated on the alluvial cones formed by the principal watercourses that traverse the city, namely, the Kishi Almaty and Ulken Almaty Rivers (Duskayev *et al.* 2021). The location of the study area is shown in Figure 1.

2.2. Available data

To identify typical variations in the river channels of the selected rivers, hydrological time-series data were gathered and subjected to statistical analysis. Specifically, data pertaining to the maximum water flow values covering the period from 1970 to 2021 were collected. These data were sourced from the State Water Cadastre of the Republic of Kazakhstan, which provides annual information regarding the regime and resources of surface waters. The data collection process focused on two hydrometric gauges: the first located along the Kishi Almaty River, below the mouth of the Sarysay River, and the second situated along the Ulken Almaty River, approximately 2 km upstream from the mouth of the Prokhodnaya River. The data collection timeframe spanned from 1970 to 2021 (State Water Cadastre of the Republic of Kazakhstan 2021).

To ascertain the morphometric and hydrological characteristics of the selected river channels, a combination of topographic maps and satellite images from various years was employed. Topographic maps, which offer comprehensive geographical information about the study area, played a crucial role in this process. As a foundation for georeferenced satellite imagery, the base topographic map provided by ArcGIS Online software was selected. This map served as a reference background for overlaying and aligning the spatial imagery data (https://www.arcgis.com). The base map functions as a visual reference during the process of mapping hydrographic network features (Samardak 2005). The maps are constructed using crowdsourced data and undergo continuous real-time updates, enabling the detection of changes in the hydrographic network while taking into account temporal fluctuations in channel processes.

To assess alterations in the river channels being studied, Landsat satellites, maintained by the United States Space Agency NASA since 1972, were chosen as the primary data source (Table 1).

The satellite imagery used in this study was sourced from the USGS Earth Explorer catalog, which is maintained by the US Geological Survey (accessible at https://earthexplorer.usgs.gov). To assess the morphometric and hydrological characteristics, a combination of topographic maps and satellite images spanning multiple years was employed. Changes in river channels were scrutinized through the analysis of Landsat satellite images, a series of satellites operated by NASA (the US Space Agency) for surveying purposes since 1972. These satellite images were obtained via the USGS Earth Explorer catalog (accessible at https://earthexplorer.usgs.gov) (Faye 2022; Jabal *et al.* 2022; Mann & Gupta 2022).

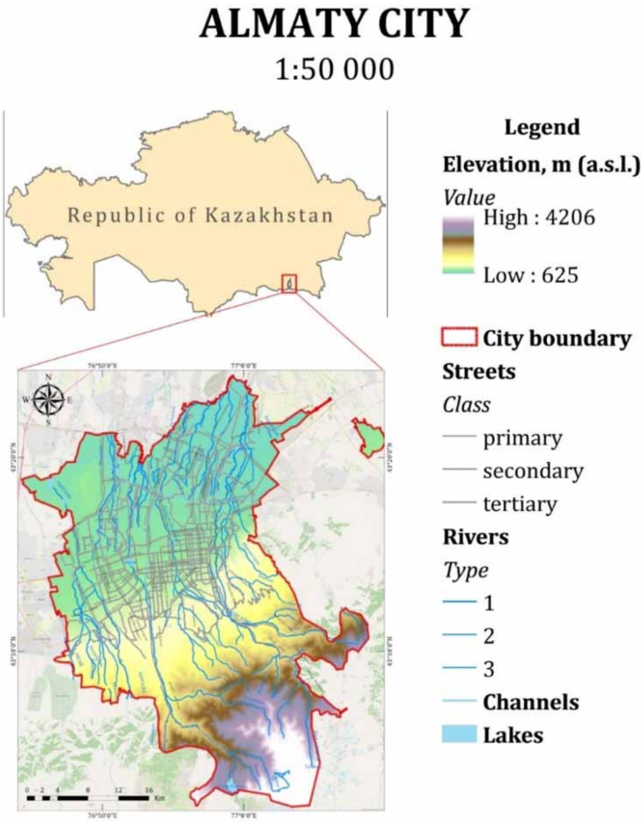

Figure 1 | Location of the study area.

Table 1 | List of satellite data used in this study

Time period	Data	Satellite and sensor	Resolution (m)	Source
1972	7 September	Landsat MSS	60	USGS
1981	29 July	Landsat ETM_+	30	USGS
1985	16 September	Landsat ETM_+	30	USGS
1992	8 August	Landsat ETM_+	30	USGS
1998	30 September	Landsat ETM_+	30	USGS
2007	6 August	Landsat ETM_+	30	USGS
2021	24 July	Landsat ETM_+	30	USGS

3. METHODS

3.1. Determination of high-water and low-water periods of rivers to identify the dynamics of channel changes

The changes taking place in the river channel are directly related to both the volume of water flowing within the channel and the angle at which the stream meets the riverbank. When there is a higher water flow, modifications to the channel's shape become more pronounced. To investigate this, we have chosen to concentrate on the maximum runoff values, which are considered indicative of significant 'channel changes'.

Maximum water discharge values were utilized to construct combined differential integral curves, facilitating the identification of periods during which the water levels in the Kishi and Ulken Almaty Rivers experienced increments or decrements.

Differential integral curves offer a more reliable method for discerning high-water and low-water cycles. These curves depict the comprehensive pattern of maximum runoff value fluctuations in relation to their average value over the entire observation period, thereby improving the precision in delineating such cycles. They are constructed by summing the deviations of the modulus coefficients from the center.

The construction of differential integral curves facilitated the identification of periods corresponding to maximum and minimum runoff values. These curves account for runoff fluctuations over relatively short individual time intervals. This process involved summing the deviations of the modulus coefficients from their average value to plot the curve, where the ordinate values of the curve are calculated as the summation of $\Sigma(K-1)$. The y-axis values on the curve represent the cumulative sum of the annual modular coefficient (K) deviations from the perennial average ($K=1$) at the end of each ith year.

To enable a comparison of multi-year runoff fluctuations among different rivers, the influence of temporal variability in the runoff, as indicated by the coefficient of variation (Cv) of the observation series, was eliminated. As a result, the expression takes the form of $\Sigma(K-1)/Cv$, where $K = Q_i/\bar{Q}$, where K is the ratio of the river's current runoff condition during a specific period to the mean perennial value of maximum runoff; Q_i is the maximum runoff value for the current year; $\bar{Q}$ is the average value of maximum runoff for the certain period; and Cv is the coefficient of variation of maximum river runoff.

The ordinates of the curve provide, at the conclusion of each ith year, the cumulative summation of deviations of annual modular coefficients (K) from the average perennial value of maximum runoff. Differential integral curves provide insights into cyclic fluctuations while mitigating the potential influence of phase shifts between cycles of different durations (Andreyanov 1959; Vinokurov 2011; Calculation recommendations 2017).

Runoff rates were calculated for identified low-water and high-water periods within specific time intervals. The runoff rate, calculated as the arithmetic mean of the statistical series, was determined using the following formula:

$$\overline{Q_N} = \frac{Q_1 + Q_2 + \cdots + Q_{N-1} + Q_N}{N} = \frac{\sum_1^N Q_i}{N} \tag{1}$$

where $\overline{Q_N}$ is the annual runoff rate (m^3/s); $Q_1 + Q_2 + \cdots + Q_{N-1} + Q_N$ are the annual runoff values for a long period (N years), in which a further increase in the number of observations does not change or slightly changes the arithmetic mean value (Goroshkov 1979; RussianGost 2003).

Because of the limited duration of the actual observation data series for annual runoff, the annual runoff rate calculated using formula (1) may deviate from the true mean value $\overline{Q_N}$ for $N \to \infty$ by a certain amount σ_{Q_n}, i.e.:

$$\overline{Q_N} = Q_{0n} + \sigma_{Q_n} \tag{2}$$

where Q_{0n} is the average annual runoff for a limited observation period (n years) and σ_{Q_n} is the mean square error of the n-year mean, calculated using Equation (3):

$$\sigma_{Q_n} = \pm \frac{\sigma_Q}{\sqrt{n}}, \tag{3}$$

where σ_Q is the mean square deviation of the unit values of the annual runoff Q_i from the average for n years, calculated by the following equation:

$$\sigma_Q = \pm \sqrt{\frac{\sum (Q_i + Q_{0n})}{n-1}}, \tag{4}$$

The primary and consistent factor that governs the overall water content of rivers is the runoff rate, which is also referred to as the average long-term runoff (Goroshkov 1979). In this research, accordance to these formulas instead of average annual runoff utilized the maximum runoff.

3.2. Identification of the outlines of river channels by using Earth remote sensing data

The riverbed, located at the lowest point of the valley, undergoes continuous changes in its shape due to the flow of water and sediment over both time and space. To quantify these alterations, Landsat images spanning from 1972 to 2021 were analyzed.

The Landsat program is one of the most enduring satellite imagery initiatives globally. For the analysis of specific segments of the riverbeds in the Ulken and Kishi Almaty Basins, multi-spectral imagery bands and classification techniques were employed within semi-automatic interpretation methods.

All satellite data have been converted to conform to a projected coordinate system. The study focused on the examination of three river valley sections to identify changes in channel outlines over time (Figure 2):

- Ulken Almaty, 12.9 km long from the Ulken Almaty gauging station – 2 km upstream of the mouth of the Prokhodnaya River (43°06′24.47″ N–76°55′11.45″ E).
- The Kishi Almaty River, 14.7 km long from the gauging station of the Kishi Almaty River – downstream the mouth of the Sarysay River (43°08′23.03″ N–77°04′6.02″ E).
- The Esentai River, 12.1 km long from the separation point from the Kishi River Almaty (43°11′23.08″ N–76°59′34.60″ E).

The lower boundaries for the rivers under study were established by identifying specific points where they intersect Raiymbek Avenue. In both the Ulken Almaty and Kishi Almaty River Basins, the zone where the mountain rivers gradually widen typically begins below Raiymbek Avenue, generally at or below an elevation of 750 meters above sea level (m BS), which corresponds to the point where the rivers intersect with the avenue (Chigrinets *et al.* 2021). The wedging-out zone of a river typically develops naturally as the river approaches a plain, and the slope gradually becomes less steep.

The chosen segments of the rivers were depicted on a map at a 1:25,000 scale through manual digitization, involving the creation of a linear shapefile (see Figure 3).

The lengths of the chosen river segments were precisely determined by extracting digital parameter values from the acquired vector data using the ArcToolbox function → Data Management Tools → Add Geometry Attributes.

The coefficient of river tortuosity, a significant hydrographic parameter, was computed using the derived parameters using Equation (5). This indicator can offer insights into the size and shape of the catchment area by dividing the river's length from its source to its mouth by the length of the valley (along the thalweg):

$$K = \frac{l}{l^1} \tag{5}$$

where l is the measured length of the whole river, taking into account the meandering (m) and l^1 is the length of the straight line connecting the mouth and the river source (m).

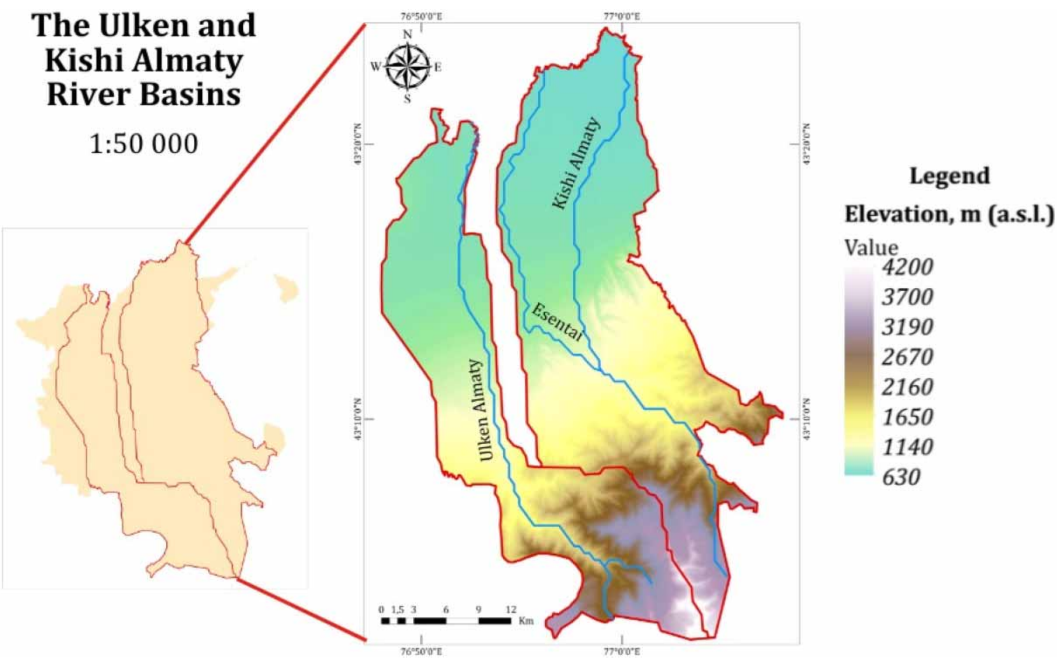

Figure 2 | Location of the three river valley sections under study.

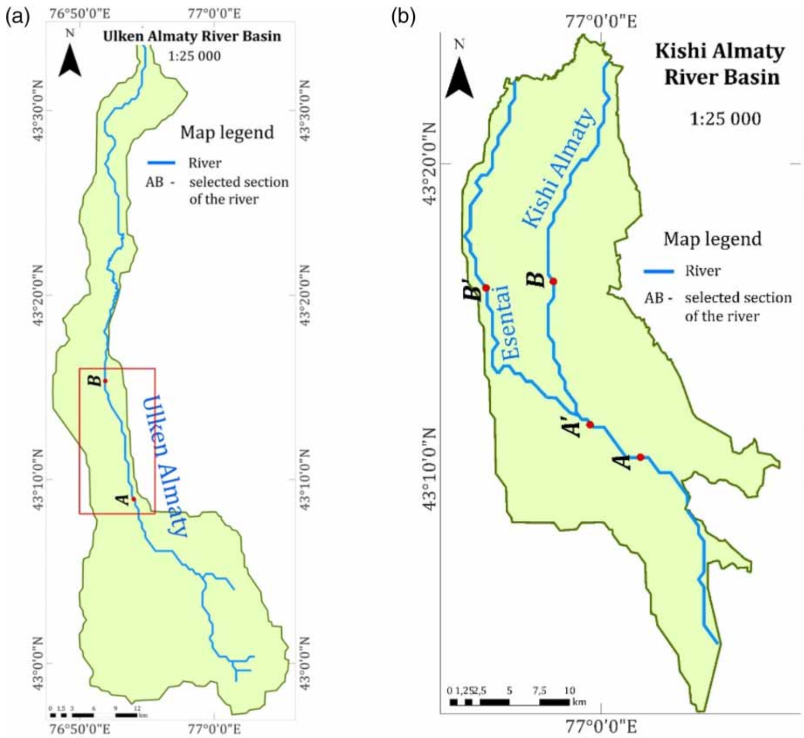

Figure 3 | Selected study sections of the rivers (a) Ulken Almaty and (b) Kishi Almaty & Esentai.

The conditions necessary for the formation of different types of river channels were assessed using the QI diagram method. This method involves examining the positioning of points that correspond to specific channel types, which are contingent upon the flow power determined by the river's water volume and gradient. Because of the uneven distribution of flow, the extent to which discharge influences channel formation is determined not only by its volume but also by its frequency. Even though lower discharge values occur more often, they can significantly impact channel formation over extended periods, even if they are less potent than infrequent floods with larger water volumes. Discharges that result in the highest sediment transport over an extended duration, and thus exert the greatest influence on channel formation, are referred to as channel-forming discharges (Chalov 2016). The coordinate axes of QI diagrams represent the values of channel-forming discharge and the slope of the channel or valley bottom. Russian scientists have further refined this method, initially developed by L. Leopold and M. Wolman (Borshchenko & Chalov 2014).

The average slope values of the studied rivers for specific time periods were computed by processing relevant remote sensing data using the slope tools available within the ArcToolbox module. This methodology facilitated the evaluation of slope characteristics and offered insights into the terrain dynamics of the rivers during the designated periods. Slope, in this context, signifies the rate of elevation change for each digital elevation model cell. It serves as the first derivative of the DEM, capturing the steepness or gradient of the terrain at a particular location. The measurements of river slope angles were initially acquired in degrees and were subsequently converted to the unit of meters per kilometer (m/km) to facilitate the construction of the QI diagram.

4. RESULTS

River flow and its channel are in constant interaction, with the flow capable of altering the shape of the river channel. In this study, the authors utilized maximum runoff values, considered as channel-forming discharges during high-water years, to identify changes in the configuration of river channels.

Differential integral curves (see Figure 4) were generated for the Kishi and Ulken Almaty Rivers spanning the period from 1970 to 2021. This timeframe was chosen for two primary reasons: it aligns with the onset of space imaging development in the 1970s and corresponds to the prevalence of hazardous hydrological phenomena in the study area (Medeu *et al.* 2016).

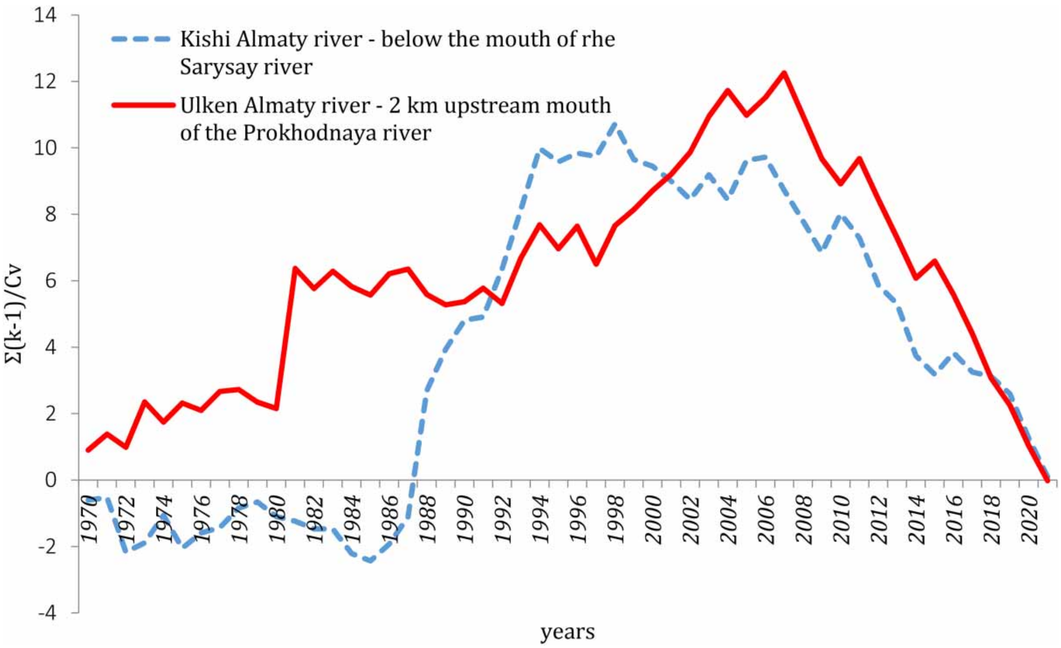

Figure 4 | Combined differential integral curves of maximum runoff of the Kishi Almaty and Ulken Almaty Rivers.

These curves were built using maximum runoff data for the analyzed period for two hydrometric gauging stations:

- Kishi Almaty River – below the mouth of the Sarysay River.
- Ulken Almaty River – 2 km upstream mouth of the Prokhodnaya River.

As depicted in Figure 4, the low-water periods of the Kishi Almaty River correspond to the intervals of 1970–1985 and 1999–2021, while 1986–1998 is identified as a high-water period. For the Ulken Almaty River, low-water periods were identified spanning from 1982 to 1992 and 2008 to 2021, while high-water periods occurred from 1970 to 1981 and 1993 to 2007.

The analysis focused on examining the maximum runoff values of both the Ulken and Kishi Almaty Rivers during the specified time periods. The results revealed that the maximum runoff series of the Ulken Almaty River comprised two complete cycles, whereas the Kishi Almaty River displayed one complete cycle and an incomplete cycle consisting solely of a low-water period. The values of maximum runoff for these periods and cycles are presented in Table 2.

Table 2 | Periods of high-water and low-water rivers of Almaty city

1	**Kishi Almaty River – below the mouth of the Sarysai River**				
Low-water periods		**High-water periods**			
Period, years	**Maximum runoff for the period, m³/s**	**Period, years**	**Maximum runoff for the period, m³/s**	**Cycle duration, years**	**Maximum runoff for the cycle, m³/s**
1970–1985	4.59	1986–1998	6.18	29	5.31
1999–2021	4.17	-	-	23	4.17
2	**Ulken Almaty River – 2 km above the Prokhodnaya River**				
High-water periods		**Low-water periods**			
Period, years	**Maximum runoff for the period, m³/s**	**Period, years**	**Maximum runoff for the period, m³/s**	**Cycle duration, years**	**Maximum runoff for the cycle, m³/s**
1970–1981	11.7	1982–1992	8.03	23	9.9
1993–2007	11.3	2008–2021	3.50	29	7.5

According to Table 2, the observed cycles indicate a decrease in the maximum runoff values, a trend that can be attributed to the increasing anthropogenic influence stemming from urbanization in the area (Chigrinets *et al.* 2021).

Average channel slopes were computed using the available accessibility features within ArcGIS 10.8. These slope measurements served as the foundation for constructing a QI diagram, which considered the correlation between channel slopes and liquid runoff (see Figure 5).

The QI diagram possesses the capability to predict the transformation or complexity of the morpho-dynamic type of a river channel when alterations in channel development occur due to both natural and anthropogenic factors (L'vovskaya & Chalov 2013). The first case arises due to fluctuations in the river's water content, either an increase or decrease, while the second case is common in channels where the slope undergoes substantial alterations.

Flow power, represented by QI, is characterized by both water discharge and the riverbed slope (Mikhailov 2015). QI diagrams provide the capability to anticipate changes in river systems when human activities, such as the construction of hydroelectric installations, quarrying, and ongoing adjustments, exert influence on the channels. During such times, processes akin to natural changes rapidly take place in the river's channel regime. Therefore, alterations in the conditions affecting the evolution of the channel due to human economic activities can be regarded as a reflection of the impact of climate change on the riverbed.

Temporal changes in the riverbeds of the study rivers were determined from the processed satellite images for the periods, as outlined in Table 2. An analysis of the diagram presented in Figure 5 indicates that, in the formation of the morpho-dynamic type of the Ulken Almaty River channel within the city, the influence of its water content predominates. It has been observed that the development of channel processes in the Kishi Almaty River depends on the terrain slope.

Figure 6 clearly illustrates the pronounced dynamics of channel processes in the Esentai River. Previous efforts to stabilize the channel have been ongoing since 1977. Notably, significant channel alterations occur at the point where the Ulken Almaty River flows into Lake Sairan, a phenomenon attributed to variations in the volume of the artificial reservoir over the years, including seasonal fluctuations. Furthermore, in 1981, channel normalization work was conducted along the Ulken Almaty River, extending from the current al-Farabi Avenue to Satpayev Street, which involved the installation of solid reinforced concrete channels to facilitate the safe passage of large water flows. Adjacent to the Kishi Almaty River area, specifically Satpayev Street, a channel was created in 1984 using Γ (gamma)-shaped blocks, reaching a depth of 1.5 m. This measure was implemented to protect nearby multi-story buildings and the Schoolchildren's Palace from potential flooding events.

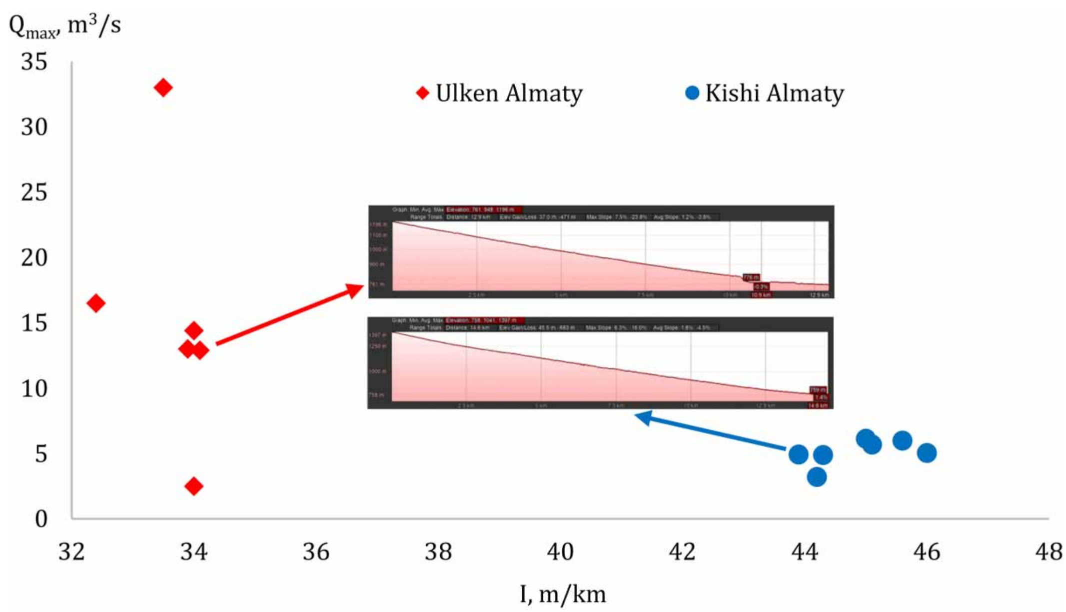

Figure 5 | QI diagram of the Kishi Almaty and Ulken Almaty Rivers.

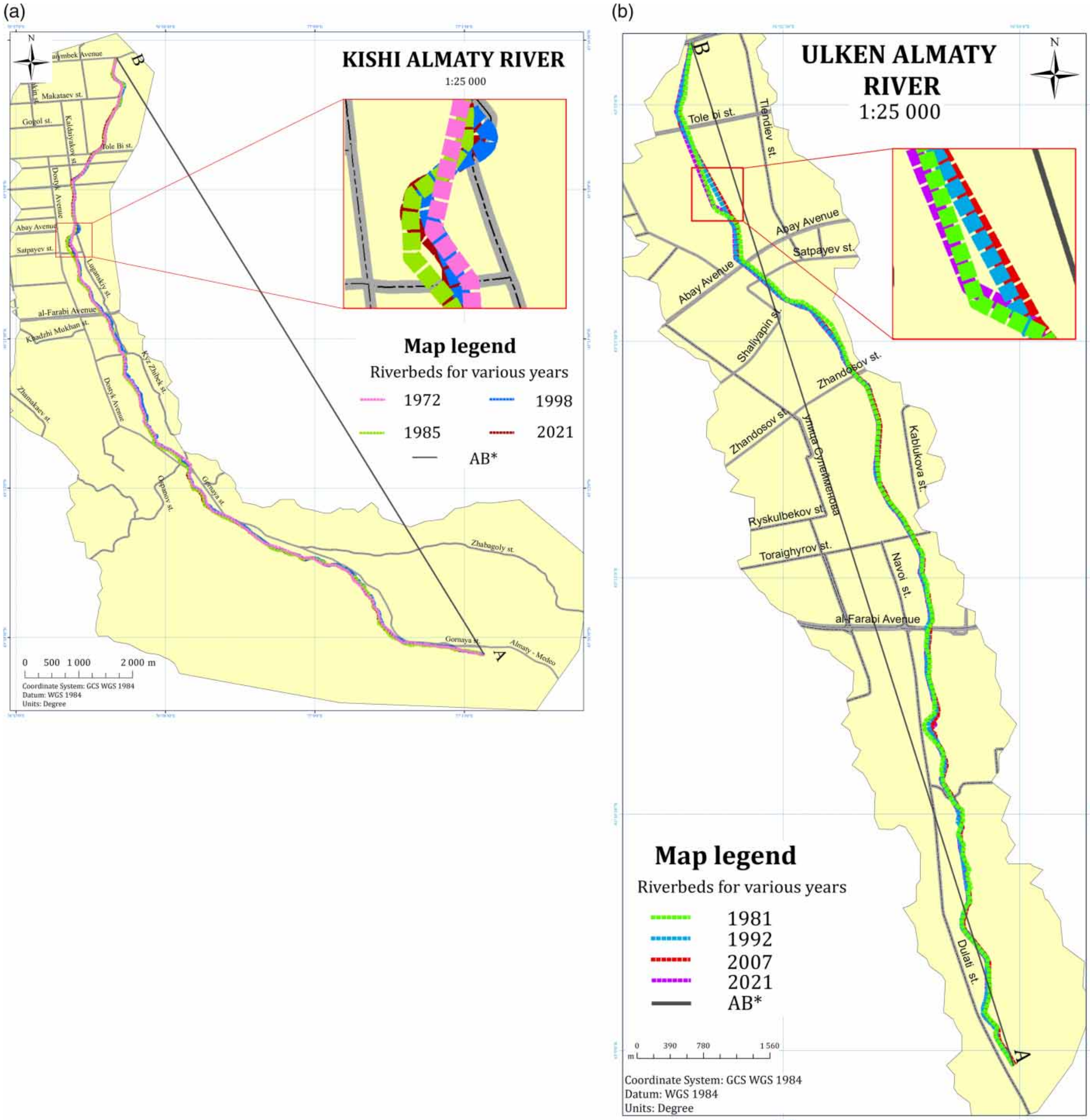

Figure 6 | Outlines of the riverbeds of the Kishi Almaty, Ulken Almaty, and Esentai: (a) Kishi Almaty River, (b) Ulken Almaty River, and (c) Esentai River (AB* – a straight line connecting the starting and ending points along the river). (*continued*.).

Presently, there is a growing impact of hydro-technical construction projects on river systems, coupled with a noticeable trend towards heightened human activities that affect river channel processes. The latter is marked by changes in the morphological structure of the riverbed and floodplain (Baryshnikov 1990). However, when assessing changes in the hydrographic network of a vast metropolis like Almaty, it is insufficient to consider solely the anthropogenic influence. It should be noted that climate change, which has gained urgency in recent years, impacts every facet of the hydrographic network. To determine the tortuosity coefficient of the riverbeds, data from satellite images and topographic maps were selected and processed for the years corresponding to the peaks of the curves depicted in Figure 4. Once the river lengths were clarified for each period, the designated points marked along them were connected by straight lines on the digital map's surface. Thus, based on the collected quantitative data, the tortuosity coefficients of the river channels were calculated using Equation (5). The calculation results are presented in Table 3.

(c)

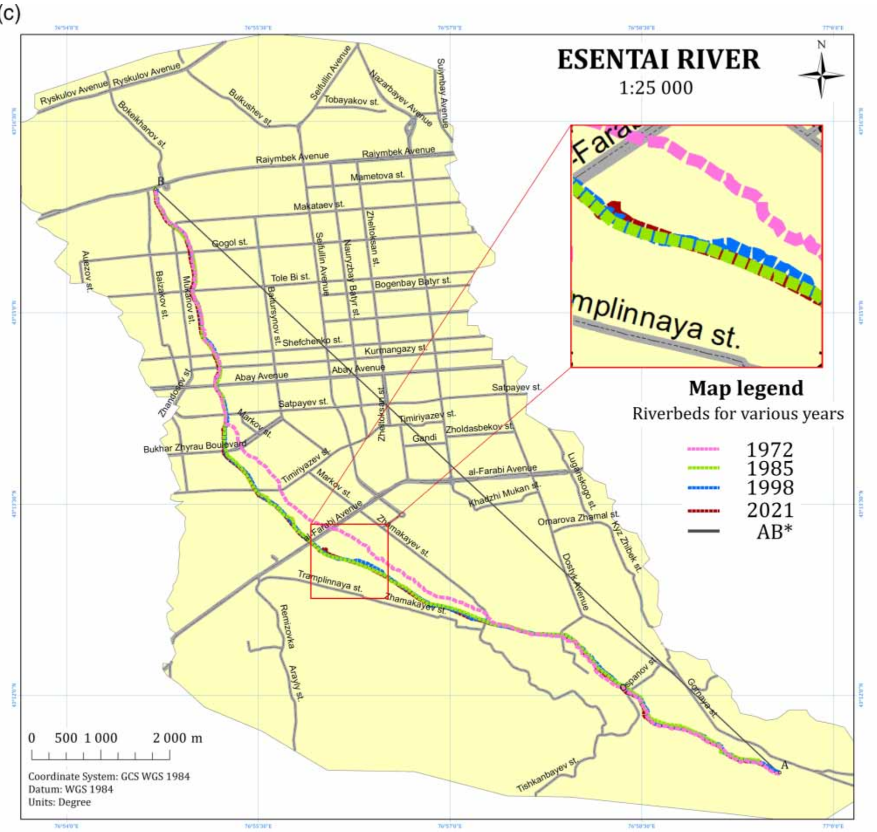

Figure 6 | Continued.

Table 3 | Tortuosity coefficient values of the Kishi Almaty, Ulken Almaty and Esentai riverbeds

No. 1	Name of the river 2	Years 3	Length, m 4	Straight length, m 5	Slope, m/km 6	Tortuosity coefficient 7	The degree of meandering of the river (STO GGI 52.08.40-2017) 8
1	Kishi Almaty	1972	14,627	12,180	44.1	1.20	Slightly tortuous
		1985	14,189		45.6	1.16	
		1998	14,885		43.9	1.22	Moderately tortuous
		2021	14,671		44.2	1.20	Slightly tortuous
2	Esentai	1972	12,109	10,756	34.6	1.13	Slightly tortuous
		1985	11,747		35.7	1.09	
		1998	12,166		34,4	1.13	
		2021	12,074		34.7	1.12	
3	Ulken Almaty	1981	13,072	12,319	33.5	1.06	Curved or bowed
		1992	12,881		34.0	1.04	
		2007	12,887		34.1	1.05	
		2021	12,884		34.0	1.04	

As indicated in Table 3, the Kishi Almaty River exhibits the highest value and deviation of the tortuosity coefficient. This can be attributed to the fact that the riverbed has undergone relatively fewer stabilization efforts and may also be linked to the frequent occurrence of hazardous phenomena. Consequently, a reduction in channel stability can potentially result in an increase in the water content of the rivers (Chalov Geomorphology 2020).

The tortuosity coefficient in the Ulken River Almaty's channel exhibited the lowest value, primarily due to the peculiarities of its shape and the implementation of measures to mitigate the impacts of catastrophic floods and mudflows. Upon analyzing satellite images, it was observed that the section of this river entering the city flows through a completely concrete-lined channel, resulting in a much more straight-line contour.

The Esentai River is an ancient tributary of the Kishi Almaty River, which was reestablished in 1921 following a mudflow disaster (Chigrinets *et al.* 2021). The deviation of the tortuosity coefficient of the river during the years 1972–1986 can be attributed to the construction of hydraulic structures and channel stabilization efforts carried out during this period. Consequently, the present course of the Esentai River has been landscaped over a distance of 11.7 km, stretching from Al-Farabi Avenue to the Ainabulak microdistrict within the city of Almaty (Chigrinets *et al.* 2021).

5. CONCLUSIONS

The absence of significant deviations in the tortuosity coefficients of the channels of Almaty city's main rivers suggests that these water bodies are influenced by a complex interplay of anthropogenic activities and climatic factors. A positive trend in annual temperature values impacts the occurrence of catastrophic events such as glacier melting and soil moisture saturation, which, in turn, leads to the intensified development of channel processes. When certain critical values of these channel processes are exceeded, the concurrent flow loses stability, transitioning from a laminar to a turbulent regime, and lateral erosion of the channel commences (Sidorchuk 2018).

Channel erosion is primarily driven by climatic factors and, consequently, by the maximum water discharge within the channel. However, the construction of hydraulic structures and the implementation of bank protection measures play a significant role in stabilizing river channels. Indeed, the construction of hydraulic structures designed to safeguard against hazardous hydrological events and efforts aimed at stabilizing river channels serve to impede the progression of river channel processes. Consequently, the outcomes of this research hold valuable applications in urban construction planning, horticulture, city landscaping, and the formulation of preventive measures to address potential hazardous hydrological events.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 30 June 2023; accepted in revised form 14 October 2023. Available online 30 October 2023