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Flood hazard assessment in the Yesil River basin

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ABSTRACT

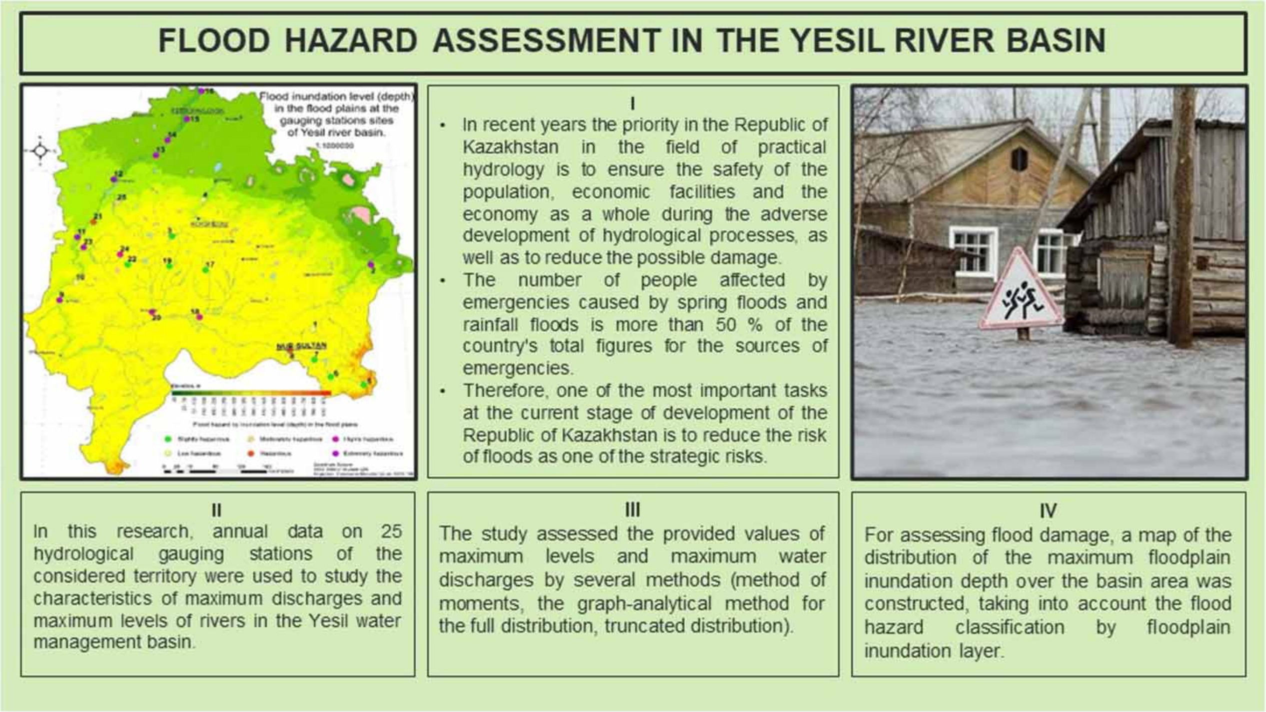
Due to population growth and densification, and expanding construction, disaster risk in the world and its specific parts of the world is steadily increasing. Earthquakes cause the most damage, followed by floods. Floods are characterized by the highest frequency of events. In this research, annual data on 25 hydrological gauging stations of the considered territory were used to study the characteristics of maximum discharges and maximum levels of rivers in the Yesil water management basin. Data on maximum water levels and discharges are generalized because they are most important in the study of floods and the organization of flood control. It is the maximum level that determines the area and depth of flooding of territories. This study assessed the provided values of maximum levels and maximum water discharges by several methods (method of moments, the graph-analytical method for the full distribution, truncated distribution). For assessing flood damage, a map of the distribution of the maximum floodplain inundation depth over the basin area was constructed, taking into account the flood hazard classification by floodplain inundation layer. Quantitative assessment of hydrological extremes characterizing the danger of flooding has been carried out for gauging stations of Yesil water management basin during this research.

Key words: flooding, hydrological disasters, maximum depth of floodplain inundation, maximum water discharge, maximum water level

HIGHLIGHTS

- Hydrological disasters include high/low water level, ice phenomena, and mudflow.
- Snow accumulation is the principal source of feeding the Yesil river.
- The possible cause of increased flood risk is human activities in the catchment.
- Assessment of flood risk for individual sections of river systems is of paramount importance for flood prevention.

GRAPHICAL ABSTRACT



FLOOD HAZARD ASSESSMENT IN THE YESIL RIVER BASIN

I

- In recent years the priority in the Republic of Kazakhstan in the field of practical hydrology is to ensure the safety of the population, economic facilities and the economy as a whole during the adverse development of hydrological processes, as well as to reduce the possible damage.
- The number of people affected by emergencies caused by spring floods and rainfall floods is more than 50 % of the country's total figures for the sources of emergencies.
- Therefore, one of the most important tasks at the current stage of development of the Republic of Kazakhstan is to reduce the risk of floods as one of the strategic risks.

II

In this research, annual data on 25 hydrological gauging stations of the considered territory were used to study the characteristics of maximum discharges and maximum levels of rivers in the Yesil water management basin.

III

The study assessed the provided values of maximum levels and maximum water discharges by several methods (method of moments, the graph-analytical method for the full distribution, truncated distribution).

IV

For assessing flood damage, a map of the distribution of the maximum floodplain inundation depth over the basin area was constructed, taking into account the flood hazard classification by floodplain inundation layer.

INTRODUCTION

In recent years, the priority in the Republic of Kazakhstan in the field of practical hydrology is to ensure the safety of the population, economic facilities, and the economy as a whole during the adverse development of hydrological processes, as well as to reduce the possible damage. Considerable attention is given to the prevention of natural hazards. The frequency of disasters caused by spring floods (the melting of accumulated snow during the spring thaw) and rainfall floods (floods caused by heavy rainfall) is about 30% of all disasters (this is twice the frequency of emergencies caused by dangerous meteorological phenomena). The number of people affected by emergencies caused by spring floods and rainfall floods is more than 50% of the country's total figures for the sources of emergencies (Plekhanov 2004). Therefore, one of the most important tasks at the current stage of development of the Republic of Kazakhstan is to reduce the risk of floods as one of the strategic risks.

Floods can occur in any country in the world. According to the UN (World Disaster Report 2014) in the twentieth century, about 9 million people died from floods in the world (2 million from earthquakes and hurricanes). There are many specific examples, according to the World Meteorological Organization, there have been six catastrophic floods in the world since 1990: Bangladesh (1991), China (1991, 1994, 1996, 1998), and Pakistan (1992). In 1998, floods in China affected almost the entire country (13 floods were recorded) and 240 million people were affected by them (Avakyan & Istomina 2000).

Kazakhstan, certainly, is no exception – its territories are prone to flooding. The distinctive irregularity of flow over time in the plain catchments enhances this danger. During the period from 1991 to 2012, there were 437 hydrological extremes in the republic: floods were associated with the passage of the flood wave, rainfall and snowmelt floods, and jamming phenomena (Galperin *et al.* 2016). They affected 9,600 people; the total damage is estimated at 20 billion tenge.

In the Republic of Kazakhstan, an illustrative example of catastrophic risks associated with the water factor is 1993, when in the spring period (on all plain rivers) floods and waterlogging affected simultaneously 669 settlements and destroyed houses having a total area of 635,000 m^2. The direct economic damage was at least 500 million U.S. dollars. Recently, the frequency and extent of damage caused by floods have increased rapidly, as evidenced by the catastrophic floods on the Syrdarya River in 2004–2007, floods in the East Kazakhstan region (2010), in the West Kazakhstan region on the river Zhaiyk on the river Zhabai (Sharipkhanov *et al.* 2015).

According to the research of Golitsyn & Vasiliev (2001), hydrological disasters include:

- High-water level: refers to the water level at the gauge during floods, inundations, clogs, and ice jams, when flooding of lowered areas is possible in settlements, agricultural fields and lands, roads and railroads, and when there is damage to large industrial and transport facilities.
- Low water level: describes the water level below the design elevations of water intakes of large cities, industrial areas, and irrigation systems.
- Ice phenomena: refers to the formation of ice in river beds and floodplains, which poses a threat to settlements and hydraulic structures.
- Mudflow: encompasses mudflows of all types and sizes, caused by heavy precipitation, the breakthrough of landslides and glacial lakes, and poses a threat to settlements, industrial facilities, transport highways, irrigation systems, and other facilities.

On the territory of the Yesil water management basin, spring floods are the most harmful to the economy and population among hydrological phenomena. The main climatic factors determining the amount of spring runoff of the rivers in the Yesil River basin are snow accumulation in the river basin to the beginning of the flood, the intensity of snowmelt, rainfall during the flood, the degree of moisture, and the depth of freezing of soils in the catchment. Snow accumulation is the principal source of feeding the river. Precipitation falling during floods is of secondary importance in the formation of spring runoff in the study area. On average, they constitute 5–10% and only in rare years 20–30% of the snow reserves. Snow reserves accumulated during the long spring just melt in a few days (Moldakhmetov *et al.* 2019), and therefore the river discharge increases tens or hundreds of times (Galperin 1997), while river beds of the concerned basin do not always contain all the water, and it goes out of banks, causing floods.

According to B.D. Zaikov classification, the rivers of the Yesil water management basin belong to the Kazakhstan type. The peculiarity of this regime is an extremely sharp and high flood wave (from several weeks to 1–2 months), with up to 90% of the total annual flow (Moldakhmetov *et al.* 2020). The regime of rivers is usually distinguished by floods, high-water and low-water levels. A flood is understood as a significant and relatively prolonged rise in the water level of a river that occurs every year in the same season and is usually caused by snowmelt on plain rivers. During floods, the water level in rivers reaches its highest value, which is called the maximum water level during the flood period (or high water). Data on maximum water levels and discharges are generalized because they are most important in the study of floods and the organization of flood control, as it is the maximum level that determines the area and depth of flooding of territories.

Therefore, the causes of floods and waterlogging in the river basins of the Kazakhstan type (the rivers of Yesil water management basin) are a seasonal melting of snow cover on the plains, ice jams, liquid precipitation falling out during floods, as well as floods arising from breaches of ponds and reservoirs. One of the possible causes of increased flood risk is human activities in the catchment (urbanization, plowing, etc.). There is also an assumption that the increase in the number of catastrophic floods is associated with climate change (Karches 2012; Karches 2018).

According to RSE Kazhydromet, on average in the territory of Kazakhstan, there is an increase in the mean annual air temperature of 0.31 °C every 10 years for 1976–2019. Trends in annual precipitation over most of Kazakhstan's territory were mostly positive, but insignificant. A statistically significant decrease in precipitation (7–10%/10 years) was observed at stations in Central and Southern Kazakhstan (Annual Bulletin of Monitoring over Climate State and Climate Change in Kazakhstan 2020). In this regard, in the plain rivers of the republic, there is a decrease in flow due to increased evaporation and reduced precipitation.

The purpose of this research is to assess and quantify the hydrological extremes that may cause flooding in the Yesil water management basin, which includes Nur-Sultan city, Kamenny Karyer village, Pokrovka village, Petropavlovsk city, and Atbasar city, in order to better understand and manage flood hazards in the area. One of the main challenges related to this topic is the difficulty in accurately predicting and assessing hydrological extremes and their effects on flood hazards. This is due to the complex and dynamic nature of water systems, which can be influenced by a range of factors such as climate change, land use, and human activities. Another challenge is the lack of comprehensive data and information on past floods and their impacts, which can make it difficult to develop effective flood management strategies. Finally, the implementation of effective flood management measures can be constrained by limited financial resources and competing priorities in the area.

METHODS

Study area

Cadastre data of RSE Kazhydromet (Surface water resources… 1977, 1980; State Water Cadastre 1987, 2002, 2004) were used as reference materials to study characteristics of maximum discharges and maximum levels of rivers in the Yesil water management basin. The annual data on 25 gauging stations of the considered territory were the reference materials to analyze the characteristics of the maximum discharge and maximum level of the rivers of the Yesil water management basin. The most critical characteristic of flood hazard is the value of the possible maximum flood level or the related value of the possible maximum discharge (Mori *et al.* 2021).

Currently, most flood prevention measures are based on an assessment of the exceedance (probability) of a given value of maximum discharge (maximum level). However, increasing requirements for the accuracy of the assessment of possible damage from floods and, in particular, considering the environmental component of the damage makes the use of the maximum level and water discharge during the flooding insufficient. It is necessary to estimate the hydrograph of the maximum flow, which allows us to take into account the duration of high levels when determining the possible damage, dynamics of flooding areas, and runoff volume.

In water engineering practice, considerable experience has been accumulated in determining maximum discharges of given probabilities. Based on this experience, normative documents for calculations taking into account available observations have been developed in different countries (Galperin 2001; Code of Rules 2004). In cases where there is a long series of flow observations for which the probability of the observed maximum discharge is close to a given probability, the rates of a given probability are most often determined using a selection of probability distributions that best approximate the estimated probability of the observed discharge. Discharge rates of a given probability are found by interpolation or extrapolation of selected dependencies (Rozhdestvensky 2007a, 2007b, 2010).

When flow observations are insufficient, empirical formulas that relate water discharge rates to flow formation factors are often used to determine the maximum discharge of different probabilities. Such dependencies are reliable for a range of discharge changes that is close to the observed discharge. At present, the main method for determining the maximum discharges of possible floods is based on constructing maximum discharge probability distributions from available flow observations and then extrapolating the distribution curves to the low probability range (Oubennaceur *et al.* 2021). It should be noted that the extrapolation of empirical distribution curves obtained from a short period of observations into the low probability range can lead to large errors. The magnitude of these errors depends on the type of theoretical distribution curves, the method for determining their parameters, and the length of the available flow observation series. Risk reduction in determining the maximum design discharge is achieved by introducing guarantee corrections (Code of rules 2004); the calculated values can be increased by a correction of up to 20%.

Used datasets

Theoretical curves are used for alleviation of an element of biased approach to extrapolation of probability curves of considered characteristics (maximum discharge, maximum level). However, when processing a series of maximum discharges, upper points corresponding to the highest discharges deviate upwards from theoretical probability curves (Naeem *et al.* 2021). And by no means always increasing skewness coefficient (*Cs* selection) corrects the situation, as a rule, the curve obtained as a result of such actions deviates already from the main mass of points. The reason is that the empirical probability of upper points significantly deviates from the theoretical curve.

According to Naydenov (2002) '…catastrophic floods occurring on our planet are not out of the ordinary events but have a fairly high probability, and this probability must be taken into account'. Next, regarding the calculation methodology used: 'If we use a distribution from the exponential family for standard processing of time hydrological series, as recommended (Code of standards & rules 1983), obviously catastrophic floods will always be unexpected for us' (Naydenov 2003). And then: 'Floods of exceptional strength in recent years have convincingly demonstrated that it is necessary to calculate protective dams, dikes, and other hydraulic structures on the basis of other probabilistic laws.' In particular, these authors propose a power law distribution.

But due to different conditions of formation of high and low floods, the series of maximum discharges are often heterogeneous. That is, the two parts of the ordered series are subject to different distribution laws (Farhadi & Najafzadeh 2021). In these cases, it is doubtful that a single probability curve can be successfully selected for the entire series, irrespective of whether the distribution law is log-normal or power law. There is another way of 'adjusting' theoretical curves to empirical data. These are truncated distribution curves, which, when applied, make the empirical points correspond to the theoretical curve for only the part of the distribution we are interested in. For high discharges and water levels, this is the upper part of the ordered series. The possibility of using truncated distributions was envisaged in Chen (2014) and in Handbook on

Determining Calculated Hydrological Characteristics (1984) for the nonuniform series, although no recommendations for its application were given there.

The new Russian Code of Design and Construction Regulations (Galperin 1999; Code of rules 2004) recommends the use of truncated distributions for nonuniform maximum flow series. But the proposed methodology is far from controversial. In particular, the following are suggested: fixed truncation point, using only normal and gamma distributions. According to the recommendations (Rozhdestvensky 2010) when using statistical methods in engineering hydrological calculations, statistical homogeneity of the initial spatial and temporal hydrometeorological information is assumed as one of the main assumptions. The analysis of temporal homogeneity should be performed when constructing analytical distribution curves, including estimation of parameters and inverted distribution, and when analyzing groupings of years of different water availability (Hendrawan & Komori 2021).

As a result, it is necessary to take into account that the use of empirical curves of maximum discharge distributions is based on the hypothesis of stationarity of a series of long-term observations. This hypothesis assumes that the characteristics of river basins that affect the formation of flow and a sequence of climatic characteristics are constant in time. However, increasing human economic activity in catchments, as well as anthropogenic climate changes, now require justification of this hypothesis for each specific river basin.

Applied methods for flood risk assessment

In the absence of surveys of the area flooded in high water, the study of the width of flooding in specific gauging stations can be done as follows: calculation of the statistical series of maximum level followed by an estimate of the width of the spill along the section (there are certain difficulties due to the disturbance of the natural river regime and channels). In the case of maximum discharges, their formation is combined by several factors, but the formation of maximum levels is also influenced by such changes as river channels, ice phenomena, activities on the floodplain, etc. Hence, theoretical probability curves do not always adequately describe the distribution of the element over the entire amplitude, and this happens more often for maximum levels than for other hydrological characteristics (Hu *et al.* 2021). Therefore, it is necessary to use non-standard methods of statistical processing of observation series, such as the use of truncated distribution (Galperin 1999).

The initial basis for the study of maximum water levels in the river and the possible flooding of the territory is the static observation data – time series of maximum water levels $H_{\max}$ in the sites of hydrological gauging stations. Construction Norms and Regulations (Code of Standards and Rules 1983) recommend two options for obtaining maximum water levels of low recurrence: the first option – according to the equal maximum flow $Q_{\max}$ using the known dependence $Q = f(H)$; the second option by the empirical probability curve of maximum water level in the site of a hydrological gauging station. In the first option, the estimation of maximum water levels of low recurrence has several errors, first of all, errors in determining the maximum water discharge, the error of the named dependence.

The feasibility of using particularly the empirical probability curve was proved by the classic hydrologist Sokolovsky (1968). According to his statement, the distribution of maximum water levels is characterized by negative skewness, and extrapolation of the probability curve to the area of low recurrence is simple and cannot lead to significant errors. As calculations for Kazakhstan have shown (Galperin 1994), the series of maximum water levels can have a significant positive skewness. On the rivers of plain Kazakhstan, in particular, the skewness of maximum levels Cs can reach values of 2–2.5. Thus, the original thesis justifying the use of empirical curves is not valid.

For the purposes of hydrological calculations, it is preferable to use theoretical distribution curves, in particular, due to the possible significant positive skewness of the series of maximum water levels, but the use of such curves is often difficult. In the upper and lower parts of the ordered series obeying different distribution laws, it is practically impossible to select a theoretical curve that adequately describes the distribution over the whole amplitude. The logical way out is to use truncated distributions – only for the part of the series of interest, in this case – for the highest water levels.

It is reasonable to use the graph-analytical method of Alekseev (1960) in the following modification:

1. An empirical probability curve of the upper part of the ordered series is constructed. The lower boundary of the used part can be the area of obvious change in distribution (break point of single probability curve, if it can be traced) or, for example, the level of probability of 50%;
2. Two reference ordinates of probability P_1 and P_2 are taken from the curve – for example, $P_1 = 5\%$ and $P_2 = 40\%$;

3. Mean square deviation is calculated by the following formula;

$$\sigma = (Hp_1 - Hp_2)/[\Phi\times(P_1, Cs) - \Phi \times (P_2, Cs)] \quad (1)$$

where Hp_1 and Hp_2 are reference ordinates taken from the empirical curve; $\Phi(P_1,Cs)$, $\Phi(P_2,Cs)$ are the corresponding normalized (in fractions of σ) deviations from the mean ordinates of the probability curve (Handbook for determination of hydrological characteristics 1984). The skewness coefficient *Cs* is assigned by the standard method of selection used by hydrologists. For the first option, it is taken randomly, based on the type of truncated curve;

4. Other inversed distributions are calculated – for different *Pi* probabilities. The ordinates are calculated as the excess over the value of one of the reference ordinates, for example, over the level of probability P_2 by the following formula:

$$Hpi = Hp_2 + \sigma \times [\Phi \times (Pi, Cs) - \Phi \times (P_2, Cs)] \quad (2)$$

5. The calculated ordinates *Hpi* are plotted on the probability, and it is evaluated how well they correspond to the empirical distribution in the study area. If the correspondence is unsatisfactory, the selection is continued by testing new values of *Cs*.

The difference between these methods (Galperin 1999) from the standard method of Alekseev (1960): first, a truncated distribution is used. The validation of the truncated distribution used in the analysis of maximum water discharge and water levels in the Yesil River basin involves verifying the accuracy and reliability of the data, assessing the adequacy of the sample size, evaluating the assumptions of the distribution, conducting goodness-of-fit tests, performing sensitivity analysis, comparing with other studies, and seeking expert review. By considering these steps, the validity and reliability of the analysis can be evaluated, ensuring confidence in the findings and their implications for understanding the behavior of the rivers in the Yesil River basin.

Second, two reference ordinates are taken instead of three; third, *Cs* is determined by the selection method. However, practice has shown that in this version the assignment of one or another value of *Cs* gives less different results than in the traditional method of calculation. And this can be attributed to the benefits of the modification, because the determination of *Cs* is always approximate. Thus, the advantages of using this method are: greater approximation to the field data; consideration of distribution features only in the range of probabilities of interest; less dependence of calculation results on the usually roughly determined skewness coefficient.

During calculations in this study, the provided values of maximum levels and maximum water discharges were estimated as follows. A binomial curve of full distribution was constructed on the basis of parameters calculated by the method of moments. Since in this case we are interested specifically in characteristics of low recurrence, the 'move' of the lower part of curves to negative values at $P > 95\%$ (which is possible when using a binomial curve) does not have special importance.

If the theoretical curve did not adequately fit the empirical points, an empirical curve was drawn, and the graph-analytical method was used for the full distribution. If even in this case an adequate description of the curve of empirical points was not provided, a truncated distribution was used for the upper part of the ordered series. If possible, the range of probabilities was taken up to 60%, $H_{\max}$ or $Q_{\max}$ values of 5 and 40% probability or 10 and 40% probability were used as reference points. In some cases, when the break of the empirical curve (due to different laws of distribution of the upper and lower parts of the ordered series) fell within very low probabilities, the ordinates at $P = 5\%$ and $P = 30\%$ were used.

RESULTS AND DISCUSSION

The flow of all large rivers in Kazakhstan is regulated by large reservoirs. Currently, there are 45 reservoirs in the Yesil River basin: 3 multipurpose reservoirs with a capacity of over 100 million m^3; 6 – with a capacity of over 10 million m^3; 36 reservoirs for special purposes with a capacity from 1 to 10 million m^3. The total full capacity of multipurpose reservoirs and reservoirs for special purposes of the project is 1,584 million m^3, total usable capacity is 1,446 million m^3, which is 80% of the annual volume of the basic flow of the Yesil River basin. The water surface area of the reservoirs is 312 km^2 (Moldakhmetov *et al.* 2007).

As the calculations show (Table 1), even the mean of the maximum water discharge $Q_{\max}$ decreased from 10 to 60%, so the current situation does not fully characterize the natural values. These calculations are based on studies conducted by Alekseev (1960), Galperin (1999) and Code of Rules KR 33-101-2003 (2004).

Table 1 shows the calculated values of maximum water discharge of 1% probability (100-year period), the calculations used periods with the conditionally natural and disturbed flow. The periods corresponding to the conditionally natural and

Table 1 | Maximum water discharge (fragment)

River – hydrological alignment	Area, km^2	Period	Q_{max}, m^3/s	Q_{max}, m^3/s $P = 1\%$[a]	Q_{max}, m^3/s $P = 1\%$[b]	Q_{max}, m^3/s $P = 1\%$[c]
Silety – Prirechnoe	1,670	1961–2016	70.6	298	316	372
		1974–2016	66.1	359	338	398
Silety – Izobilnoe	14,600	1959–2016	276	1,369	1,330	1,476
		1974–2016	242	1,460	1,611	1,629
Yesil – Nur-Sultan	7,400	1933–2016	223	1,387	1,194	1,473
		1974–2016	135	843	682	851
Yesil – Kamennyi Karier	86,200	1947–2016	788	3,917	3,928	5,000
		1974–2016	640	2,292	2,681	3,375
Yesil – Petropavlovsk	106,000	1933–2016	699	4,079	4,204	4,603
	118,000	1974–2016	552	2,522	2,280	–
Kalkutan-Kalkutan	16,500	1937–2016	322	1,591	1,418	1,759
		1974–2016	369	1,939	1,617	–
Zhabai– Balkashino	922	1960–2016	71.8	191	184	–
		1974–2016	75.1	184	180	–
Zhabai– Atbasar	8,530	1937–2016	365	1,614	1,519	1,828
		1974–2016	340	1,712	1,515	2,192
Imanburlyk – Sokolovka	3,870	1951–2016	121	564	544	–
	4,070	1974–2016	129	557	521	613

Note: Q_{max} is the equal maximum flow.

[a] According to Alekseev (1960).

[b] According to Code of Rules (2004).

[c] According to Galperin (1999).

disturbed flows for each river are as follows: for Silety – Prirechnoe, the period 1961–2016 represents the conditionally natural flow, while the period 1974–2016 corresponds to the disturbed flow. For Silety – Izobilnoe, both periods, 1959–2016 and 1974–2016, represent the conditionally natural and disturbed flows, respectively. Similarly, for Yesil – Nur-Sultan, the period 1933–2016 represents the conditionally natural flow, while the period 1974–2016 corresponds to the disturbed flow. The same pattern applies to Yesil – Kamennyi Karier, Yesil – Petropavlovsk, Kalkutan-Kalkutan, Zhabai– Balkashino, Zhabai– Atbasar, and Imanburlyk – Sokolovka, where the earlier periods represent the conditionally natural flow and the later periods represent the disturbed flow.

The results shown in the table suggest that even after significant flow regulation, the rivers in the concerned region can form more than 2,000 m^3/s. The level regime of the rivers of the Yesil water management basin, which determines the risk of flooding, is characterized by a well-defined rise in levels during the high water and low levels during the low water period. Maximum rises in water levels during the spring flood in the rivers of the concerned area reach a significant value. The height of the flood wave varies greatly depending on the amount of water carried by the river from its basin in a year, the size of the catchment area, the nature of the channel and floodplain, and the structure of the river banks (Galperin *et al.* 2016). The annual amplitude of water level fluctuations on the rivers of the concerned territory changes within a significant range (Heinrich & Penning-Rowsell 2022). In the Atlas of natural and technogenic hazards (Atlas of natural and technogenic hazards in the Russian Federation 2008) Russian scientists adopted the amplitude of water levels in the river as the main characteristic of the danger. In Kazakhstan, based on the characteristics of rivers, the highest gradation represents the exceptionally high danger of flooding, indicated by a water level amplitude of more than 10 m. The somewhat lower danger is classified as the high danger of flooding, characterized by a water level amplitude ranging from 6 to 10 m (Galperin *et al.* 2016). Just to let you know, in Kazakhstan – an exceptionally high risk of flooding is characteristic to our plain rivers (Yesil River about 12 m, Torgai river about 12.5 m), the second gradation with an amplitude of 6–10 m includes rivers Zhaiyk, Yelek, Yrgyz, Arys.

Statistical analysis of multi-year series of maximum annual water levels of the rivers in the Yesil water management basin was carried out for 25 hydrological gauging stations with the duration of the series of 40 years and more, up to 2016 inclusive. The whole period of instrumental observations was considered to assess the observational series of maximum water levels for non-stationarity or stationarity, i.e., for the presence or absence of trends. The results of calculations of the linear trend of maximum water levels of the main rivers in the Yesil water management basin are presented in Table 2; Figure 1 shows graphs of maximum water level fluctuations.

Analysis of the data given in Table 2 shows that significant trends during the maximum water levels are observed on the Yesil River – Nur-Sultan city, Zhabai River – Atbasar city (the value of r is greater than $2\sigma r$ at 5% level), therefore, we accept the alternative hypothesis of non-stationarity of series, that is, the presence of a linear trend. The significant trends in this analysis lie in the evaluation of the statistical significance of the regression coefficients (the slopes of the linear trend equations). The standard deviation of the regression coefficient (σr) provides information about the precision or variability of the estimated slopes. Even if the correlation coefficients (r) are relatively low, if the regression coefficient is statistically significant (i.e., significantly different from zero), it indicates that there is a linear trend present in the data. The standard deviation of the regression coefficient quantifies the uncertainty associated with the estimated trend.

As calculations show (Table 3), even the mean of the maximum water levels $H_{\max}$ decreased slightly to 10% (Shagagaly river – Pavlovka village, Yesil River – Kamenny Karyer village, Imanburluk – Sokolovka village), and the decrease in the mean of maximum water levels reaches values up to 15% (Yesil River – Nur-Sultan city, Yesil River – Petropavlovsk city, Zhabai River – Atbasar city, Akkanburluk river – Vozvyshenka village). Therefore, the current situation does not fully characterize natural values. These calculations are based on research conducted by Alekseev (1960) and Code of Rules of KR 33-101-2003 (2004).

The calculations show that the mean of the maximum water levels in some areas has decreased slightly by 10%, while in other areas, there has been an increase in the mean of maximum water levels up to 15%. Human activities can have significant impacts on river systems, potentially altering their natural flow patterns and maximum water levels. The current situation may not fully represent natural values, it`s the need for further investigation and monitoring to better understand the underlying causes of the observed changes. Human-induced factors, such as land use changes and water management practices, could be contributing to the alterations in the maximum water levels. These activities can modify the landscape, disrupt natural drainage patterns, and affect the availability and distribution of water.

Consequently, the current water levels and flood risks may be influenced by these human interventions, leading to deviations from the rivers' natural behavior. The rationale for emphasizing the need for additional research and monitoring is to promote a more comprehensive understanding of the causes behind the observed changes. By gaining a better understanding of the underlying mechanisms, it becomes possible to develop appropriate management strategies to mitigate flood risks in the affected areas. Such strategies may involve implementing measures to restore natural hydrological processes, managing land use practices to reduce their impact on water flow, or adopting sustainable water management techniques.

Table 2 | Equations of linear trends of maximum water levels of major rivers in Yesil water management basin (fragment)

River – hydrological alignment	Period	Trend equation	r	σr	$2\sigma r$	$3\sigma r$
Silety – Prirechnoe	1961–2016	$y = 0.48x + 324$	0.08	0.14	0.28	0.43
Shagalaly – Pavlovka	1940–2016	$y = -0.57x + 192$	0.22	0.11	0.23	0.34
Yesil – Turgen	1975–2016	$y = 0.21x + 352$	0.03	0.16	0.31	0.47
Yesil – Nur-Sultan	1933–2016	$y = 1.80x + 355$	0.32	0.10	0.20	0.30
Yesil – Kamennyi Karier	1947–2016	$y = -1.67x + 646$	0.14	0.12	0.24	0.35
Yesil – Pokrovka	1949–2016	$y = -2.34x + 854$	0.14	0.12	0.24	0.36
Yesil – Petropavlovsk	1933–2016	$y = 2.04x + 656$	0.17	0.11	0.21	0.32
Kalkutan – Kalkutan	1955–2016	$y = 0.33x + 515$	0.05	0.13	0.26	0.38
Zhabai– Balkashino	1960–2016	$y = 0.34x + 322$	0.05	0.13	0.27	0.40
Zhabai– Atbasar	1944–2016	$y = 1.96x + 506$	0.33	0.11	0.21	0.32
Akkanburlyk – Kovylnoe	1959–2016	$y = 0.10x + 326$	0.17	0.13	0.26	0.39
Akkanburlyk – Vozvyshenka	1951–2016	$y = 0.26x + 596$	0.03	0.12	0.25	0.37
Imanburlyk – Sokolovka	1951–2016	$y = -0.45x + 304$	0.10	0.12	0.25	0.37

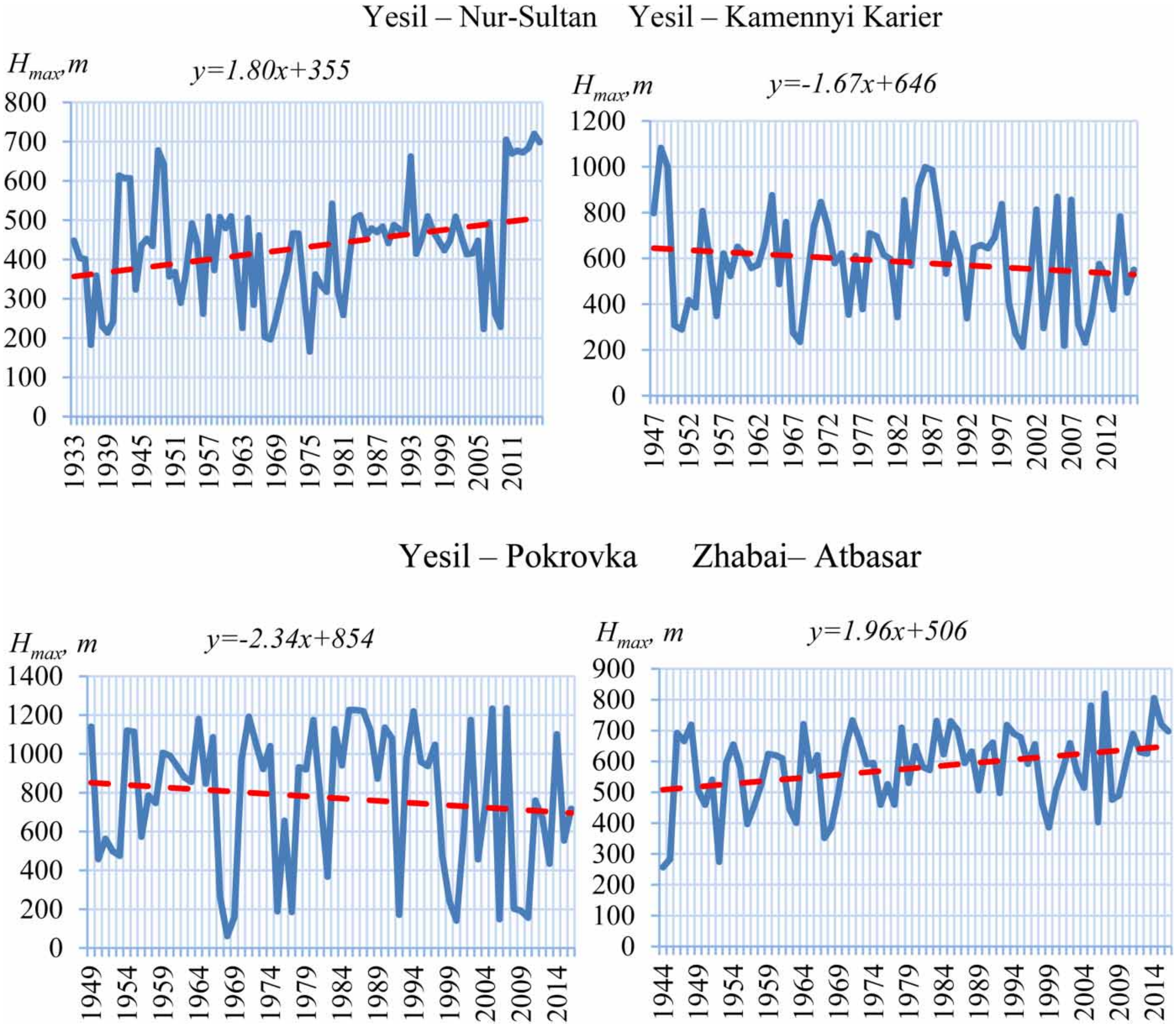


Figure 1 | Dynamics of maximum water levels in the Yesil River basin.

An important characteristic for assessing flood damage is the depth of floodplain inundation. The maximum floodplain inundation depth ΔH is defined as the difference between the maximum observed water level $H_{\max}$ and the level of discharge to floodplain H_n for each hydrological gauging station. A schematic map of the distribution of maximum floodplain inundation depth across the basin is shown in Figure 2. This information can be used to identify areas that are particularly at risk of flood damage and prioritize flood prevention or mitigation measures. The authors used a flood hazard classification system developed by Golitsyn & Vasiliev (2001) to classify the maximum floodplain inundation depth. The classification system includes six gradations of flooding depth, ranging from extremely hazardous to slightly hazardous, based on the periodicity of flooding and the maximum floodplain inundation layer in the riverine zone (Table 4) (Golitsyn & Vasiliev 2001).

The greatest depths of floodplain inundation are observed at the following gauging stations: Yesil River – Nur-Sultan city (182 cm), Yesil River – Kamenny Karyer village (337 cm), Yesil River – Pokrovka village (639 cm), Yesil River – Petropavlovsk city (623 cm), Zhabai River – Atbasar city (279 cm).

In the upper reaches of the basin, the depth of floodplain inundation is less than in the lower reaches. This is due to the size of streams and the water content of streams. Streams in the lower reaches of a basin tend to be larger and have higher water content. As shown in Figure 2, the frequency of flooding in the coastal area occurs once every 2 years in the Yesil River, in the Zhabai River frequency is once every 3–5 years, which are in line with the studies of the authors (Galperin *et al.* 2016) on the

Table 3 | Maximum water levels (fragment)

River – hydrological alignment	Area, km^2	Period	H_{max}, m	H_{max}, m $P = 1\%$[a]	H_{max}, m $P = 1\%$[b]
Silety – Prirechnoe	1,670	1961–2016	337	545	312
		1974–2016	337	560	304
Shagalaly – Pavlovka	1,750	1940–2016	171	301	329
		1974–2016	163	267	258
Yesil – Turgen	3,240	1975–2016	356	609	574
Yesil – Nur-Sultan	7,400	1933–2016	432	761	796
		1974–2016	463	805	840
Yesil – Kamennyi Karier	86,200	1947–2016	587	1,141	1,142
		1974–2016	577	1,128	1,108
Yesil – Pokrovka	104,000	1949–2016	774	1,527	1,383
	115,000	1974–2016	761	1,523	1,427
Yesil – Petropavlovsk	106,000	1933–2016	743	1,123	1,125
	1,180,001	1974–2016	800	1,383	1,203
Kalkutan – Kalkutan	16,500	1955–2016	525	768	720
		1974–2016	528	751	724
Zhabai– Balkashino	922	1960–2016	332	556	556
		1974–2016	330	574	559
Zhabai– Atbasar	8,530	1944–2016	579	844	963
		1974–2016	608	887	846
Akkanburlyk – Privol'noe	910	1951–2016	355	605	665
		1974–2016	356	603	643
Akkanburlyk – Grigor'evka	5,620	1951–2016	605	973	974
	6,250	1974–2016	621	970	993
Imanburlyk – Sokolovka	3,870	1951–2016	574	992	541
	4,070	1974–2016	577	1,142	558

[a] According to Alekseev (1960).

[b] According to Code of Rules (2004).

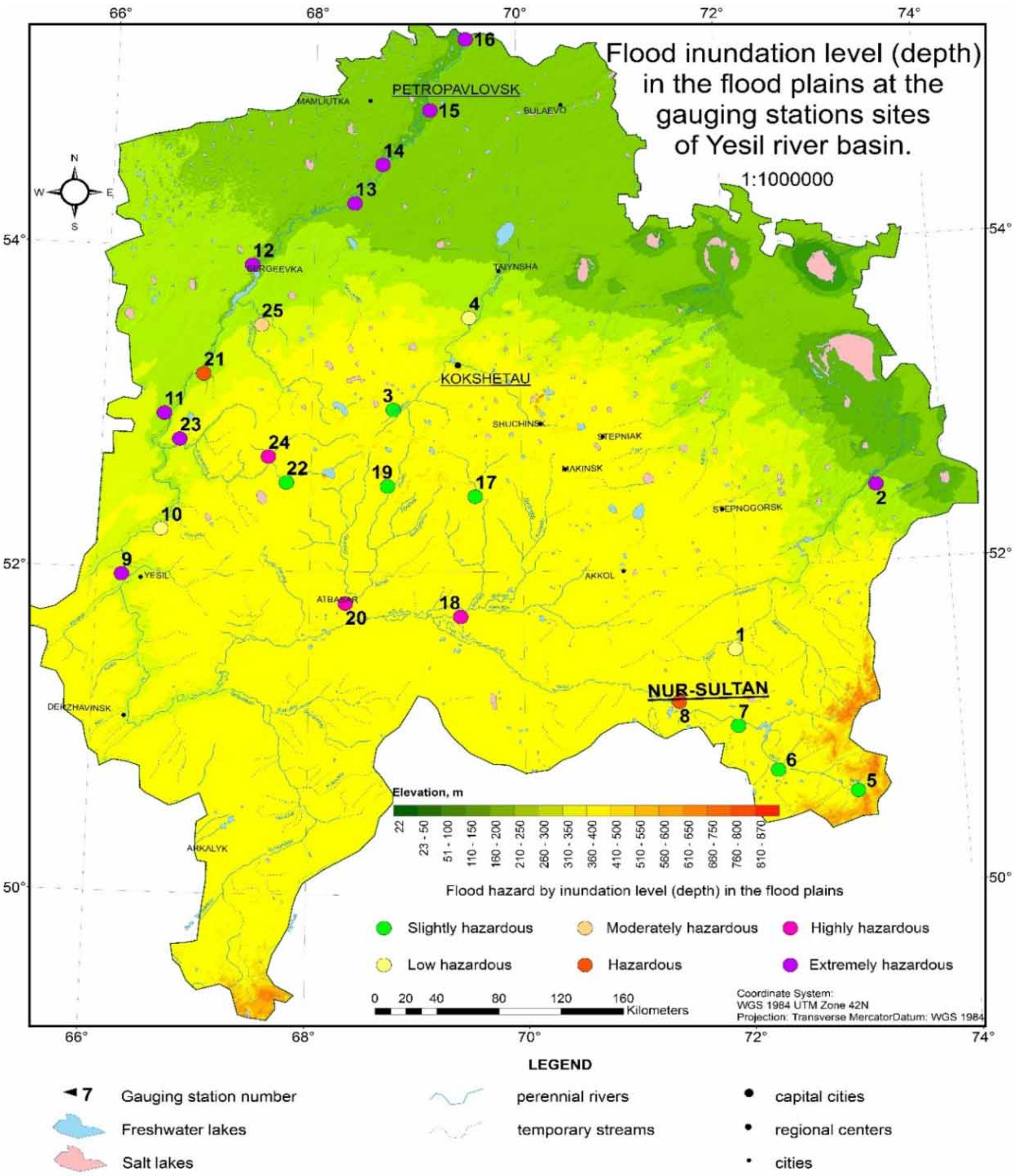
excess of dangerous levels in major plain rivers of Kazakhstan (in particular on the rivers Yesil, Nura, Kon, exceeding dangerous levels occur extremely often – almost once every 2 years).

It is important to note that frequent flooding can have significant impacts on the environment, infrastructure, and human populations in the affected areas. Understanding the frequency and severity of flooding in a particular area is essential for developing effective flood management strategies, including early warning systems, evacuation plans, and measures to reduce the risk of damage and loss of life. Therefore, ongoing monitoring and research are needed to better understand the patterns and causes of flooding in these rivers and to develop appropriate management strategies to mitigate the risk of flooding in affected areas. This could involve a multidisciplinary approach that considers factors such as hydrology, topography, climate, land use patterns, and human activities.

CONCLUSIONS

Flooding is usually understood as flooding of territories as a result of an intensive increase in water content and rising water levels in rivers. As for the concerned territory, the most dangerous floods can occur during the spring floods. But not all high-water levels cause floods, only when the rise of water in the river (reservoir) leads to flooding of areas and causes material damage, it is commonly referred to as a flood. Assessment of flood risk and potential flood sizes for individual sections of river systems is of paramount importance for the implementation of comprehensive flood prevention or mitigation measures: flow regulation by means of hydraulic structures; introducing measures to reduce maximum flow (agroforestry measures, flow regulation from urbanized areas, building system of water regime forecasts, development of a system of emergency measures).

Under conditions of unsteady climate, densification of population and infrastructure near water bodies, and deterioration of hydraulic structures, the risk associated with floods increases significantly. Quantitative assessments of hydrological



Gauging N	River	Hydrological alighnment	Gauging N	River	Hydrological alighnment	Gauging N	River	Hydrological alighnment
1	Silety	Prirechnoe	10	Yesil	Kalachi	18	Kalkutan	Kalkutan
2	Silety	Izobilnoe	11	Yesil	Zapadnoe	19	Zhabay	Balkashino
3	Shagalaly	Pavlovka	12	Yesil	Sergeevka	20	Zhabay	Atbasar
4	Shagalaly	Severnoe	13	Yesil	Pokrovka	21	Akkanburlyk	Privolnoe
5	Yesil	Priishimskoe	14	Yesil	Novonikolskoe	22	Akkanburlyk	Kovylnoe
6	Yesil	Turgen	15	Yesil	Petropavlovsk	23	Akkanburlyk	Vozvyshenka
7	Yesil	Volgodonovka	16	Yesil	Dolmatovo	24	Babykburlyk	Rukhlovka
8	Yesil	Nur-Sultan	17	Moiyldy	Nikolaevka	25	Imanburlyk	Sokolovka
9	Yesil	Kamennyi Karier						

Figure 2 | A schematic map of maximum floodplain inundation depth ΔH (cm) in the sections of the gauging stations of the Yesil water management basin.

extremes characterizing the flood hazard have been carried out for hydrological gauging stations in the Yesil water management basin. The following results were obtained: the maximum water discharge may exceed on the Yesil River – 4,000 m^3/s, on the Zhabai River – 1,700 m^3/s; the water levels amplitudes on the Yesil River surpass 12 m. Quantitative results on the

Table 4 | Flood hazard classification by floodplain inundation layer

Characteristic	Periodicity	Maximum floodplain inundation layer of the riverine zone, m
Extremely hazardous	Once in 2 years	More than 3.0
Highly hazardous	Once in 3–5 years	2.0–3.0
Hazardous	Once in 5–10 years	1.5–2.0
Moderately hazardous	Once in 10–12 years	0.70–1.5
Low hazardous	Once in 12–15 years	0.30–0.70
Slightly hazardous	Once in 15–20 years	Does not exceed 0.30

maximum depth of floodplain inundation were obtained – the greatest depths of floodplain inundation in the Yesil River basin are observed at the hydrological gauging stations of Nur-Sultan city, Kamenny Karyer village, Pokrovka village, Petropavlovsk city, and Atbasar city. The frequency of flooding in the coastal area occurs once every 2 years on the Yesil River, while on the Zhabai River frequency is once every 3–5 years.

Future researchers may use the output of this study to further understand and develop strategies for mitigating the risks associated with flooding in Kazakhstan. For example, the information on the maximum water discharge and water level amplitudes can help to identify areas that are particularly at risk of flooding and prioritize flood prevention or mitigation measures. The frequency of flooding in the coastal areas of the Yesil and Zhabai Rivers can also help researchers and policymakers to develop effective flood warning and emergency response systems. The information on the maximum depth of floodplain inundation can be used to develop flood maps and identify areas where flood protection infrastructure, such as levees or floodwalls, may be necessary. Additionally, the study's findings on the non-stationarity of maximum water levels over time can inform future research on the causes and implications of these trends. Further research could explore the factors contributing to the non-stationarity of maximum water levels, such as climate change or human activities, and develop strategies to mitigate the risks associated with these trends.

DATA AVAILABILITY STATEMENT

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

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CONFLICT OF INTEREST

The authors declare there is no conflict.

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