

Article

Geo-Ecological Analysis of the Causes and Consequences of Flooding in the Western Region of Kazakhstan

Shakhislam Laiskhanov ¹, Zhanerke Sharapkhanova ², Akhan Myrzakhmetov ², Eugene Levin ^{3,*},
Omirezhan Taukebayev ^{4,5}, Zhanbolat Nurmagambetuly ¹ and Sarkytkan Kaster ¹

¹ Abai Kazakh National Pedagogical University, Almaty 050010, Kazakhstan; laiskhanov@gmail.com (S.L.); zhanbo_87@mail.ru (Z.N.); kaster0102@mail.ru (S.K.)

² Institute of Geography and Water Security, Almaty 050010, Kazakhstan; sharaphanova@gmail.com (Z.S.); ahan_myrzakhmetov@mail.ru (A.M.)

³ School of Applied Computational Sciences, Meharry Medical College, Nashville, TN 37208, USA

⁴ Space Technologies, and Remote Sensing Center, Al-Farabi Kazakh National University, 71 Al-Farabi Ave., Almaty 050040, Kazakhstan; omirzhan.taukebayev@kaznu.edu.kz

⁵ Department of Cartography and Geoinformatics, Faculty of Geography and Environmental Sciences, Al-Farabi Kazakh National University, 71 Al-Farabi Ave., Almaty 050040, Kazakhstan

* Correspondence: elevelin@mmc.edu

Abstract: The intensifying effects of climate change have led to increased flooding, even in desert regions, resulting in significant socio-economic and ecological impacts. This study analyzes the causes and consequences of flooding in the Zhem River basin using data from ground stations, including Kazhydromet, and satellite platforms such as USGS FEWS NET and Copernicus. Spatial analyses conducted in ArcGIS utilized classified raster data to map the dynamics of flooding, snow cover, vegetation, and soil conditions. This enabled a geoecological analysis of flood damage on the vital components of the local landscape. Results show that flooding in the Zhem River basin was driven by heavy winter precipitation, rapid snowmelt, and a sharp rise in spring temperatures. The flood damaged Kulsary city and also harmed the region's soil, vegetation, and wildlife. In July 2024, the flooded sail area tripled compared to the same period in 2023. Additionally, the area of barren land or temporary water bodies (pools) formed three months after the water receded also tripled, increasing from 84.9 km² to 275.7 km². This study highlights the critical need for continued research on the long-term environmental effects of flooding and the development of adaptive management strategies for sustainable regional development.

Keywords: Zhem River basin; Kulsary city; climate anomaly; river flooding; flood formation factors; geoecological analysis of flood damage



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1. Introduction

Flooding has emerged as one of the most critical global challenges due to the increasing frequency of extreme weather events and climate anomalies. These changes have intensified the need for studying and monitoring river systems and their basins at regional, national, and international levels [1]. Flooding, often ranked among the most destructive natural disasters, results in profound socio-economic and environmental impacts, including significant economic losses, social disruptions, and ecological degradation [2]. Its devastating consequences make it one of the costliest disasters in terms of both human and financial tolls [3]. According to data from the Emergency Events Database (EM-DAT), the total number of natural disasters in the 21st century has increased sharply compared to the 20th century. Since 1970, there have been 14,558 natural disasters worldwide, with

more than half of them (7565) attributed to floods [4]. The growing urgency to understand and mitigate these impacts has driven greater attention to the dynamics of rivers and their changing basins in the context of climate change. Floods and freshets pose significant dangers to national economies, ecosystems, and landscapes, impacting both natural and human-modified environments. They have direct and indirect environmental impacts, including ecosystem destruction, water and soil contamination, reductions or extinctions of animal and plant populations, and sometimes even altering landforms [5,6]. Between 2008 and 2018, floods caused an estimated USD 21 billion in agricultural losses (crops and livestock) in developing countries, according to the Food and Agriculture Organization of the United Nations (FAO) [7]. For sustainable development, it is essential to study these environmental impacts and conduct geo-ecological analyses of their consequences.

Despite its arid climate, Kazakhstan frequently faces flood risks. Flooding on rivers such as the Syr Darya, Shu, Talas, Zhaiyk, Tobyl, Nura, Esil, Uba, Bukhtarma, and Irtysh has caused significant economic and ecological damage [8]. Cheng et al. [8] highlighted that border areas of Russia and Kazakhstan are particularly vulnerable to droughts and floods. In spring 2024, large-scale flooding affected northern, western, and eastern Kazakhstan, resulting in significant economic losses and even fatalities [9,10]. This event, considered the largest natural disaster in Kazakhstan and Central Asia in the last 80 years, prompted a state of emergency in 10 regions. Over 118,000 people were evacuated, while more than 12,000 residential buildings and 7000 summer cottages were submerged. In total, 12,000 livestock animals perished, with an estimated damage of USD 452.8 million [11].

In April 2024, major flooding occurred in the lower reaches of the Zhem River basin, inundating the city of Kulsary. Sharp changes in the Zhem River's water flow, linked to climate anomalies, highlighted the role of spatial-temporal mismatches in precipitation and temperature in causing both floods and droughts [12]. Floodwaters affected several areas in the Zhylyoi District, flooding 2810 private homes and 5 social facilities, necessitating the evacuation of 28,551 people, including 6719 children. Infrastructure damage included electricity outages, while 5184 cubic meters of water were pumped out to mitigate the flood's impact [10]. Despite these efforts, the disaster underscored the importance of understanding the factors contributing to such events.

The frequent occurrence of floods over the past half-century has become a pressing issue for the global scientific community. While river flooding has been widely studied [13,14], research on the Zhem River remains scarce. Previous studies by Kazakhstani scientists have primarily focused on rivers like the Ural (Zhaiyk) and Atbasar in Western Kazakhstan [15–17]. Although trends in river flow changes in the Zhem River basin have been documented, this study represents the first comprehensive analysis of flooding in this area. Such studies are critical to understanding the environmental impacts of flooding, particularly on soil, vegetation, and wildlife [18].

This study leverages ground data and satellite imagery to conduct a geo-ecological analysis of the causes and impacts of flooding in Kulsary. Platforms such as USGS FEWS NET and Google Earth Engine, along with satellite indices like NDWI and MNDWI, have been employed for spatial analysis [19–22]. By combining these tools, this research aims to enhance understanding of flood dynamics in the Zhem River basin, strengthen early risk detection systems, and support the development of geo-ecological strategies for sustainable ecosystem management and disaster mitigation [23].

This research introduces a novel approach to understanding flooding in the Zhem River basin by integrating ground data from meteorological stations with high-resolution satellite imagery and advanced geo-ecological analysis tools. Unlike prior studies that primarily focused on long-term hydrological trends, this study provides a detailed, event-specific analysis of the causes and impacts of the 2024 flood. It utilizes indices such as

NDWI and MNDWI for flood mapping and incorporates vegetation and soil condition assessments, offering a multi-dimensional perspective on flood dynamics. This comprehensive methodology provides a more robust framework for understanding both immediate and long-term consequences of floods, making this the first study to address such aspects of the Zhem River basin.

This study hypothesizes that climatic anomalies, including excessive precipitation, rapid snowmelt, and abrupt warming, are the primary drivers of the 2024 flood in the Zhem River basin. The objectives are to (1) analyze the environmental factors contributing to flooding, (2) assess the impacts on soil, vegetation, and wildlife, and (3) propose geo-ecological strategies for mitigation and sustainable management of the basin. By achieving these objectives, this study aims to contribute to flood risk management practices and enhance resilience against future climatic challenges.

2. Materials and Methods

The Zhem River is the second-largest river on the eastern coast of the Caspian Sea and in the western region of Kazakhstan. Its 700 km long course serves as a boundary between Europe and Asia. The river is fed by snow and follows the Kazakh water regime type. Its basin is entirely located within an arid and semi-desert zone. Due to the fact that evaporation in these climatic zones significantly exceeds precipitation, the river has a low water volume.

In many scientific works, especially those from the Soviet period, as well as among some contemporary post-Soviet researchers, the river is referred to as the “Emba”. The local population, however, calls it by its historical name, “Zhem”. Currently, the name “Zhem” is used in the National Atlas of Kazakhstan, on other maps, and in official documents. The Zhem River basin spans the territories of two regions: Aktoobe and Atyrau. The river’s water primarily forms at altitudes of 200–300 m in the Mugodzhur Mountains in the Aktoobe region. In the river’s lower course, within the Atyrau region, lies the Kulsary city, home to a population of over 65,000 people (Figure 1).



Figure 1. Zhem River basin.

The Zhem River basin covers an area of 40,400 km², with the area around the city of Kulsary, located in the lower part of the basin, accounting for 29.4 thousand km². The upper part of the Zhem basin lies within the Aktobe region, while the lower part is situated in the Atyrau region. The basin's large size and diverse topography contribute to the distinctly different climates in its upper and lower parts. According to data from the National Meteorological Service, Kazhydromet [24], January is a typical winter month for the Aktobe Region and is the coldest across the area. The average January temperature ranges from −11.4 °C to −16.2 °C. July is the hottest month of summer, with average temperatures ranging from 20.5 °C to 26.1 °C. The average annual precipitation is between 240 and 400 mm.

The climate of the Atyrau Region is sharply continental and arid. The average temperature in January, the coldest month, ranges from −7 °C to −11 °C. However, in particularly cold winters, temperatures can drop to as low as −36 °C to −42 °C (the absolute minimum). Summer across most of the region is hot and prolonged, with average July temperatures (the hottest month) not dropping below 25.0 °C. In certain years, air temperatures can rise to 41 °C to 46 °C. The average annual precipitation does not exceed 140–200 mm, with the majority, 85–120 mm, falling during the warm season. The climate of the Atyrau Region is also typical for the city of Kulsary.

At the upper reaches of the Zhem River basin lies a pine plateau, dissected by erosion, while the lower part features the Caspian Lowland, with a barely perceptible slope toward the Caspian Sea. The main tributaries that form the Zhem River are the Temir and Adzhaks rivers. The annual flow variations in the Zhem River are highly pronounced, due to significant changes in the main factors influencing its formation [24].

In studying the causes and effects of flooding in the Zhem River basin, key methods such as cartographic analysis, spatial analysis, and geoeological analysis were employed. Ground-based observation data and satellite imagery were downloaded and utilized from global and Kazakhstani web resources (Figure 2).

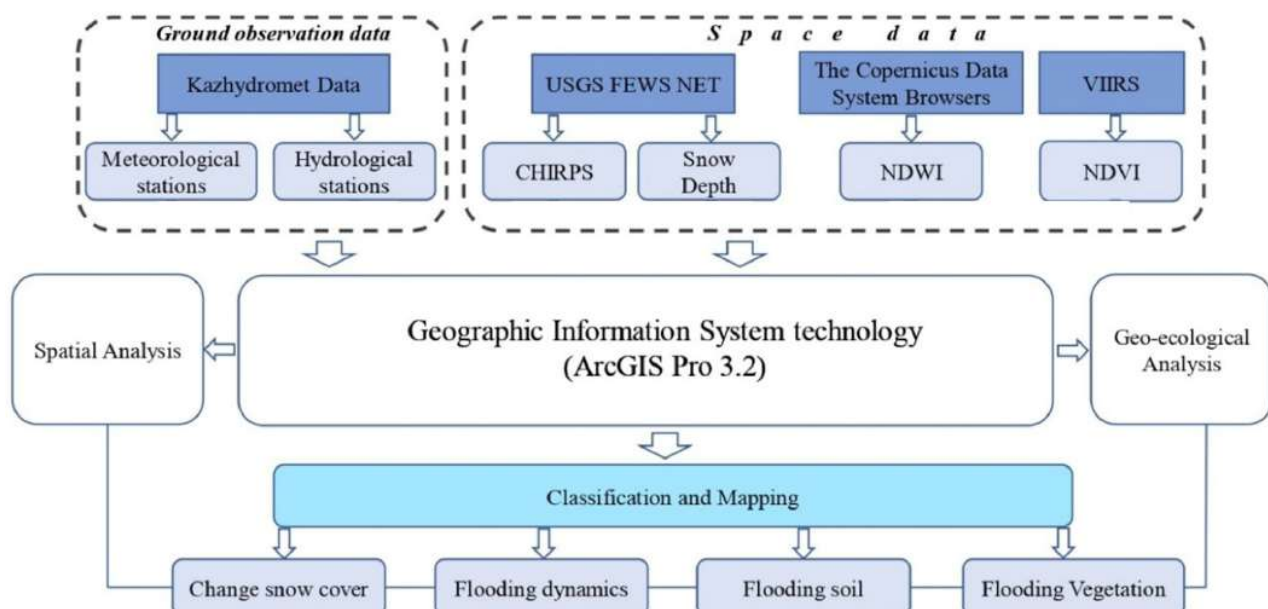


Figure 2. Conceptual diagram of the methodology.

In the study, variations in atmospheric temperature and the surface soil layer temperature in the Zhem River basin were analyzed based on daily data (from 13 March to 13 April 2024) and ten-day measurements (from the first decade of February to the first decade of April) from the “Emba”, “Temir”, “Ilyin”, “Mugodzhazhar”, and “Kulsary” meteorological stations.

logical stations of the national meteorological service “Kazhydromet” [25]. The water level in the Zhem River was studied weekly using data collected from 1 January to 30 July 2024, from the hydrological posts “Akkystogai”, “Saga”, and “Zhagabulak”.

The annual precipitation volume in the Aktobe region was presented using five-day precipitation data for Central Asia from the USGS FEW NET portal (CHIRPS—Climate Hazard group InfraRed Precipitation with Stations). CHIRPS provides spatially linked global precipitation data (50° S–50° N, 180° E–180° W, resolution of 0.05°). Raster data on daily snow depth in Central Asia (Snow Depth) from this portal were used to analyze snow cover thickness in the Zhem River basin, while five-day raster vegetation condition data (NDVIeVIIRS) were employed to assess vegetation condition after flooding. The NDVI index (Normalized Difference Vegetation Index) measures chlorophyll density in vegetation based on satellite data VIIRS.

The raster data on snow cover thickness and vegetation condition were selected through the Early Warning eXplorer (EWX) interactive web tool on the USGS FEW NET portal. To display dynamic changes in snow cover, Snow Depth raster data (with a bi-weekly interval) from February 10 to March 27 of this year were used, while NDVIeVIIRS data from 16 July 2023, and 2024 were downloaded for comparative analysis of vegetation changes. In ArcGIS Pro 3.2, the classification method was used to categorize data on snow cover thickness and vegetation biomass into classes. According to the map legend by Zhang et al. [25], NDVI data were divided into five classes based on NDVI values (Table 1).

Table 1. NDVI value.

Classification Ranges	The Greenness Level of the Vegetation
$-1 < \text{NDVI} < -0.03$	Non-vegetation area, open area, waterbody
$-0.03 < \text{NDVI} < 0.15$	Very low dense vegetation
$0.15 < \text{NDVI} < 0.25$	Low dense vegetation
$0.25 < \text{NDVI} < 0.35$	Moderately dense vegetation
$0.35 < \text{NDVI} < 1$	Highly dense vegetation

The main concept of NDVI is based on the fact that the internal mesophyll of healthy green leaves strongly reflects near-infrared (NIR) radiation, while the chlorophyll and other pigments in the leaves absorb most of the red visible (RED) radiation [26].

To analyze flood dynamics and types of flooded soils, Sentinel-2 (L2A) images were used, available on the Copernicus Data Space Ecosystem browser [27], along with the soil map of the Atyrau region. Flood dynamics were analyzed based on six raster NDWI (Normalized Difference Water Index) data sets for the period from 1 April to 29 April 2024, while data from 21 July 2023, and 20 July 2024, were used to assess the condition of flooded soils. The Normalized Difference Water Index (NDWI) has been successfully used to distinguish between surface water bodies [28]. NDWI formula: $\text{NDWI} = (\text{NIR} - \text{SWIR2}) / (\text{NIR} + \text{SWIR2})$. NIR—near-infrared spectral channel; SWIR 2—shortwave infrared spectral channel.

Using the “Training Samples Manager” tool in ArcGIS Pro 3.2 and classification by the “2011 National Land Cover Database (NLCD2011)”, raster data were divided into four classes (water, open land, grass cover, and shrubs). To calculate the area of flooded territories, raster data were converted to vector format, and an overlay operation was applied to display soil types in flooded areas.

As a result of the study, maps were created showing changes in snow cover thickness and flood dynamics, as well as the condition of vegetation and soil cover following flooding. A geo-ecological analysis of changes in the study area was conducted.

3. Results

3.1. Origin of the Flood

The most significant and costly flood, in both economic and social terms, occurred in the lower reaches of the Zhem River, resulting in the flooding of Kulsary city and causing substantial damage (Figure 3).

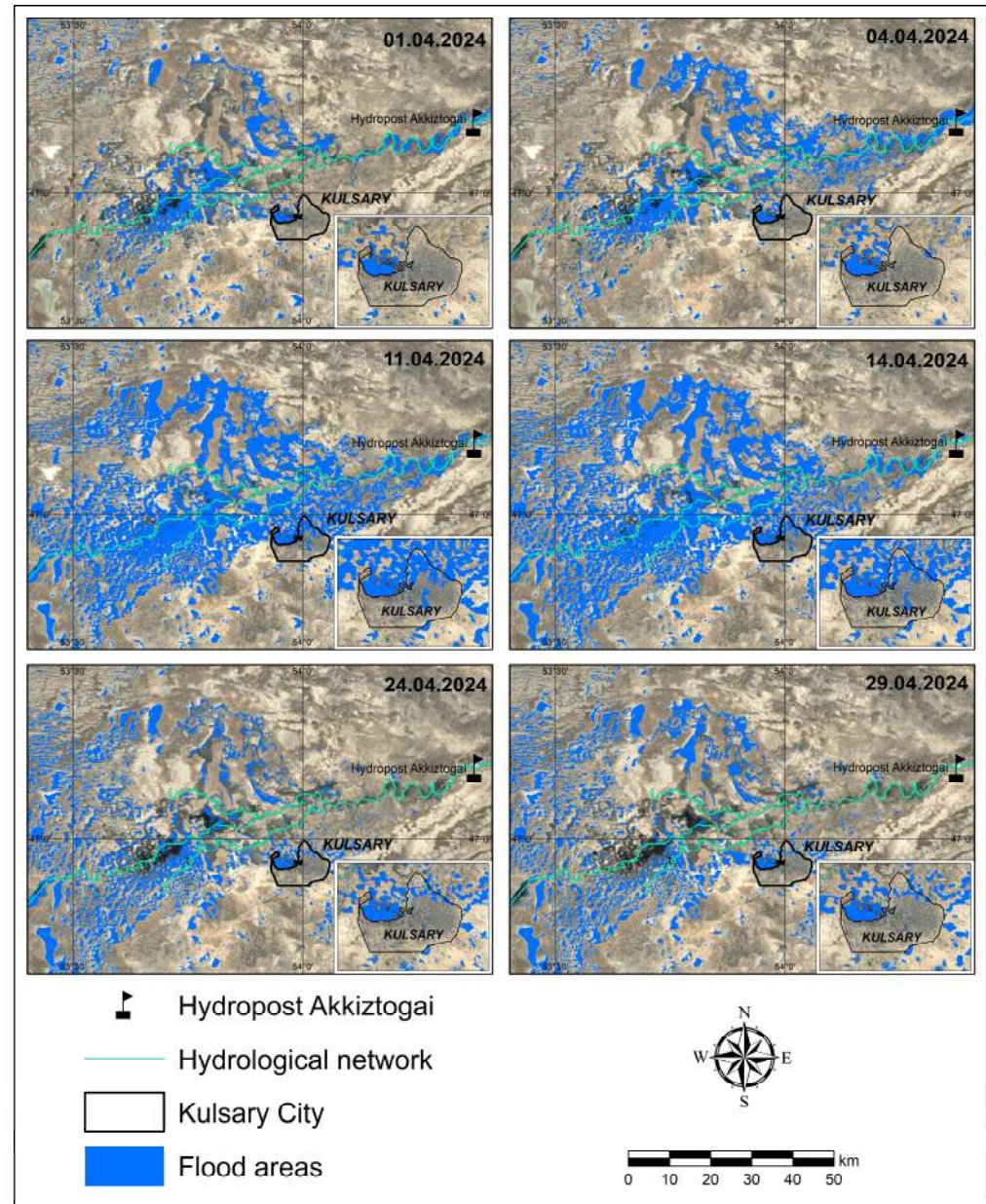


Figure 3. Flooding Situation in the lower part of the Zhem River Basin.

Figure 3 illustrates the dynamics of changes in the lower reaches of the Zhem River, downstream from the “Akyztogai” hydrological post (GP), covering the period from 1 February to 29 April 2024. The volume of floodwaters surged dramatically on 4 April, peaking on 11 April, before gradually receding by the end of the month (Table 2).

Table 2 provides the flooded area sizes and their percentage shares of the total area for regions downstream of the “Akshoky” hydrological post and within the Kulsary city. On 1 April 2024, the flooded area downstream of the Akshoky hydrological post covered 269.4 km², representing 6.9% of the total area. In Kulsary city, the flooded area was significantly smaller, at 0.4 km², or 1.0% of the city’s total area. The maximum extent of

flooding was recorded on 11 April 2024, with 836.8 km² (21.4% of the total area) submerged downstream of the Akshoky hydrological post and 7.3 km² (18.0%) within Kulsary.

Table 2. Dynamics of flooding in the lower Zhem River basin.

Date	Flooded Area Below Akkiztogai GP (km ²)	% of Total Area Below Akkiztogai GP	Flooded Area in Kulsary City s (km ²)	Percentage (%) of Flooded Areas of Kulsary from the Total Area
1 April 2024	269.4	6.9	0.4	1.0
4 April 2024	351.0	9.0	0.4	0.9
11 April 2024	836.8	21.4	7.1	18.0
14 April 2024	824.5	21.1	5.8	14.6
24 April 2024	410.8	10.5	2.4	6.1
29 April 2024	403.8	10.3	1.8	4.6

Following the peak, the flooded areas began to recede. By 24 April, the flooded area downstream of Akshoky had decreased to 410.8 km² (10.5%), while in Kulsary it had reduced to 2.4 km² (6.1%). Further decline was observed by 29 April, with the flooded area in Kulsary shrinking to 1.8 km². Thus, the flooded areas continued to diminish, and the flood risk significantly decreased by May. However, the remnants of the floodwaters (small ponds) did not dry up until the end of July.

3.2. Causes of the Flood

Like many rivers in regions with a continental climate, the spring fluctuations of the Zhem River's water level are largely dependent on precipitation levels. The primary formation of the river's flow occurs within the Aktobe region.

According to data from the USGS FEW NET portal, the precipitation in Western Kazakhstan, including the Aktobe region, over the last five days of October and the last five days of March (over five months) was higher compared to previous years, as well as the multi-year average for the 2000–2018 period (Figure 4).

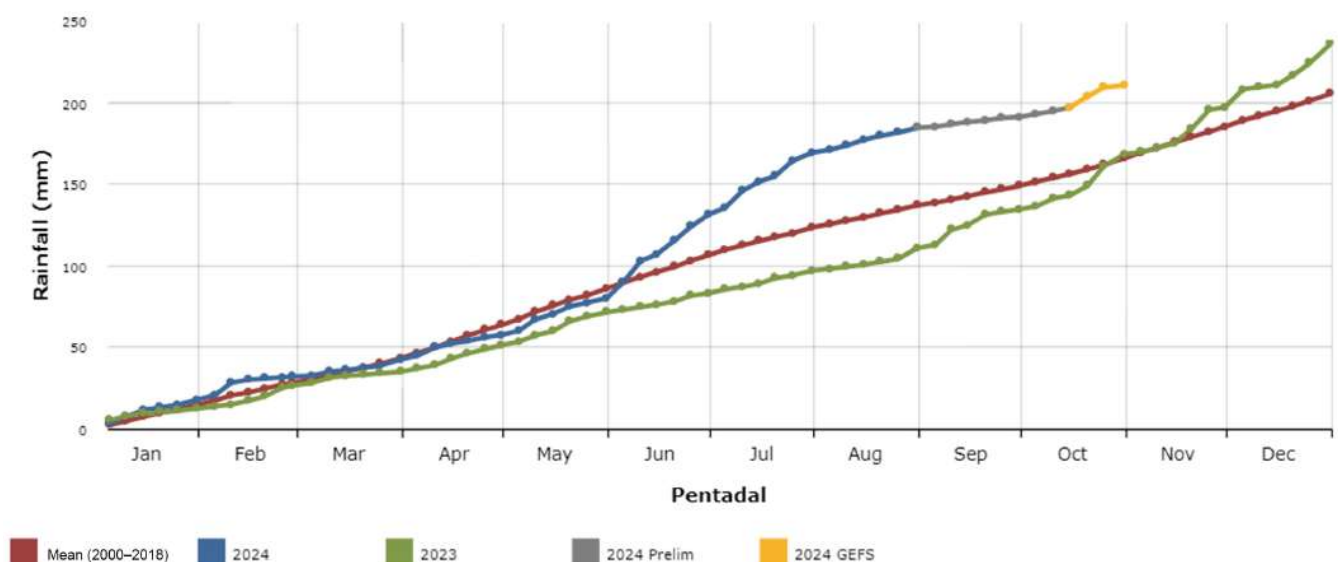


Figure 4. Dynamics of precipitation in the Aktobe region, mm (compared with the annual average).

Figure 3 shows that during the winter period, characterized by low temperatures and heavy snowfall, there was a significant amount of precipitation. The latter part of 2023 was especially rainy (Figure 5).

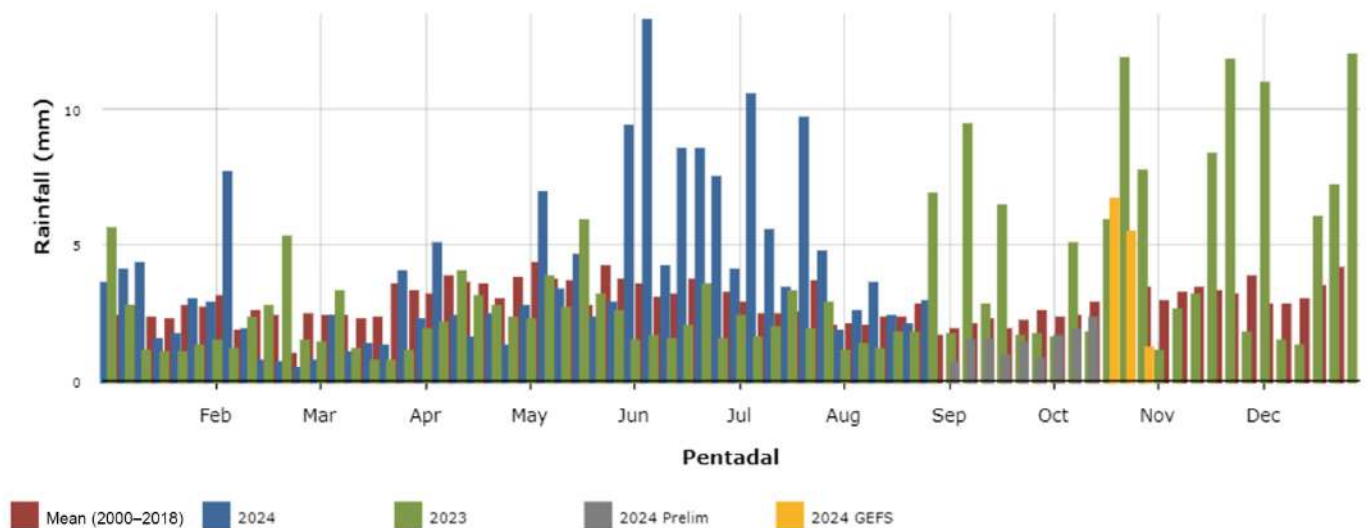


Figure 5. Annual precipitation dynamics in the Aktobe region, mm.

Figure 5 illustrates that the highest amount of precipitation over the past year occurred in the final months of 2023. In November, 29.25 mm of precipitation fell, which is 44% higher than the annual average, while December recorded 38.63 mm, 48.5% above the multi-year average. The greatest precipitation for the year was concentrated during the last five days of December 2023 (26–31 December), amounting to 11.9 mm.

Relatively heavy precipitation was also observed during the first three months of 2024. For example, in January 2024, 18.04 mm of precipitation fell, which was 5.3 mm (or 41.6%) more than in January 2023, and 3.05 mm (20.3%) above the long-term average. The peak winter–spring precipitation for 2024 was recorded from 5 February to 10 February, totaling 7.62 mm.

The significant winter precipitation contributed to a denser snow cover in the Zhem River basin compared to previous years, which also impacted flood formation. The main catchment area of the Zhem River is characterized by substantial snow cover, and the flow regimes of rivers fed by snow and ice melt are directly influenced by melting intensity. Satellite imagery serves as an essential data source for studying snow and ice cover, although usage can be challenged by various factors, including vegetation cover (forests). Since much of Central Asia consists of treeless plains, the absence of forests facilitates the use of satellite data for modeling snow cover parameters.

Studies [29] indicated that when determining the relationship between the annual flow of snow-fed rivers and snow reserves in their basins, satellite data are more accurate than meteorological station data. Therefore, for our analysis, we selected and used daily snow depth data for Central Asia (Snow Depth FEWS NET) from the USGS FEWS NET portal, processing raster data for the period from 10 February to 27 March.

Changes in the snow cover thickness in the Zhem River basin, processed at 15-day intervals, are depicted in Figure 6.

The snow cover in the Zhem River basin became denser following the precipitation from 1 February to 5 February (Figure 5). In the upper part of the basin, the snow cover thickness reached up to 0.8 m. However, after 10 February, the thickness of the snow cover gradually began to decrease (Figure 7).

As shown in Figures 6 and 7, on 10 February, the snow cover with a thickness of 0.6–0.8 m covered an area of 800.22 km² in the upper part of the basin (to the north and northeast). In the subsequent periods, its area sharply decreased, disappearing completely by 27 March. Snow cover with a thickness of 0.4–0.6 m initially covered 5368 km² on 10 February, but by 25 March, its area had shrunk by 33%, remaining stable for half a month

before gradually melting away by the end of March. Until mid-March, snow cover with a thickness of 0.2–0.4 m was more resilient, covering a significant area in the upper basin until 12 March. During the winter period, snow with a thickness of 0.2–0.002 m occupied the most extensive territories in the middle and lower parts of the basin, reaching a maximum of 30,506 km² by 25 February, but began thinning by spring. Areas with snow cover of 0.002–0 m are zones where snow either does not exist or melts shortly after falling. While there were no such areas on 10 February, by the end of March, as temperatures rose, they expanded to cover a larger portion of the basin.

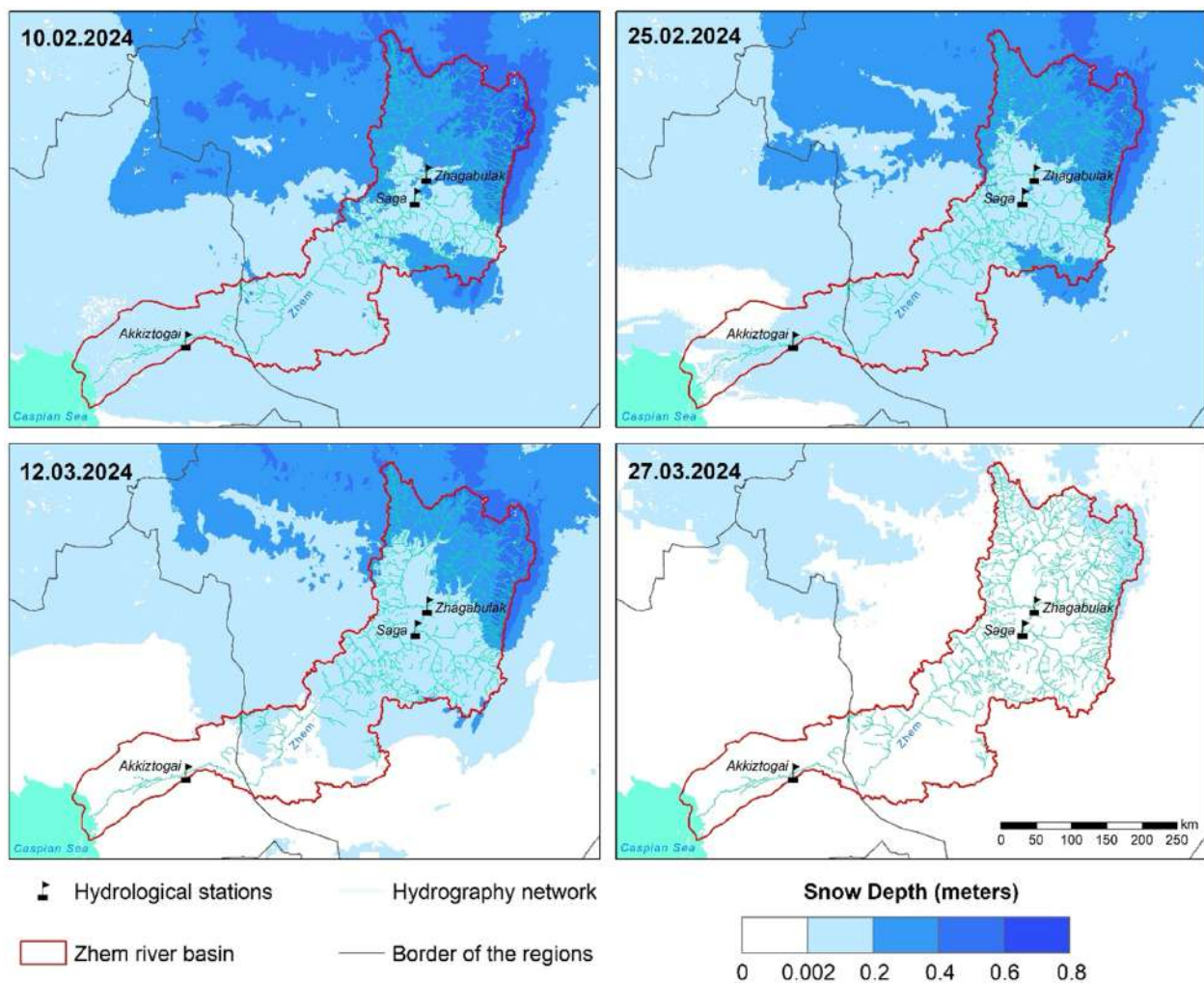


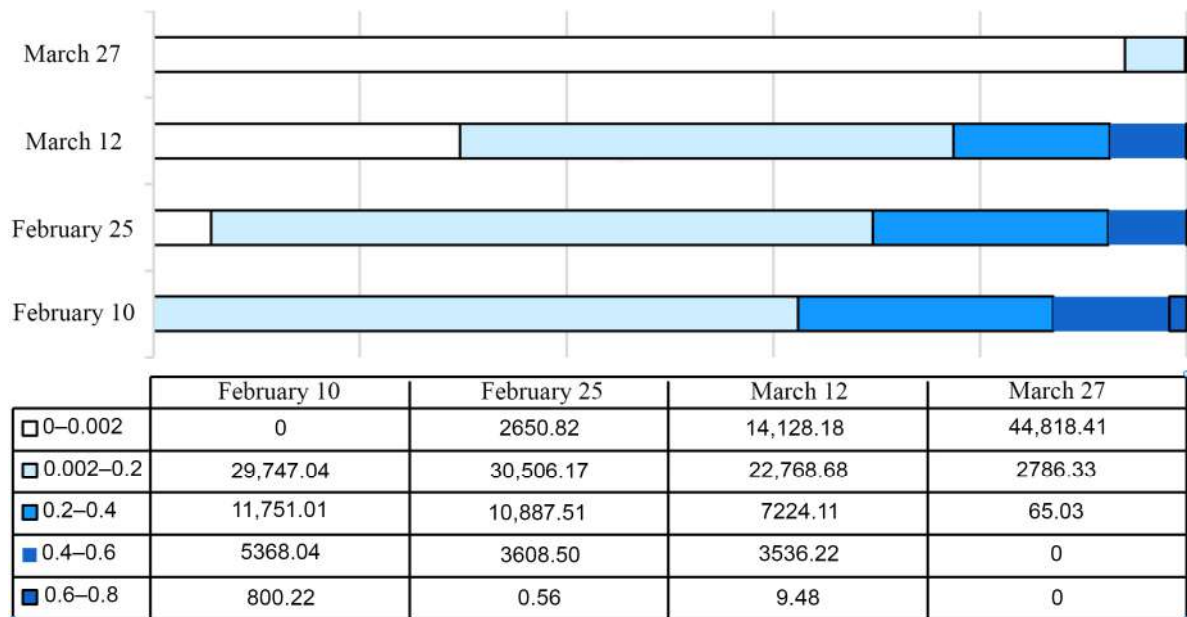
Figure 6. Change in Snow Cover Thickness in the Zhem River Basin Every 15 Days (From 10 February to 24 March).

The melting of snow is significantly influenced by the surface soil temperature. According to data from the national meteorological service “Kazhydromet”, the maximum soil surface temperature in the Zhem basin began to rise from the second decade of March (Table 3).

As shown in the table, in the upper part of the Zhem River basin, where runoff forms, the soil surface temperature began to rise in the third decade of March. At meteorological stations “Emba”, “Temir”, and “Mugodzhaz”, it reached +0 °C, while at the “Ilyin” station, it reached +2 °C. By April, the maximum soil temperature in the upper part of the Zhem River basin exceeded +15 °C. According to the “Kulsary” meteorological station, the soil surface temperature in the lower basin of Zhem began to register positive values as early as the second decade of February. The increase in soil temperature is directly linked to the rise in atmospheric temperature in this region.

Table 3. Dynamics of maximum soil surface temperature (°C) in the Zhem basin [25].

Name of the Meteorological Station	Location	February			March			April
		Ten-Day Period			Ten-Day Period			Ten-Day Period
		I	II	III	I	II	III	I
Emba	Upper part of the feed river basin (catchment area)	−10	−10	−8	−5	−2	+0	+18
Temir		−1	−7	−6	−2	−0	+0	+15
Ilyin		−1	−8	−7	−3	−0	+2	+24
Mugodzhar		−11	−2	−8	−2	−3	+0	+24
Kulsary	Lower part of the feed River basin	4	−1	+2	+8	+8	+18	-

**Figure 7.** Dynamics of snow cover thickness changes in the Zhem River basin every 15 days (period from 10 February to 24 March).

There was a sharp increase in atmospheric temperature. Since the study area is located in a desert zone, it has a sharply continental climate. Sudden temperature fluctuations in this region can trigger various natural phenomena and even natural disasters. The rapid melting of snow cover in the second half of spring is associated with a sharp rise in temperature. The monthly temperature dynamics were analyzed based on data from the “Kulsary” (in the lower basin) and “Emba” (in the upper basin) meteorological stations, provided by the national meteorological service “Kazhydromet” [30], which is sufficient for characterizing the temperature regime of the study area (Figure 8).

Figure 8 shows that the temperature increase in the study area began on 15 March. Before this date, both average and maximum air temperatures were below zero. The average air temperature in the lower part of the Zhem basin (Kulsary) began to rise from 15 March, while a significant increase in average temperature in the upper part (Emba) was recorded starting from 23 March. Overall, the average temperature in the Zhem River basin dropped slightly on 28–29 March (with temperatures in the upper basin falling to -1.6°C) but then sharply increased again starting 30 March. According to data from the “Kulsary” meteorological station, temperatures in the lower part of the basin rose rapidly in early April, reaching $+19.1^{\circ}\text{C}$ (after which the station was submerged due to flooding and ceased to operate for 6 days). Data from the “Emba” station in the upper basin showed that temperatures reached $+12.7^{\circ}\text{C}$ on 6 April. The sharp rise in temperatures in the second half of March and early April led to a rapid increase in water levels in the study basin.

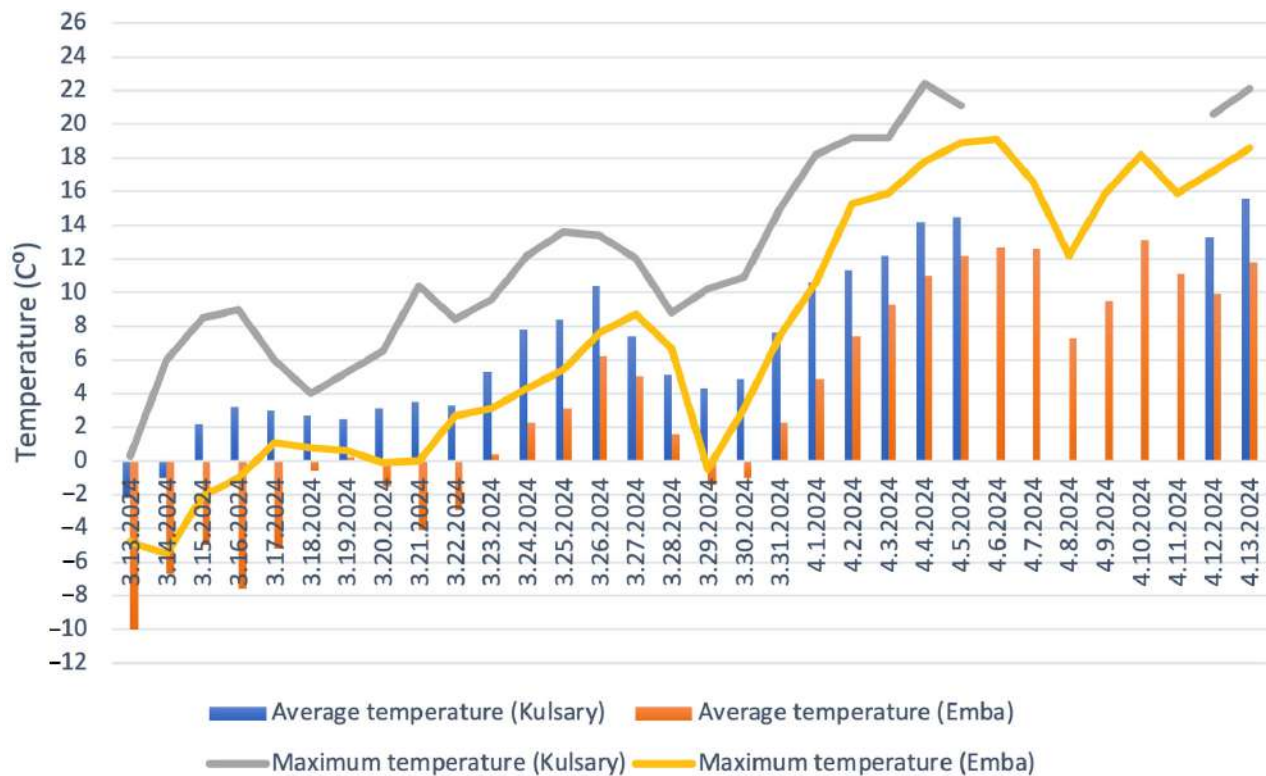


Figure 8. Monthly temperature dynamics in the Zhem River basin (March–April).

Currently, continuous monitoring of the Zhem River is conducted at three hydrological posts (“Saga”, “Akkystogai”, and “Zhagabulak”), named after the settlements in which they are located. According to data from these posts for 2024, sharp fluctuations in the Zhem River’s flow, similar to other rivers in desert regions, occurred in the spring (Figure 9).

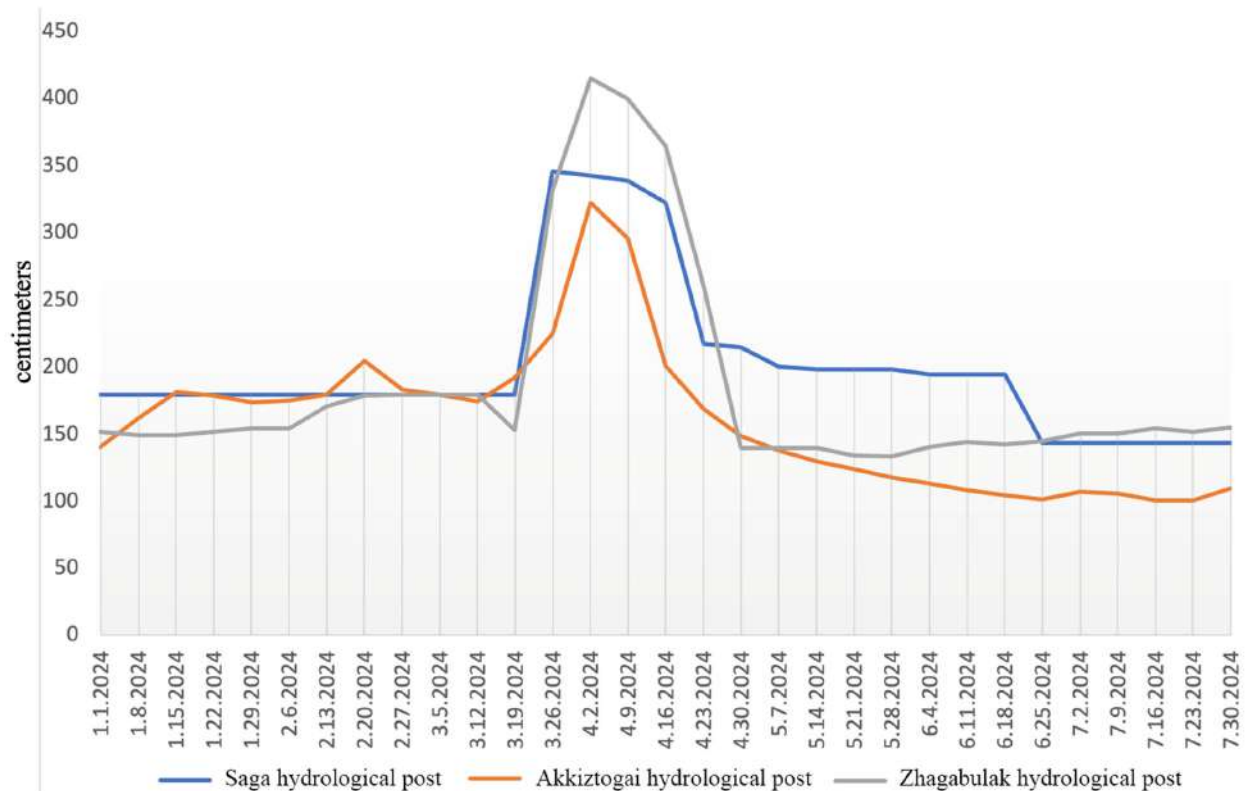


Figure 9. Water levels at hydrological posts along the Zhem River (period from January to July 2024).

A sharp rise in the water level of the Zhem River began in the second half of March. The first observation of this phenomenon was recorded at the Zhagabulak post on 19 March, when the water level reached 192.5 cm (an increase of 17.5 cm compared to the previous week). A week later, a significant water level rise was noted at all posts: at Zhagabulak, it reached 332.5 cm, at Akkystogai – 225.5 cm, and the Saga post recorded an annual maximum of 346 cm. The highest water levels at the Zhagabulak and Akkystogai posts were recorded on 2 April, reaching 415 cm and 322.5 cm, respectively. This seasonal anomaly led to flooding that impacted the city of Kulsary, located along the Zhem River.

3.3. Impact on Soil Cover

During floods, the primary focus is often on their socio-economic consequences, while the ecological impacts frequently go underexamined. However, floods significantly affect the chemical and physical properties of the soil [31], altering its structure, landscape, and biocenosis. The effect of flooding depends on the topography, volume of water, duration and frequency of the flood, vegetation density, and soil compaction [32].

Using Sentinel-2 (L2A) satellite imagery taken on 21 July 2023 and 20 July 2024, available from “The Copernicus Data Space Ecosystem Browser”, the types of soils submerged during the flood were identified. This analysis employed the Normalized Difference Water Index (NDWI) combined with soil mapping data (Figure 10).

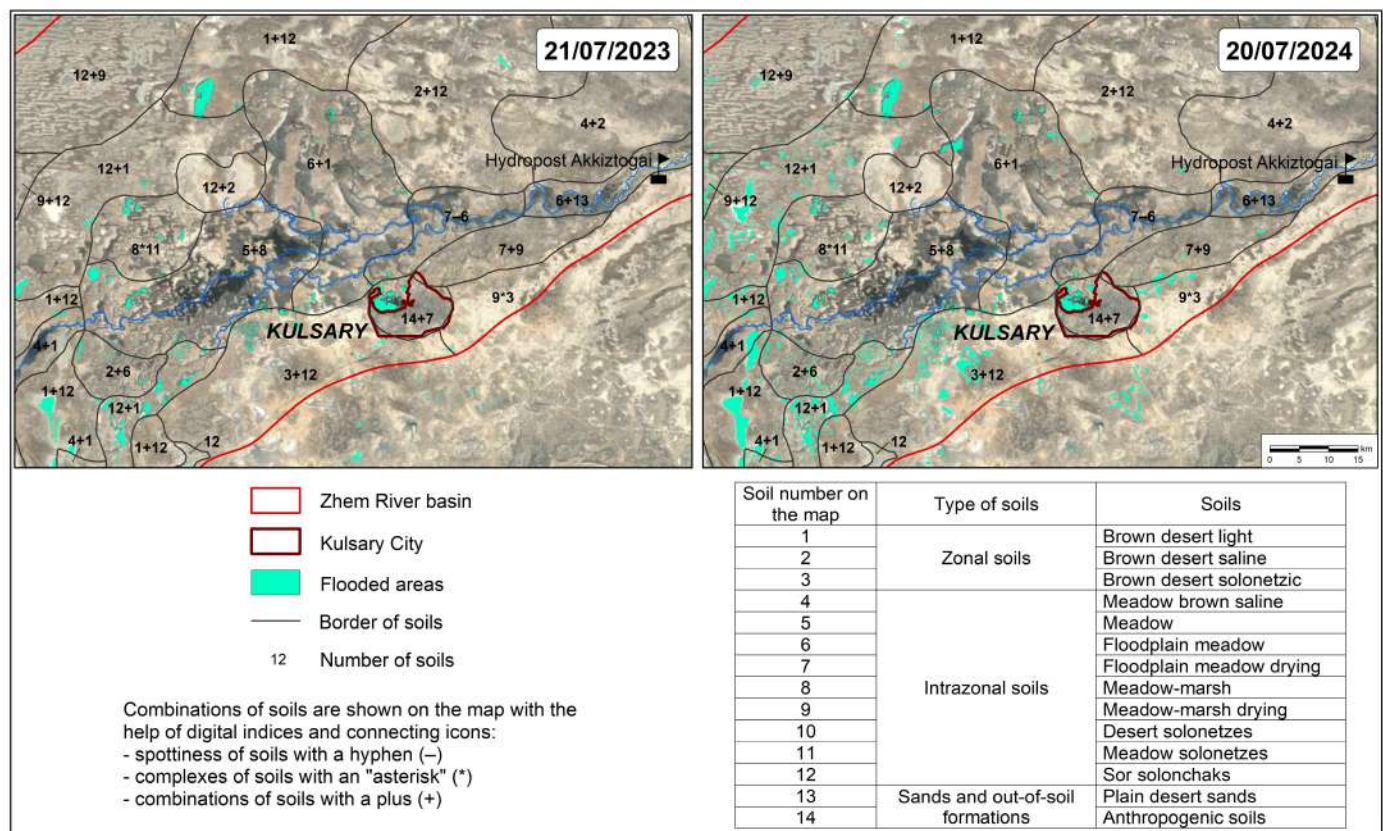


Figure 10. Flooding of various soil types in the lower part of the Zhem River basin.

In 2024, the area of flooded soils in the lower part of the Zhem basin (below the Akkystogai hydrological post) was three times larger compared to the previous year. It is evident that the flooded area increased across all types of soils (Table 4).

Table 4. Flooding status of different soil types in 2023 and 2024.

Soil Combinations	The Total Area of the Contour, km ²	The Area of Flooding, km ² (21 July 2023)	The Area of Flooding, km ² (20 July 2024)	Difference
1 + 12	385.0	10.78	23.24	12.45
10	5.6	0.59	0.41	−0.18
12	7.5	0.90	3.00	2.10
12 + 1	343.0	3.36	13.63	10.27
12 + 2	54.5	1.08	6.17	5.10
12 + 9	276.7	0.01	0.07	0.06
14 + 7	54.7	4.47	6.36	1.89
2 + 12	398.1	0.23	0.34	0.11
2 + 6	52.9	1.77	4.71	2.94
3 + 12	277.2	0.56	0.64	0.08
4 + 1	61.4	0.01	1.49	1.48
4 + 2	323.0	1.86	3.73	1.87
5 + 8	288.6	0.16	2.82	2.66
6 + 1	320.4	-	3.42	3.42
6 + 13	76.4	8.49	28.45	19.95
7 − 6	88.5	0.01	0.07	0.06
7 + 9	93.8	0.02	2.63	2.61
8 × 11	102.4	4.57	5.47	0.89
9 × 3	131.1	-	-	-
9 + 12	25.4	-	-	-
Total	3366.2	55.19	38.87	67.77

As shown in Table 1, flooding affected various soil types, except for combinations of meadow-marsh drying and brown desert solonetzic soils, as well as the complex of meadow-marsh drying soils in salt marshes. The area of many intrazonal soil types submerged this year increased significantly compared to last year. For instance, the area of floodplain meadow drying and meadow-marsh drying soils expanded by 131 times, reaching 2.61 km², while the combination of meadow and meadow-marsh soils increased 17 times, up to 2.66 km².

Even the flooding of zonal soils became more frequent. For example, in 2023, only 0.01 km² of the combination of meadow brown saline and brown desert light soils were affected by flooding, whereas this year, the flooded area expanded 149 times, reaching 1.48 km². Additionally, the combination of floodplain meadow and brown desert light soils, which were not flooded last year, was submerged over an area of 3.42 km² this year. Similar changes were observed in other zones with zonal soils.

Prolonged flooding, particularly in desert soil areas, leads to alterations in their physical and chemical properties. After water bodies dry up, buffer zones of saline soils may form in their place [33–35].

3.4. Impact on Vegetation Cover

Satellite data, including the Normalized Difference Vegetation Index (NDVI), are critical for monitoring vegetation health and assessing the condition of pastures and crops. NDVI measures vegetation density, enabling efficient tracking of stress and productivity changes across landscapes.

Recent studies have demonstrated the effectiveness of remote sensing and digital tools in monitoring vegetation dynamics and predicting crop yields in Kazakhstan. Methods such as neural networks for soil erosion prediction and UAV-based high-resolution mapping have enhanced agricultural management under climate variability [36–41]. Additionally, cloud computing and big data analytics empower community-level resilience against climate-induced vegetation changes [42].

Flooding in the Zhem River basin in 2024 significantly impacted vegetation. Barren or waterlogged areas tripled, particularly near Kulsary, while the upper basin saw increased vegetation biomass due to redistributed moisture [43,44]. However, long-term risks such as soil salinization and ecosystem destabilization highlight the need for adaptive land management [45].

Socio-economic impacts include reduced agricultural output and food security challenges. Reports emphasize the importance of rehabilitation programs and integrating vegetation monitoring technologies to enhance resilience [46–50]. By leveraging these tools, Kazakhstan can better adapt to future climate challenges while supporting sustainable development.

The classification of NDVIeVIIRS values based on raster data for July 2023 and 2024, provided by the USGS FEW NET portal, allowed for categorizing the data into five classes. This classification makes it possible to compare the biomass of vegetation cover for July 2023 and 2024 (Figure 11).

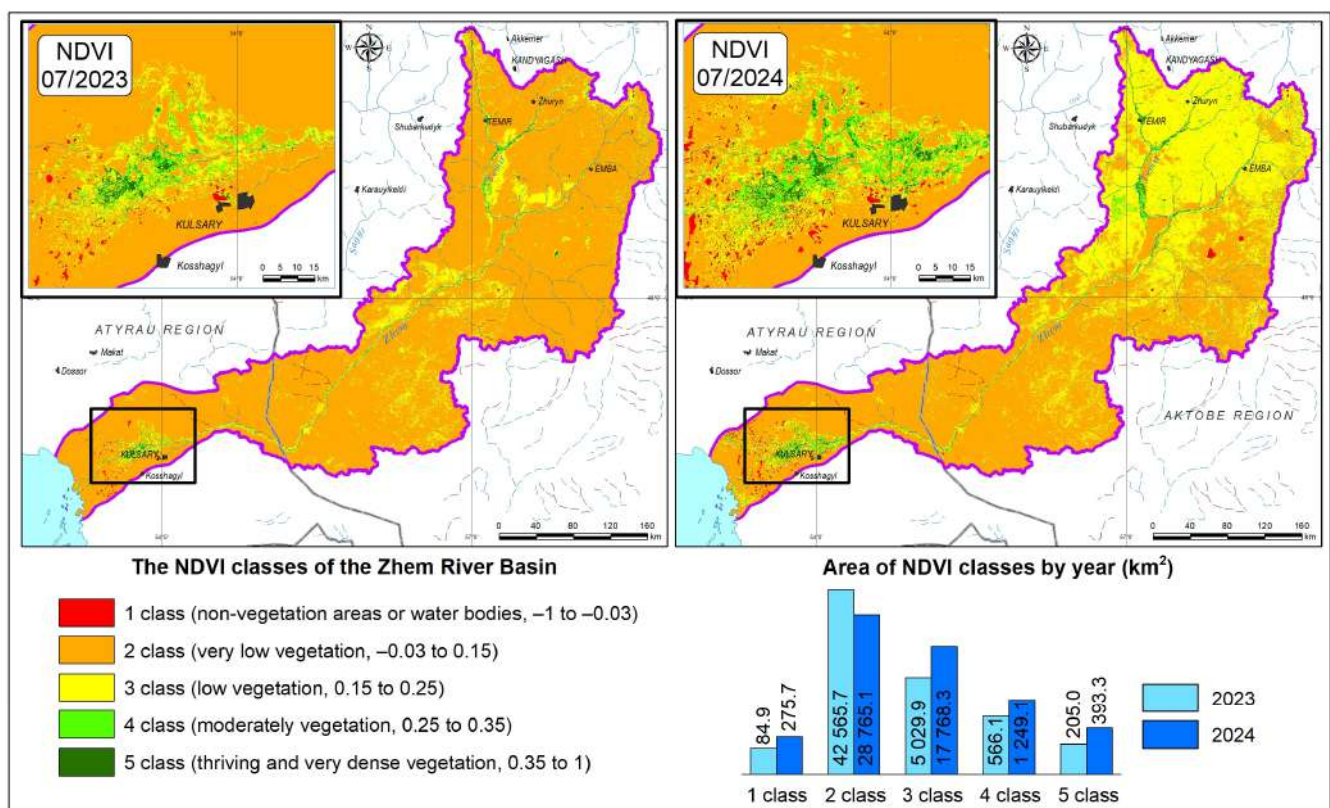


Figure 11. NDVI map of the Zhem River basin for July 2023 and 2024.

The NDVI analysis highlights changes in vegetation density and health, indicating how flooding and subsequent soil alterations have impacted plant life across the region. These insights are essential for developing adaptive land management strategies and supporting sustainable agricultural practices in flood-prone areas.

As shown in Figure 11, areas without vegetation cover or with water bodies (first class) in 2024 tripled compared to 2023, expanding from 84.9 km² in 2023 to 275.7 km² in 2024. These changes were particularly pronounced in the lower part of the basin, where regions devoid of vegetation or covered by water increased in the northern and western parts of the city of Kulsary. Conversely, areas with very low vegetation density (second class) decreased by 68% this year compared to the previous year. At the same time, regions with low vegetation cover (third class) increased more than threefold, reaching 17,768.3 km², with the most significant growth observed in the northern part of the basin. Additionally,

areas with moderate (fourth class) and dense vegetation (fifth class) also doubled compared to 2023.

The upper part of the basin exhibited notable improvements in vegetation cover, attributed to favorable summer weather conditions and increased soil moisture. However, the post-flood scenario in the lower basin led to significant challenges, including an expansion of areas without vegetation and the formation of temporary water bodies. Regions lacking vegetation were primarily shaped by water erosion, while temporary water bodies resulted from the flood-induced reservoirs.

While the increased water bodies initially appeared to benefit soil moisture, they pose long-term risks to the ecosystem. This process, driven by climatic anomalies, can result in soil composition alterations, reduced habitat quality, and potentially severe landscape degradation. The effects of prolonged water presence are particularly concerning for vegetation recovery, as oxygen levels in saturated soils may decline, leading to vegetation die-off. These findings highlight the urgent need for continuous environmental monitoring and the implementation of adaptive management strategies. Such measures are essential to mitigate the adverse effects of climatic fluctuations and ensure the sustainable development of ecosystems in the Zhem River basin.

These results demonstrate a robust correlation between the observed changes and the post-flood environment. However, the limited temporal and spatial scope of available data necessitates cautious interpretation. Future studies should prioritize long-term monitoring and detailed spatial analysis to validate these findings and support more accurate predictions of post-flood ecological dynamics. This approach will address potential data limitations and reinforce the reliability of conclusions, thereby alleviating concerns about the robustness of the study.

4. Discussion

Flooding of settlements along the Zhem River basin is a rare phenomenon. Until now, no major natural disaster capable of inundating an entire city had occurred in this region. Recent analysis indicates a trend of decreasing river flow in the Zhem, with occasional instances of river drying in certain lower areas. Over the past two decades, a significant reduction in precipitation has been observed in the Zhem basin, which has led to a marked decline in the river's average annual flow. This reduction is linked to both human activity and climatic changes. However, the increasing frequency of extreme weather events has resulted in more frequent floods in both rural and urban areas.

The hydrological dynamics of the Zhem River reflect the complex interplay of factors influencing spring floods. These floods are primarily triggered by heavy precipitation, abundant snowfall during winter, and a sharp rise in atmospheric and surface temperatures in spring. The terrain's slope significantly affects the spatial distribution of floodwaters. The volume of spring floods is largely determined by the interaction between soil infiltration and surface runoff processes, with key contributing factors including snow volume, melting intensity, and soil freezing. Among these, the most critical are rapid snowmelt, heavy precipitation during the flood period, and soil conditions.

The environmental consequences of flooding are substantial, ranging from loss of biodiversity in flora and fauna to the deterioration of water and soil quality and significant alterations in the landscape. Floods also transport chemicals and pollutants into water bodies, upsetting ecological balances and contaminating water resources. In urban areas, flooding has become more frequent, posing risks to human life and health. For example, the flood in April 2024 in Kulsary city caused severe damage, submerging thousands of homes and social facilities, an event unprecedented in the city's history.

A study of the hydrological changes in the Zhem River basin indicates that declining water resources have significantly reshaped the landscape, encouraging the development of residential zones near the river. Adaptation to low-flow conditions over time likely exacerbated the economic losses incurred during the flood. Flooding affects not only the socio-economic domain but also the natural landscape, with both positive and negative outcomes. In the lower basin, flooding has caused economic and social damage, as well as loss of life, while its long-term impact on soil, vegetation, and wildlife remains uncertain.

Flooding can temporarily reduce soil salinity, but prolonged floods often result in increased salinity by mid-summer, forming buffer zones. Long-lasting floods can also adversely affect soil fertility and vegetation. For instance, water presence for extended periods disrupts oxygen levels in the soil, slows plant growth, and may lead to plant death. Furthermore, prolonged inundation can promote the formation of silt and clay layers, negatively impacting vegetation diversity. In arid climates, post-flood conditions often result in the development of saline soils and deserts.

In the upper basin of the Zhem River, some positive changes have been observed. Vegetation cover has improved significantly, with areas of moderate and dense vegetation doubling compared to the previous year. These changes are attributed to smaller tributary sizes, favorable water flow, relief features, and increased soil moisture during spring. Moderate floods lasting for short durations typically do not harm meadow vegetation and can even support rapid plant growth due to moist soil conditions.

5. Conclusions

The spring flood of 2024 in the Zhem River basin of western Kazakhstan had profound and multifaceted impacts on both natural and human-made landscapes. The primary triggers of the flood included heavy precipitation (up to 38.63 mm in December 2023, exceeding the long-term average by 48.5%), substantial snow accumulation (with snow cover thickness reaching 0.8 m in the upper basin), and an abrupt rise in temperature (soaring to +19.1 °C in early April). These factors culminated in severe flooding that caused significant economic and social damage, including the inundation of 2810 private homes and five social facilities in Kulsary, the loss of 876 livestock animals and 532 birds, and the evacuation of 28,551 people, including 6719 children. The analysis of flood dynamics revealed the maximum water levels in the Zhem River, with peaks recorded at the Zhagabulak hydrological post (415 cm on 2 April 2024). The flood dynamics offer valuable insights into identifying flood-prone zones within the Zhem River basin, underscoring the urgent need for implementing robust mitigation measures.

Geo-environmental analysis highlighted both immediate and potential long-term consequences. The flood submerged habitats of diverse soil and plant species, tripling the flooded soil area from 84.9 km² in July 2023 to 275.7 km² in July 2024. This expansion raises concerns about soil salinization and vegetation die-off, particularly in the lower basin. Additionally, newly formed water bodies, while initially beneficial for soil moisture, present risks of accelerating soil degradation and disrupting vegetation regrowth in the future. Positive outcomes were observed in the upper Zhem River basin, where vegetation biomass doubled compared to 2023. Areas with moderate and dense vegetation cover expanded, highlighting the ecological benefits of controlled natural water exchange. This underscores the need for the efficient utilization of water resources in the basin, tailored to local natural conditions, and informed by best practices in water management from developed countries.

The flood's complex impact emphasizes the urgent necessity for further in-depth research addressing both natural and anthropogenic factors. Future studies should prioritize integrating satellite data with ground-based monitoring to refine flood prediction models,

develop adaptive strategies to mitigate flood risks and implement sustainable land and water resource management practices. These efforts are critical to bolstering resilience against climate-induced hydrological challenges and ensuring the long-term socio-economic and ecological stability of the region.

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