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CATASTROPHIC FLOODS IN THE TYSA RIVER BASIN WITHIN UKRAINE: CHARACTERISTICS AND CONSEQUENCES

Researching the causes of floods and their main hydrological characteristics contributes to the efficient use of resources, environmental protection, human safety, and infrastructure resilience to emergencies. The Tysa River basin is an area that has historically been vulnerable to significant hydrological events. In the paper, the hydrological characteristics (maximum water levels, bankfull elevation, etc.) of catastrophic floods observed in the Tysa River basin (within Ukraine) up to 2020 are analysed. The findings highlight the increasing intensity and frequency of these natural disasters since the late 1960s. Furthermore, an overview of the causes and characteristics of catastrophic floods during the cold (November - May) and warm (June - October) periods in the Tysa River basin is provided. A detailed analysis of the 1998 and 2001 floods has been conducted, emphasizing the meteorological and hydrological conditions that contributed to their formation, as well as the extensive social and economic impacts they caused. This paper aims to enhance flood protection strategies through improved understanding of flood genesis, progression, and effects. The outcome will be useful for better regional planning and disaster preparedness for potentially affected areas.

Keywords: catastrophic flood, maximum water level, bankfull elevation, precipitation.

Introduction. Floods are natural phenomena characterized by a high-water stage during which water overflows its natural or artificial banks onto normally dry land, for instance, a river flooding its floodplain. However, floods can escalate into disasters causing extensive damage, health issues, and even loss of life. This is particularly evident when rivers have been disconnected from their natural floodplains, confined within artificial channels, and when residential and industrial areas have been developed in regions naturally liable to flooding. Studying phenomena like floods, especially catastrophic ones, is a pertinent task for hydrology scientists worldwide, particularly in countries where the occurrence of such natural disasters poses significant challenges. Understanding their genesis, passage conditions, and having information on frequency, periodicity, and consequences will help respond appropriately to the occurrence of such phenomena. This understanding can enhance flood protection measures, thereby reducing the adverse effects of future catastrophic floods.

Based on the analysis of recent publications, conclusions have been drawn regarding the existence of various directions and approaches to studying floods. Some countries, such as Vietnam [14], Croatia [8], Austria [6], Italy [7] and Sweden [18], have studied the conditions and consequences of catastrophic floods that have occurred on their territory in specific years and have mapped the flooded areas. Scientists from European [1, 2, 9, 27], Asian [5, 15, 16, 28], and American countries [17, 19] have analyzed the characteristics of catastrophic floods and flood frequencies over specific periods for particular territories and river basins, utilizing statistical methods and HEC-RAS Modelling. Scientists from Spain have proposed a new approach to estimate extreme flooding using continuous synthetic simulation supported by inputs from a regional study of extreme precipitation and non-systematic flood information (such as historical and/or paleoflood records). The aim is to validate the generated discharges using a fully distributed hydrological model [4].

As the Ukrainian Carpathians, particularly Zakarpattia (the Tysa River basin), belong to the storm-hazardous regions of Europe, where the risk of catastrophic floods is ever-present, Ukrainian scientists are actively engaged in researching this matter. The main publications are co-authored by scientists from the Ukrainian Hydrometeorological Institute and Taras

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Shevchenko National University, specifically Susidko M. and Lukianets O. Thus, a catalog of rain and rain-snow flood characteristics in the rivers of the Carpathian region for the years 1989-2002 was compiled [23]. Also, the methodological and technological basis of a basin runoff forecasting system in Zakarpattia was developed [22]. Susidko M. and Lukianets O. have divided the territory of Ukraine into zones based on the level of hydrological risk, derived from an analysis of flood recurrence in the Carpathian region [21]. In later publications, an assessment of the maximum river runoff and its multi-annual variability in the basins of the Tysa and Prut rivers within Ukraine was carried out [13]. Additionally, in the work [11], in collaboration with German scientists, the potential impacts of climate change on floods in the Carpathian region were assessed. This assessment utilized the eco-hydrological model SWIM and focused on the Upper Tysa and Upper Prut River catchments.

In Ukraine, since the late 1960s, a tendency of increasing intensity and frequency of floods and their impact on the economy was observed. Thus, in the present study, all floods within the Tysa River Basin were analysed, and among them, the most catastrophic floods were selected with the aim of researching their main hydrological characteristics and consequences.

The information provided in the paper about the maximum water levels during catastrophic floods and their exceedance above the bankfull elevation allows to identify certain indicators of catastrophic flood formation in the Tysa River basin. This information is crucial during the forecasting of flood inundation, and it should be taken into account when planning developments in flood-prone areas.

The study area. The transboundary Tysa River basin is the largest subbasin in the Danube River basin and is located within the territories of four countries: Ukraine, Romania, Hungary, and Slovakia (Fig. 1). The catchment area of the Tysa River basin in Ukraine is 12,777 km², covering 2,1% of Ukraine's territory. The total length of the Tysa River is 967 km, with 262 km of it flowing within Ukraine. One distinctive feature of the Ukrainian part of the Tysa River subbasin is its location within a single administrative region, the Zakarpattia Oblast (southwestern Ukraine). This fact has positive implications for river basin management, including flood protection [3]. The surface runoff within the region is formed by right-bank tributaries of the Tysa River, namely the Teresva, Tereblia, Rika, and Borzhava rivers, as well as the Uzh and Latorytsia rivers, which flow into the Laborec and Bodrog rivers on the territory of Slovakia. The territory of the subbasin is located within two orographic regions: the mountains and foothills of the Carpathians (the major part), and the Hungarian Plain (Zakarpattia Lowland).

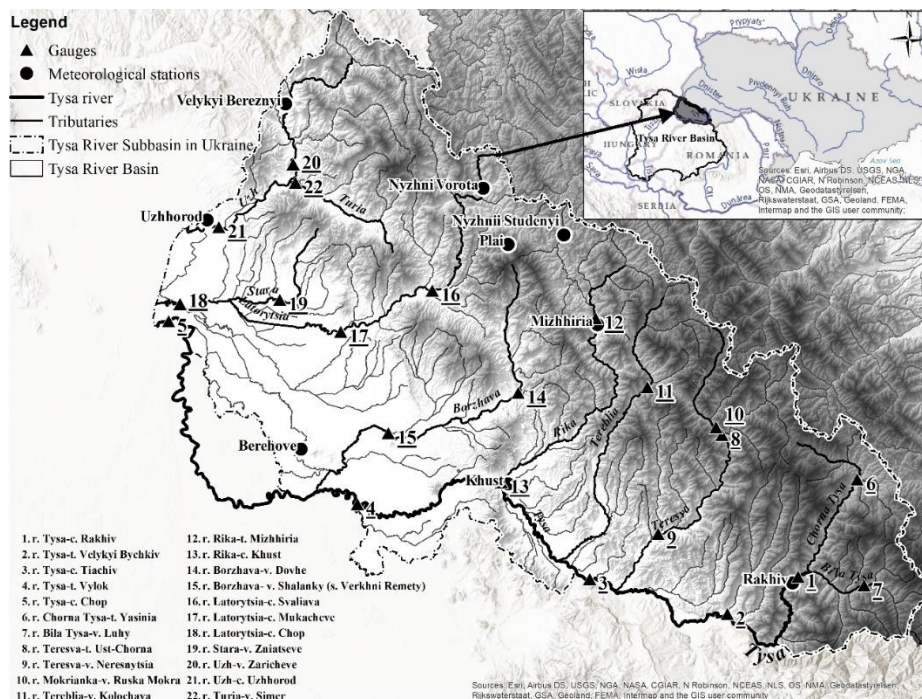


Fig. 1. Location of the Tysa River Basin and water gauges

The Tysa River basin is influenced by Atlantic, Mediterranean, and continental climates, resulting in regional precipitation patterns. Warm air masses from the Mediterranean Sea and the Atlantic Ocean induce cyclones accompanied by heavy rainfall on the southern and western slopes. The average multi-year precipitation values within the basin vary from 870 mm (at Velykyi Bereznyi meteorological station) to 1600 mm (at Plai meteorological station).

Hydrometeorological factors (intense and prolonged rainfall across the entire catchment area in the upper reaches of the Tysa River and its tributaries, etc.) and the orographic features of the Tysa River basin (steepness and size of slopes, shallow bedrock depth, rugged topography) are the main factors contributing to the occurrence of floods with a frequency of 3-6 times per year across all seasons within the region. The significant slopes of the terrain contribute to rapid floods on mountain rivers, where water levels can rise by 1,5-2,5 meters within 3-4 hours. Simultaneously, there is a rapid flow of floodwaters from mountains to lowlands within the Tysa River and its tributaries, causing inundating of floodplains and riparian areas [20].

The Tysa River basin, unlike other river basins in the Carpathian region, is characterized by mixed-origin floods (snow-rain, mostly dominated by rainfall runoff) that occur during the cold season. Floods in the rivers of the subbasin are formed by precipitation, which frequently occurs in this area (165-175 days per year). However, the onset of flooding begins when the total amount of precipitation exceeds 20 mm per day. In the case of extremely heavy downpours, when precipitation exceeding 100 mm, floods take on a catastrophic nature [10]. The highest water levels and water discharges are typical for autumn-winter floods. On average, these floods account for 20-30% of the total number of floods occurring throughout the year.

In the subbasin, according to administrative-territorial division, there are 6 administrative districts (there were 13 until July 2020), 11 cities, 597 villages, with the population of approximately 1,25 million people. It should be noted that the density of development along the banks and floodplains of the Tysa River basin is high, especially in the plains, and the presence of protective structures and dams do not provide 100% protection against the catastrophic floods.

Methodology and data. For the research, 22 gauges within the Tysa River basin were chosen, where daily water level observations are conducted. For the entire observation period (up to 2020), maximum instantaneous water levels were selected for each year at each gauge. Additionally, an analysis of floods during both cold and warm seasons was carried out, and paper includes only those that had catastrophic consequences (urban areas flooding, damage and destruction of infrastructure, human losses, etc.).

The following data were collected from gauges to analyse floods in the Tysa River basin: maximum water level values and their corresponding dates of occurrence, bankfull elevation, gauge zero elevation, and water discharges observed during maximum water levels (Table 1). In paper, term "bankfull elevation" refers to the level of a river at which water just begins to overflow its banks and inundate the adjacent floodplain. Also, not all gauges in the basin have information on water discharges.

Table 1. Hydrological features of the most significant floods at the gauges in the Tysa River basin within Ukraine

Gauges	Observation period	H _{max} , m BS	Data H _{max}	H _{bankfull} , m BS	ΔH _{max} , m	H ₀ , m BS	Q _{max} / Q _{av} , m ³ s ⁻¹
r. Tysa – c. Rakhiv	1950-2020	435,48	05.03.2001	433,63	1,85	429,73	938/25,6
r. Tysa – t. Velykyi Bychkiv	1946-2020	301,1	27.07.2008	299,38	1,72	294,78	-
r. Tysa – c. Tiachiv	1943-2020	216,51	05.03.2001	211,56	4,95	209,06	-
r. Tysa – t. Vylok	1933-41, 1946-2020	122,11	14.05.1970	118,95	3,16	115,15	3650/197
r. Tysa – c. Chop	1951-2020	105,82	09.03.2001	102,95	2,87	92,35	-

Gauges	Observation period	H_{max} , m BS	Data H_{max}	$H_{bankfull}$, m BS	ΔH_{max} , m	H_0 , m BS	Q_{max}/Q_{av} , $m^3 s^{-1}$
r. Chorna Tysa – t. Yasinia	1947-2020	651,14	23.03.1964	649,00	2,14	646,50	48,8/ 4,78
r. Bila Tysa – v. Luhv	1947-2020	604,69	13.05.1970	603,65	1,04	602,05	285/ 5,10
r. Teresva – t. Ust-Chorna	1947-2020	527,68	05.03.2001	526,66	1,02	523,86	665/ 18,3
r. Teresva – v. Neresnytsia	1949-55, 1959-2020	301,87	01.04.1962	300,08	1,79	298,38	840/ 34,4
r. Mokrianka – v. Ruska Mokra	1938, 1940, 1945, 1947- 2020	552,16	04.11.1998	549,89	2,27	549,04	-
r. Tereblia – v. Kolochava*	1952-2000	534,77	05.11.1998	533,17	1,60	531,17	407/ 14,5
	2001-2020	527,42	21.11.2015	526,67	0,75	524,67	-
r. Rika – t. Mizhhiria	1946-2020	439,06	14.12.1957	438,08	0,98	434,28	735/ 13,6
r. Rika – c. Khust	1946-2020	163,26	30.12.1947	160,91	2,35	156,41	807/ 43,1
r. Borzhava – v. Dovhe	1946-2020	173,82	04,05.11.1998	172,35	1,47	168,35	439/ 10,9
r. Borzhava – v. Shalanky (v. Verkhni Remety)	1961-2006	123,22	05,06.11.1998	119,32	3,9	114,32	-
	2007-2020	687	17.12.2017	0,500	1,87	0,00	-
r. Latorytsia – c. Svaliava	1962-2020	194,16	01.03.1967	193,00	1,16	190,00	540/ 14,3
r. Latorytsia – c. Mukacheve	1948-2020	122,47	05.11.1998	118,7	3,77	115,60	1310/ 26,1
r. Latorytsia – c. Chop	1956-2020	104,12	18.12.2017	101,28	2,84	96,58	366/ 34,9
r. Stara – v. Zniatseve	1946-2020	109,91	23.07.1980	108,72	1,19	104,92	54,6/ 2,21
r. Uzh – v. Zaricheve	1947-2020	159,02	29.01.1979	158,06	0,96	154,56	956/ 20,5
r. Uzh – c. Uzhhorod	1949-2020	115,88	17.11.1992	112,78	3,1	112,38	1280/ 28,1
r. Turia – v. Simer	1957-2020	154,55	23.07.1980	152,73	1,82	151,23	621/ 8,93

Notes:

H_{max} – maximum water level for the entire observation period, m BS;

$H_{bankfull}$ – bankfull elevation at the gauge, m BS;

ΔH_{max} – maximum water level H_{max} above the bankfull elevation $H_{bankfull}$, m;

H_0 – the gauge zero elevation, m BS;

Q_{max} – water discharge observed during the maximum water level H_{max} , $m^3 s^{-1}$;

Q_{av} – multi-annual water discharge at the gauge, $m^3 s^{-1}$;

* – two values of the maximum water level are provided for the gauge, since it was relocated in 2001.

Based on the collected data, the exceedance of the maximum water level above the bankfull elevation (ΔH_{max}) was calculated using the formula [1]:

$$\Delta H_{max} = H_{max} - H_{bankfull}, \quad (1)$$

where

H_{max} – the maximum water level of catastrophic flood, m BS,

$H_{bankfull}$ – the bankfull elevation, m BS.

Furthermore, data from 8 meteorological stations located within the study area were used to analyse the conditions leading to the occurrence of the most significant catastrophic floods in the Tysa River basin: daily and monthly precipitation amounts. Additionally, the average precipitation for each month from 1961-1990 was calculated for meteorological stations according to the requirements of the World Meteorological Organization [26].

Also, for better visualization Inverse Distance Weighting (IDW) interpolation method was applied to create maps of precipitation height during the floods in 1998 and 2001 on the catchment scale. IDW is commonly used interpolation method in Geographic Information Systems for spatial analysis and mapping. For this purpose, the ArcGIS Spatial Analyst extension was used. IDW is a simple and versatile interpolation method that can be applied to a wide range of spatial data analysis applications to estimate values at unmeasured locations based on the values of nearby measured points. The main principle behind IDW is that the influence of a measured data point decreases with increasing distance from the unmeasured location.

Results and discussion. The occurrence of catastrophic floods has always been typical for Zakarpattia. Since 1779, there were 26 of them, including 6 in the 19th century and 17 floods in the 20th century. Their recurrence has certain trends, which are observed in the alternation of low and high-water periods. In Zakarpattia, floods occur when annual precipitation reaching up to 1600-1700 mm (with an annual norm of 1000-1100 mm), and in some months – up to 250-300 mm (compared to the monthly norm of 70-120 mm).

The paper provides a general overview of floods of warm and cold periods, which led to significant consequences and were observed at most gauges within the studied basin.

Overview of catastrophic floods observed in the Tysa River basin during the cold period (November - May). The flood in December 1947 was historically high. The maximum water level was observed on the Tysa River on December 30, 1947. The main factors contributing to the formation of the catastrophic flood were a rapid increase in air temperature, which caused intense snowmelt combined with simultaneous heavy rainfall. The exceedance of maximum water levels above bankfull elevation at the gauges of the Tysa and Rika rivers ranged from 1,42 meters (gauge on the Tysa River in Rakhiv) to 4,24 meters (gauge on the Tysa in Tiachiv) (Fig. 2).

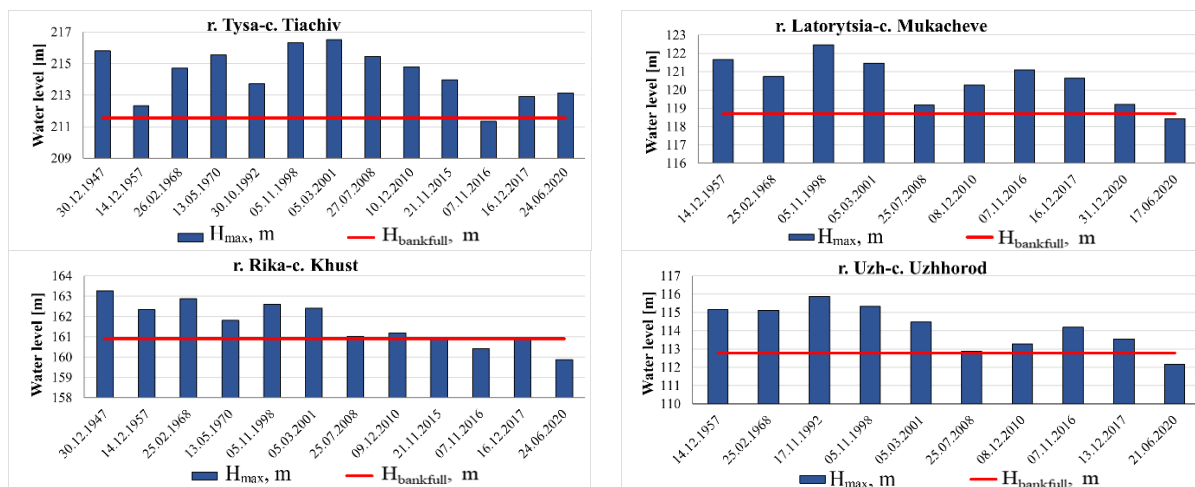


Fig. 2. The maximum water levels (H_{max}) and bankfull elevation ($H_{bankfull}$) during the passage of catastrophic floods at selected gauges in the Tysa River basin

Especially high (historic) floods occurred on the tributaries of the Tysa river (the Tereblia, Rika, Borzhava, Latorytsia, and Uzh rivers) from December 13th to 23rd, 1957. The flood reached its peak on December 14th. It formed during a thaw due to intense rainfall and snowmelt. The exceedance of maximum water levels above bankfull elevation at the gauges of these tributaries ranged from 0,52 meters (gauge on the Uzh River in Zaricheve) to 2,96 meters (gauge on the Latorytsia River in Mukacheve) (Fig. 2).

The flood in February 1968 had a mixed nature. The main factors contributing to the formation of the flood were a sudden warming and the passage of high-intensity rainfall. The passage of this flood was recorded at 18 gauges (82% of their total number) within the studied

basin, while at two gauges overflow onto the floodplain was not observed. The exceedance of maximum water levels above bankfull elevation at the gauges ranged from 0,73 meters (gauge on the Mokrianka River in Ruska Mokra) to 3,14 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

In May 1970, the formation of a catastrophic flood in the Tysa River basin was caused by simultaneous flooding in Romania and Zakarpattia due to heavy rainfall in the upper streams of the Tysa River and its tributaries. During the passage of this flood from May 12th to May 18th, 1970, an increase in water levels was observed in all rivers within the Tysa river basin. In some rivers, water levels were influenced by the backwater effect [24]. For example, on May 13, 1970, at the gauge in Khust on the Rika River, there was a significant increase in water level by 5,4 meters, but at the same time, this level was influenced by backwater from the Tysa River, and the water discharge was $134 \text{ m}^3 \text{ s}^{-1}$. During autumn flood on October 29, 1992, at this gauge, with a water level of 5,45 meters, the water discharge was $738 \text{ m}^3 \text{ s}^{-1}$, which is 5,5 times higher. High water levels pose a hazard and have catastrophic consequences, especially with significant water discharges, which leads to increased flow velocities. Exceeding the maximum water levels above the bankfull elevation in May 1970 at the gauges of the Tysa basin ranged from 0,9 meters (gauge on the Rika River in Khust) to 3,98 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

Significant floods in November 1998 and March 2001 were characterized by substantial and devastating consequences. The flood in November 1998 was caused by heavy rainfall occurring from November 3rd to November 5th, which covered almost the entire mountainous territory of Zakarpattia, as well as by the high soil moisture within Tysa River basin due to significant rainfall at the end of October [25]. The floods affected the entire area of the researched basin. The peak of the flood occurred from November 5th to November 8th, 1998 at various gauges. The overflow of the banks was observed along rivers such as the Tysa, Tereblia, Teresva, Borzhava, Latorytsia, Uzh, and others. Exceeding the maximum water levels above the bankfull elevation in November 1998 at the gauges of the Tysa River basin ranged from 0,83 meters (gauge on the Teresva River in Ust-Chorna) to 4,76 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

It should be noted that in addition to meteorological and agrometeorological factors, the formation of catastrophic floods within the researched basin is also influenced by high water content of river preceding the event. The flooding from March 3rd to March 5th, 2001, was caused by heavy rainfall combined with intense snowmelt [25]. Over three days, more than 300 mm of precipitation fell in the basins of the Borzhava, Latorytsia, and Tysa rivers, with slightly less in the western part of Zakarpattia. No natural factor can retain such amount of water on the slopes. The maximum water levels recorded during the flood in March 2001 in some rivers either exceeded or were close to the maximum water levels observed during the flood in November 1998. The exceedance of maximum water levels above the bankfull elevation in March 2001 in the Tysa basin gauges ranged from 0,72 meters (gauge on the Tysa River in Zaricheve) to 4,95 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

Due to heavy precipitation, the catastrophic snow-rain flood occurred in the rivers of Zakarpattia from December 7th to December 13th, 2010. During the three days from December 7th to December 9th, according to data from automated information-measuring system "Tysa", there was heavy-intensity rainfall in the Tysa River basin. The analysis of the amount and intensity of precipitation, as well as the fluctuations in water level rises in the rivers, showed that this flood was similar to the historical flood of March 2001. The exceedance of maximum water levels above the bankfull elevation at the gauges during the passage of the flood from December 7th to December 13th, 2010, ranged from 0,28 meters (gauge on the Rika River in Khust) to 3,24 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

In recent years, specifically in November 2016, according to operational data, intense rainfall, which persisted in Zakarpattia from November 5th to 7th, caused a rapid increase in water levels in rivers and streams within the Tysa River basin. The peak of the flood occurred in the rivers from November 7th to November 10th. However, the exceeding of water levels above the bankfull elevation in November 2016 was observed only in the basins of the Tereblia, Latorytsia, Uzh rivers, and in the mouth part of the Borzhava River. The exceedance of maximum water levels above the bankfull elevation at the gauges of these rivers ranged from 0,19 meters (gauge on the Tereblia River in Kolochara) to 2,39 meters (gauge on the Latorytsia River in Mukacheve) (Fig. 2).

The flood that occurred on 16-18 December 2017 in the Zakarpattia Oblast, was one of the largest in recent years. The water levels of some rivers approached the catastrophic levels of the floods that occurred in 1998 and 2001. The Borzhava River set new records for flood levels. Therefore, the highest water level (6,87 m on 17.12.2017) was recorded at the gauge on the Borzhava River in Verkhni Remety during the observation period from 2007 to 2020. The exceeding of the maximum water levels above the bankfull elevation in December 2017 was observed only in the basins of the Tereblia, Borzhava, Latorytsia, and Uzh rivers. Such exceedance ranged from 0,04 meters (gauge on the Tereblia River in Kolochava) to 2,84 meters (gauge on the Latorytsia River in Chop).

Overview of catastrophic floods observed in the Tysa River basin during the warm season (June to October). Catastrophic floods are also typical for the Tysa River basin during the warm season. However, summer floods in the Carpathian Mountains are mostly local. Thus, in July 2008, one of the largest floods of the warm season occurred due to intense thunderstorms, resulting in a rapid rise in water levels in rivers and the overflow of water onto the floodplains at almost all gauges in the region (over 70%). The peak of the flood was on 26-30 July. At some gauges, the maximum water levels were the highest for the entire observation period or close to it. The significant exceeding of maximum water levels above the bankfull elevation in July 2008 ranged from 0,1 meters (gauge on the Uzh River in Uzhhorod) to 3,9 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

From June 20th to June 30th, 2020, the catastrophic flood occurred in the Tysa River basin. Starting from the end of May 2020, there was regular rainfall, leading to soil over-saturation and the formation of small floods. Then by June 20th, a large amount of precipitation fell in the basin for several days, causing the catastrophic flood. The peak of the flood occurred in the rivers from June 23th to June 27th. Rakhiv region of Zakarpattia suffered significant damage. The exceeding of the maximum water levels above the bankfull elevation was observed only at eight gauges (36% of the total number of gauges in the basin) on the Tysa, Mokrianka, Tereblia, and Borzhava rivers, ranging from 0,03 meters (gauge on the Tereblia River in Kolochava) to 1,57 meters (gauge on the Tysa River in Tiachiv) (Fig. 2).

According to Fig. 3, over the last twenty years the occurrence of catastrophic floods was observed at almost all gauges (on average, 94% of the total number of gauges) with a recurrence interval of 1-7 years within the Tysa River basin.

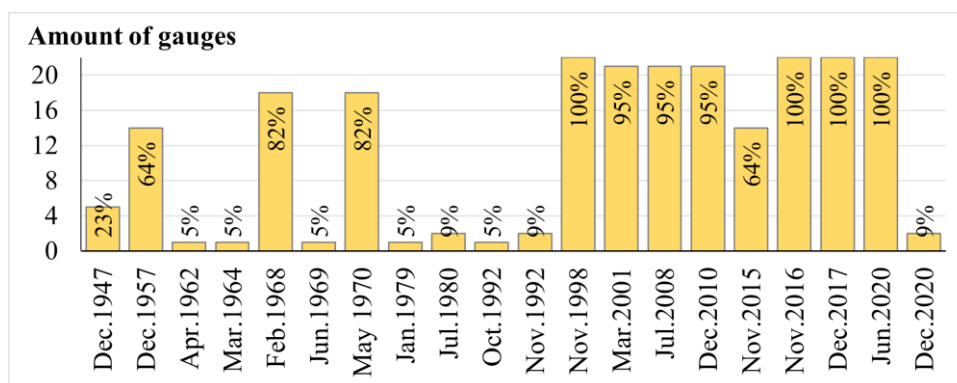


Fig. 3. The percentage of gauges at which catastrophic flood was observed in a certain year in the Tysa River basin

Since the most catastrophic floods in the Tysa River basin over the past twenty years occurred in 1998 and 2001, the paper provides a detailed analysis of their formation factors and the consequences of their passage.

Flood in November 1998. The November 1998 flood was one of the most catastrophic floods in the Tysa River basin in the last 200 years. The rainfall-induced flood, with devastating force surpassing all previous occurrences in terms of its characteristics and extent of damage, began to form on the morning of November 4th. This was against a background of the declining water

levels of the previous flood on October 29-30, resulting in significant soil oversaturation and heightened groundwater levels.

On November 4-5, very heavy and prolonged rainfall occurred throughout the entire region, with maximum intensities reaching 8-10 mm/hour. Based on Fig. 4, the total precipitation on November 4th and 5th, 1998, ranged from 31,2 mm (at the Berehove) to 186,5 mm (at the Mizhhiria) within the basin. The percentage distribution of total precipitation over the two days, compared to the monthly precipitation norm, ranged from 60% (at the Berehove) to 179,3% (at the Mizhhiria), nearly doubling the monthly norm at certain meteorological stations.

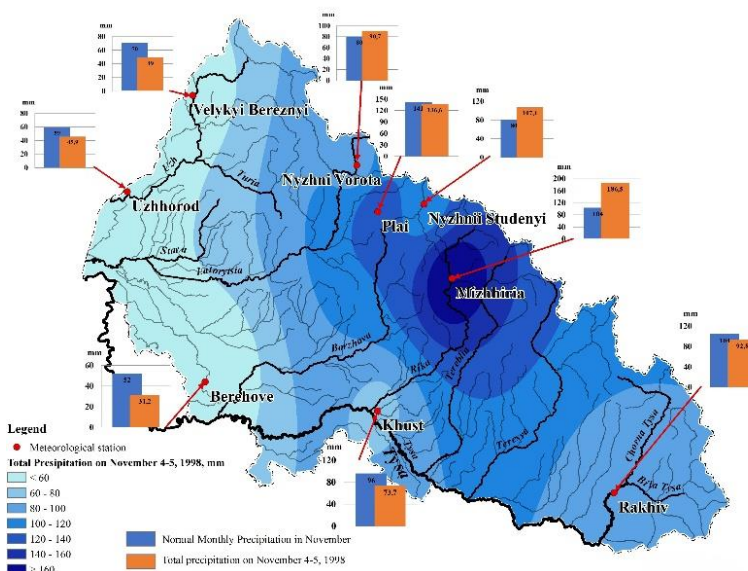


Fig. 4. The amount of precipitation during the passage of the catastrophic flood in November, 1998

As an example, Fig. 5 shows the daily water level fluctuations at the gauges within the Tysa River basin, as well as the daily precipitation during the catastrophic flood event in November 1998.

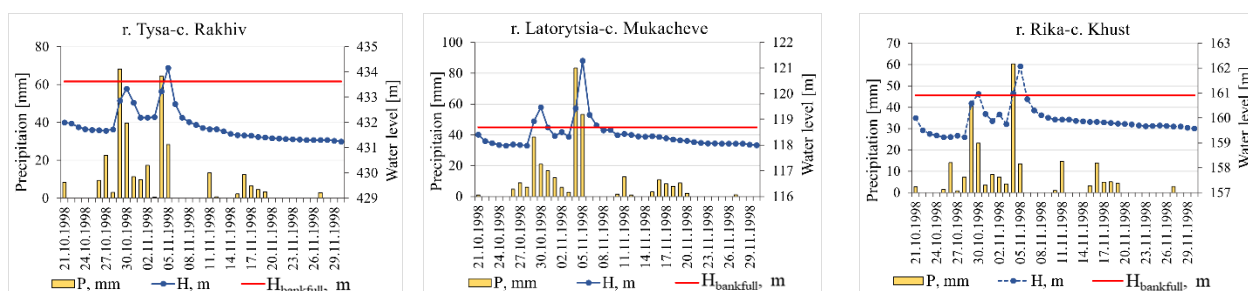


Fig. 5. Hydrological (daily water levels H, bankfull elevation H_{bankfull}) and meteorological (daily amount of precipitation P) conditions at certain gauges in the Tysa River basin at the onset and during the passage of the catastrophic flood in November, 1998

Thus, according to Fig. 5, on November 5, 1998, at the Tysa River at Rakhiv gauge, the water level exceeded the bankfull elevation by 1,1 meters. At the Latorytsia River at Mukacheve gauge, this excess was 3,77 meters, and at the Rika River at Khust gauge, it was 1,7 meters. These flood peaks were caused by precipitation that fell on November 4th. The formation of the flood was the result of a combination of heavy rainfall, rapid snowmelt in the mountains and rising air temperatures.

The maximum water levels of the flood occurred at almost all gauges during the night of November 5th and throughout the day, with the exception of Vylok and Chop on the Tysa River and Chop on the Latorytsia River.

A specific feature of the flood was that it formed simultaneously both on the Tysa River and all its right-bank tributaries, as well as on the Latorytsia and Uzh rivers, which is a rare phenomenon within the Tysa River basin. During the flood, the action of a powerful stream was directed towards hydraulic structures and riverbanks (composed of relatively loose rocks), typically where residential areas, houses, roads, utilities, and other infrastructure are located. Furthermore, water overflowed through the flood protection dams along the Tysa River, causing to their breaches near settlements such as Vyshkove, Korolove, Bobove, Chetove, and Badalove [3].

Consequences of the November 1998 flood. As a result of the November 1998 flood, 17 people lost their lives. In November, floodwaters destroyed 2,984 residential houses, inundated and flooded 269 settlements, damaged 40,793 residential houses and 2,877 buildings, leading to the resettlement of 24,340 persons. As a result of the flooding, 18 water intakes, 28 sewage pumping stations, 20 wastewater treatment plants, and 45 boiler houses were disabled [12].

The flood caused significant damage to water management facilities on the Tysa River and its tributaries throughout the region. In total, 40,4 km of flood protection embankments, 8,93 km of bank reinforcement structures, and 17 km of canals and artificial channels were damaged in the water management complex.

The road infrastructure of the region suffered significant losses: 12 bridges, 48,6 km of roads, 17,1 km of retaining walls, 5,65 km of culverts were destroyed; additionally, 48 bridges and 722,2 km of roads were damaged. As a result of the flooding, communications with 25 settlements were disrupted, and 236 km of roads were closed to traffic.

The flood in March 2001. The March 2001 flood in the Tysa River basin was also one of the most catastrophic in the last 200 years. The formation of the snow-rain flood from March 3rd to March 8th, 2001, was 80% caused by natural factors, namely very heavy, prolonged, and intense rainfall (in the headwaters of the Tysa River, 127-190 mm) and active heat advection. This advection began during the day on March 3rd and continued on March 4th, covering not only the plains (+7-+12°C) but also the highlands (up to +5°C). The high air temperature, combined with precipitation, created conditions for the intense snow melting. The water equivalent of snow cover before rain were 30-90 mm in the low-mountains and 60-120 mm in the highlands. Over three days, more than 300 mm of precipitation (2-3 monthly norms of precipitation) fell in the basins of the Borzhava, Latorytsia, and Tysa rivers, slightly less in the western part of Zakarpattia. The increase in water levels was more than 2,5 m in the mountains, and 4-10 m in the lowland areas of the Tysa, Latorytsia and Borzhava rivers.

According to Fig. 6, precipitation amount on 4th and 5th March 2001 at meteorological stations within the basin ranged from 32,1 mm at Uzhhorod to 138,5 mm at Mizhhiria. The distribution in percentages of the precipitation amount over the two days compared to the normal monthly precipitation ranged from 57,2% (Velykyi Bereznyi meteorological station) to 163% (Mizhhiria meteorological station), exceeding the monthly norm by almost one and a half times at some meteorological stations.

As an example, Fig. 7 shows the daily water levels at gauges in the Tysa River basin and the precipitation amount during the passage of the catastrophic flood in 2001.

Thus, according to Fig. 7, on March, 5 2001, the water level at the gauges on the Tysa river in Rakhiv exceeded the bankfull elevation by 1,85 m, on the Latorytsia river in Mukacheve by 2,76 m, and on the Rika River in Khust by 1,5 m. These flood peaks were formed by the precipitation that fell on March 3-4.

Consequences of the March 2001 flood. As a result of this catastrophic flood, the settlements of Rakhiv, Tiachiv, Khust, Mizhhiria, Irshava, Vynohradiv, Berehove, Uzhhorod districts and the Khust city were most affected. 245 settlements and 33,282 houses were flooded; 297 houses were destroyed, nearly 9,000 houses were in disrepair, resulting in the evacuation and resettlement of almost 14,000 people. In addition, 840 power substations were disabled, 61 settlements were completely powerless and 38 were partially disconnected. Furthermore, throughout the region, state roads were damaged in 35 sections totalling 2,795 m, while 4,5 km of local roads were affected. Three bridges were completely destroyed. As a result, 12 settlements were left without road connections and 9 km of railway tracks were damaged.

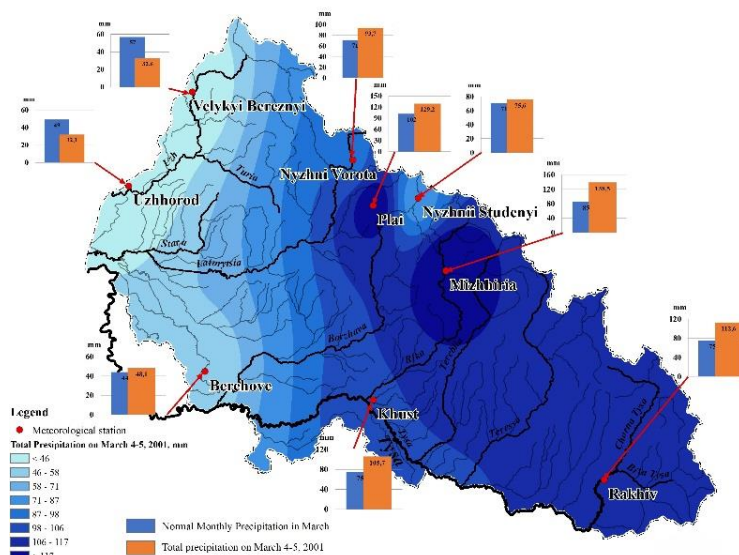


Fig. 6. The precipitation amount at the meteorological stations during the catastrophic flood in March, 2001

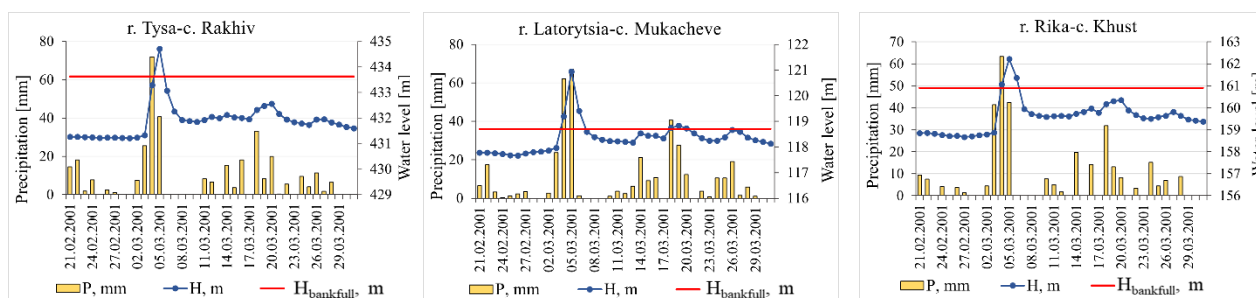


Fig. 7. Hydrological (daily water levels H, bankfull elevation H_{bankfull}) and meteorological (daily amount of precipitation P) conditions at certain gauges in the Tysa River basin at the onset and during the passage of the catastrophic flood in March, 2001

All sectors of the national economy suffered significant losses in areas affected by the natural disaster. The region's agricultural sector was particularly heavily affected. As a result of the flood, fertile soil layers were washed away, and winter crops were destroyed in many farmsteads and private plots. Additionally, the flood led to the destruction of fodder reserves, planting materials, as well as the submersion of livestock facilities and agricultural buildings. As a result of damage to numerous shoreline reinforcement areas, approximately 40,000 hectares of agricultural land were flooded, causing losses to 38 enterprises [3].

The situation was exacerbated by the failure of the protective dam on the territory of Hungary to withstand this flood. On March 6, 2001, the right bank dam of the Tysa River ruptured near the village of Tarpa, resulting in water flowing back from Hungarian territory into the Berehove and Uzhhorod districts of Ukraine. The breach of this dam resulted in 150 million cubic meters of river water flooding 11 villages in Hungary and 4 villages in the border area of Ukraine. Due to the unique capacity of the Berehove transboundary polder system, an amount of water equal to the volume of Lake Balaton was passed through with minimal damage to the surrounding villages.

Conclusion. Floods are natural events that may have devastating consequences. For millennia, rivers have been flooding and overflowing their banks, forming a channel-floodplain complex. And therefore, preventing floods is essentially impossible, but it is possible only to mitigate the consequences of their passing.

In the paper, the hydrological characteristics (highest maximum water levels and bankfull elevation, etc.) for 24 catastrophic floods in the Tysa River basin within Ukraine were analysed for the entire observation period.

Catastrophic regional floods on the southwestern macroslope of the Ukrainian Carpathians (Zakarpattia) during the cold season (November - May) were observed in 1926, 1947, 1957, 1968, 1970, 1998, 2001, 2010, 2015, 2016, 2017. During the winter period, the main factors contributing to the occurrence of catastrophic floods are rapid rising of air temperatures, intense snow melting, and heavy rainfall. Most floods of mixed origin (often dominated by rainfall runoff) occur in late autumn and the first half of winter. Significant floods are also observed in the summer season. Summer floods in the Carpathians are mostly local events. However, in July 2008 and June 2020, there were catastrophic floods that affected the entire Tysa River basin. The disaster was caused by intense thunderstorms.

Extremely high floods in Zakarpattia occur simultaneously on all rivers in the region, but not all rivers have water overflowing onto the floodplain. It's also worth noting that maximum water levels are sometimes observed not due to the inflow of a significant amount of water, but rather due to backwater from ice phenomena such as dense ice run or jams, and in such cases, water discharge is usually not significant. For example, such a case was observed at the gauge on the Chorna Tysa River in Yasinia, where the highest maximum water level was recorded in March 1964 with a water discharge of $48,8 \text{ m}^3 \text{ s}^{-1}$. This water level was caused by backwater from ice phenomena. In comparison, in June 1969, a maximum water level was close to this value, but the water discharge was $204 \text{ m}^3 \text{ s}^{-1}$. Thus, if high water levels are observed due to backwater, the flow velocity (and consequently the water discharge) is low and the destructive power of the water is less.

Catastrophic floods are not rare event in the Tysa River basin. Over the past 20 years, they have been repeated almost every 1 to 5 years and have flooded significant areas, causing huge damages to nature, economy and population.

For example, an analysis of damages from floods in recent years shows that the 1998 flood caused losses of UAH 810 million (approximately USD 331 million), the 2001 flood (higher than the 1998 flood) caused losses of UAH 317 million (approximately USD 58.5 million), the 2008 flood caused losses of UAH 169 million (approximately USD 35 million), the 2010 flood, which is similar to the 1998 flood, caused losses of about UAH 73 million (approximately USD 9.2 million), and the 2020 flood caused losses of about UAH 176 million (approximately USD 6.2 million). This decrease in the cost of losses after catastrophic floods is due to the improvement of flood protection complex in the Tysa River basin.

In addition to natural factors, anthropogenic impact also leads to catastrophic consequences from the passage of floods, such as the destruction of floodplains through urban development and cultivation. Therefore, it is reasonable to take measures to control areas that are at risk of flooding.

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Катастрофічні паводки в басейні річки Тиса: їх характеристика та наслідки

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Паводки – це природні явища, однак, вони можуть стати стихійними лихами, викликаючи масштабні руйнування, проблеми зі здоров'ям і навіть людські жертви. Це особливо небезпечно, коли річки відокремлені від своїх природних заплавних територій, обмежені штучними каналами, а будівлі та промислові об'єкти побудовані в зонах, що природно схильні до затоплення.

Вивчення причин виникнення паводків та їх основних гідрологічних характеристик сприяє ефективному використанню ресурсів, захисту навколишнього середовища, безпеці людей та забезпеченню стійкості інфраструктури до надзвичайних ситуацій. У статті для аналізу паводків, що спостерігалися в басейні річки Тиса до 2020 року, зібрано дані для всіх діючих гідрологічних постів щодо максимальних значень рівнів води та дати їх проходження, рівнів виходу води на заплаву (відмітка заплави), відмітки нуля постів та витрати води, які спостерігались під час максимальних рівнів води. Крім того, для аналізу умов, що призвели до виникнення найбільш значних катастрофічних паводків у басейні р. Тиса, були використані дані восьми метеорологічних станцій, розташованих у межах досліджуваної території: добові та місячні суми опадів. Отримані дані свідчать про зростання інтенсивності та частоти цих стихійних лих з кінця 1960-х років.

Крім того, проаналізовано причини та особливості проходження катастрофічних паводків холодного (листопад - травень) та теплого (червень - жовтень) періодів року у басейні р. Тиса. Проведено аналіз умов формування та наслідків паводків у листопаді 1998 р. та в березні 2001 р.

Стаття спрямована на вдосконалення стратегій захисту від паводків шляхом покращення розуміння генезису, розвитку та наслідків паводків. Результати дослідження будуть корисними для покращення регіонального планування та готовності до стихійних лих на потенційно вразливих територіях.

Ключові слова: катастрофічний паводок, максимальний рівень води, рівень виходу води на заплаву, опади.

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