TRACING THE TORRENTIAL FLOODS: INSIGHTS FROM 110 YEARS OF RECORDS

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ABSTRACT

Torrential floods rank as Serbia's most destructive and frequent natural hazards, inflicting profound social, economic, and environmental impact. This study delivers a comprehensive analysis of torrential flood phenomenon, covering the period 1915–2024, integrating historical records with contemporary data from multiple sources. A total of 2287 flood events have been documented, claiming over 197 lives. The findings highlight a distinct seasonal trend, with floods peaking in late spring (May–June), primarily driven by intense convective storms. The highest number of events was recorded in tributaries belonging of the Zapadna Morava, Južna Morava, and Kolubara river basins. A breakthrough of this research is the development of Serbia's first inventory of torrential floods, offering unprecedented insights into their spatial and temporal dynamics. This inventory can be integrated into a multi-user national hazard database, with future applications extending to European-scale flood risk assessments. By enhancing hazard preparedness and risk mitigation strategies, this study paves the way for data-driven policies and climate resilience planning—crucial in an era of escalating extreme weather events.

Keywords: torrential floods, frequency, spatial and temporal patterns, Serbia

INTRODUCTION

As far as water resources in Serbia are concerned, there are two main problems related to hydrological extremes: suffering from floods and a lack of water. This duality is particularly evident in torrential floods, a rapid-onset hydrological phenomenon characterized by a sudden peak discharge, high suspended and bed-load sediment transport, and a concentration of destructive energy within small- to medium-sized catchments [1]. The most devastating torrential flood events since 2000 occurred in April and May 2014, resulting in over 50 fatalities and heavily affecting communities in western and central Serbia. Torrential floods remain the dominant hydrological hazards in the country, arising from the complex interplay of extreme precipitation, catchment morphology, geological conditions, and land-use practices. A significant proportion of annual sediment yield is transported during these short-lived flood events, making them powerful geomorphological agents shaping river channels [2].

The catchment slope, relief energy, and basin shape exert dominant control over runoff response [3]. Steep slopes and compact, fan-shaped basins produce short concentration times and high maximal discharges. Geological structure and soil texture significantly influence infiltration capacity, while shallow, poorly permeable soils promote rapid surface runoff. Vegetation cover plays a crucial mitigating role; forested catchments generally exhibit lower peak discharges and reduced sediment yield compared to deforested or agriculturally exploited areas. Conversely, anthropogenic activities such as deforestation and urbanization often amplify natural flood processes. On the other hand, torrential floods carry substantial destructive potential and may leave long-term socio-economic consequences increasingly threatening human lives, activities, and assets.

Given the limited availability of hydrological measurements in small mountainous and sub-mountainous catchments, torrential flood analysis in Serbia largely relies on indirect and parameter-based methods. One of the most commonly applied approaches combines the Soil Conservation Service Curve Number (SCS-CN) method for effective rainfall estimation with the Synthetic Unit Hydrograph (SCS-UH) for runoff transformation. Catchment morphometric parameters such as area, slope, drainage density, relief energy, basin shape, and stream network characteristics are derived from topographic maps and digital elevation models within a GIS environment. Land-use and soil data are incorporated to estimate infiltration capacity and surface runoff potential. Hydraulic reconstruction of peak discharge is performed using high-water marks, channel geometry, and Manning's equation. Spatial susceptibility to torrential floods is further assessed using GIS-based indices, particularly the Flash Flood Potential Index (FFPI), which integrates morphometric, geological, soil, and land-cover parameters [4, 5]. These complementary methods allow cross-validation of results and provide a robust foundation for flood assessment in data-scarce environments.

Rainfall–runoff modelling can be employed for the relatively small number of watersheds with available hydrological monitoring data. The selected hydrological model should be physically based, spatially distributed, and suitable with respect to data requirements. Such hydrological software simulates runoff at the slope-channel scale, calculating processes of infiltration, evapotranspiration, base flow, overland flow, and flow through the river network. The input data consist of hourly rainfall records and watershed characteristics, while the output includes simulated discharge values, which are subsequently compared with observed data. In terms of the spatial discretization of the watershed, the grid, channel, and river bank are linked, so that computations at the watershed level at a defined hourly time step and through the whole simulation period are enabled. The developed watershed model can be continuously updated and applied for forecasting future flood events when rainfall forecasts are available.

Climate variability, including the increase in short-duration extreme precipitation events, further amplifies the frequency and magnitude of torrential floods. Simultaneously, land-use changes such as deforestation, agricultural intensification, and urban expansion have significantly modified runoff generation mechanisms.

In Serbia, torrential floods predominantly occur south of the Sava and Danube rivers, where high relief energy, erosion-prone geology, and land-use pressures, in combination with extreme convective precipitation, favour rapid hydrological response. Previous studies [6] indicate the existence of more than 12,000 torrential streams, affecting the majority of the national territory. Despite their frequent occurrence and severe socio-economic impact, systematic documentation of torrential flood events has historically been neglected.

This paper aims to provide an integrated overview of torrential flood occurrence in Serbia by presenting insights from the *Inventory of Torrential Floods in Serbia* covering the period from 1915. This inventory represents the most comprehensive dataset of torrential flood events in Serbia to date. It was compiled by the author of this paper and was extensively presented in 2021 in the book [7] for the period by 2019. The Inventory update and revision are conducted every five years. This contribution is intended to support future research and practical flood risk management, extending insights into the torrential flood phenomenon. Understanding the mechanisms, temporal and spatial distribution of torrential floods is therefore essential for effective risk assessment and management. Results contribute to improved hazard communication, risk assessment, and sustainable watershed management under changing climatic and socio-economic conditions.

METHODS AND MATERIALS

The primary data source for this paper is the Inventory of torrential floods in Serbia, a unique and systematically compiled database of historical and recent torrential flood events. The inventory covers a period exceeding more than one century and includes information on event date, geographical location, affected catchments and settlements, triggering mechanisms, hydrological characteristics, and their aftermath—material damage, human losses, and casualties. The inventory marked a major step toward systematic archival and contemporary documentation and analysis of this phenomenon.

From a conceptual perspective, the development of the inventory followed structured data management principles, also inspired by international approaches to hazards documentation. The process included defining minimum data requirements, collecting data from diverse sources, verifying, systematizing, and categorizing records, and conducting analytical evaluation. The inventory is compiled from scientific literature, hydro-meteorological yearbooks and reports, newspaper archives, and official emergency records and reports. Each event has a geographical location and is classified by date, river basin, and documented consequences. Events were aggregated at the basin level to allow comparative analysis among major river systems.

The inventory aims to serve as a multi-purpose database adaptable to different user groups, including hydro-meteorological services, water management authorities, emergency sectors, insurers, and researchers.

RESULTS AND DISCUSSION

The updated inventory records 160 recent torrential flood events for the period 2020–2024 and 5 newly identified records for the earlier period. Altogether, the database documents 2,287 torrential flood events across Serbia with over 197 fatalities. Historical records extend as far back as 1915, although earlier documentary evidence— such as 13th-century chronicles) also describes catastrophic torrential flood events.

Figure 1. Aftermath of torrential floods in Arandjelovac, June 1969
(from the newspaper archive)

The inventory focuses on catchments south of the Sava and Danube rivers, including tributaries that belong to the Black Sea Basin (tributaries of the Drina, Kolubara, Zapadna Morava, Južna Morava, Velika Morava, Mlava, Pek, and Timok rivers), the Adriatic Basin (tributaries of the White Drim), and the Aegean Basin (tributaries of the Lepenac, Dragovištica, and Pčinja rivers). The highest numbers of events and fatalities were recorded in the Zapadna Morava, Južna Morava, and Kolubara river basins (Figure 2).

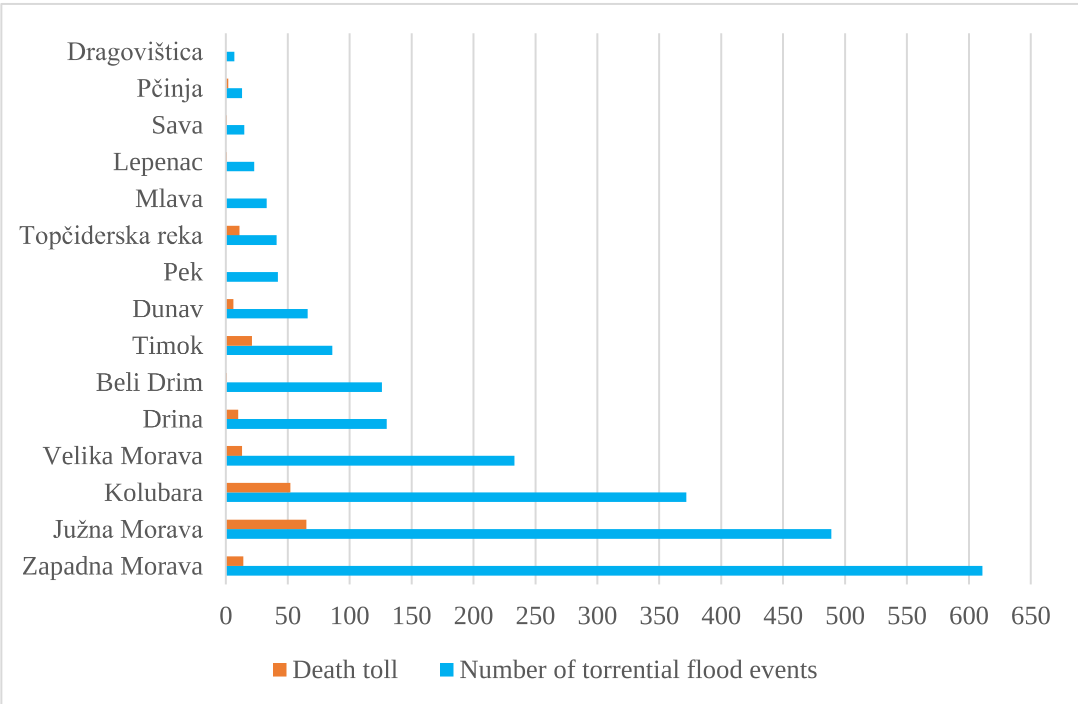

Figure 2. Torrential flood events per river basin

Temporal variability was analyzed using annual and decadal frequencies. Long-term trends were assessed by comparing early and late parts of the study period, while monthly distributions were examined to identify seasonal patterns of occurrence. Particular attention was paid to years with exceptionally high event counts. The average annual number of events increased considerably over time, reflecting not only improved documentation but also a rise in extreme rainfall episodes and heightened flood vulnerability due to urbanization in flood-prone areas.
Figure 3 reveals a clear upward trend in torrential flood occurrence across Serbia. A non-parametric Mann–Kendall (MK) test confirms the presence of a statistically significant upward trend in the annual time series covering the period of 110 years. Temporal analysis indicates a marked increase in the number of events after the 1950s. The period 2005–2014 recorded the highest decadal frequency of events and death toll; however, elevated flood occurrence was also recorded for the decades 2015–2024 and 1975–1984.

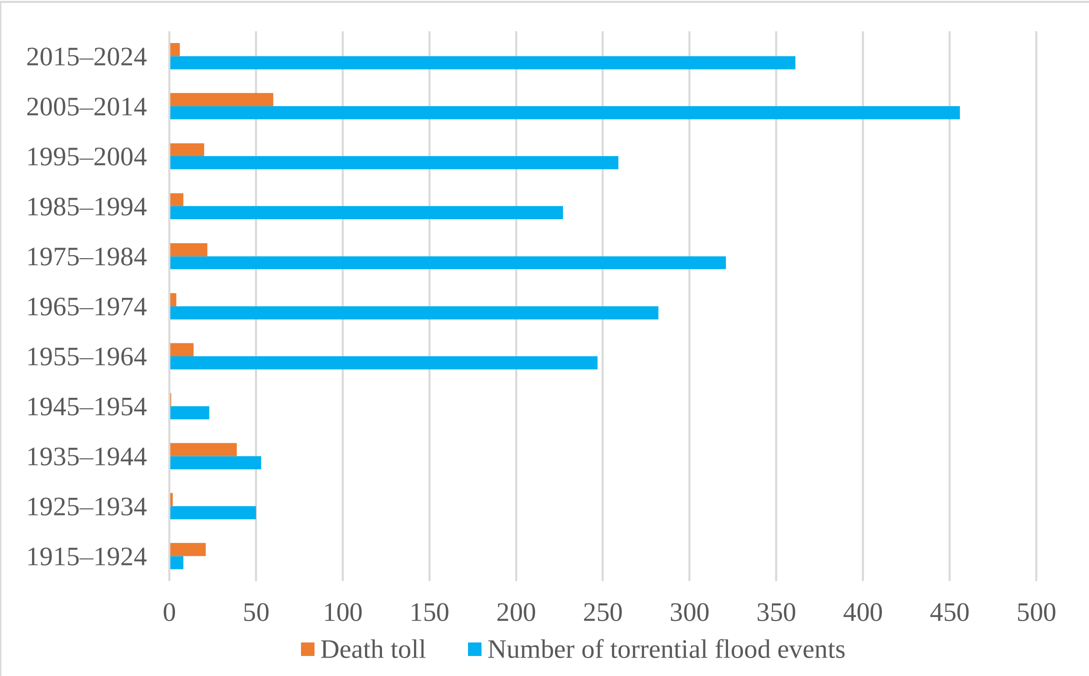

Figure 3. Decadal distribution of recorded torrential flood events

Over the past five years, the most impactful torrential floods occurred in the following watersheds:
- on 22 June 2020 in *the Ljubovića river* (watershed area A=158 km^2, Drina river basin), reconstructed as a 100-year return period flood with the specific maximal discharge, q_{max} (1%) of 1.09 m^{3}s^{-1}km^{-2} [8], *Skrapež* (A=166 km^2, q_{max}=1.27 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin), *Lopatnica* (A=116 km^2, q_{max}=1.14 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin), *Ribnica* (A=102 km^2, q_{max}=1.75 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin), *Lučka* (A=94 km^2, q_{max}=1.39 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin);
- on 12 June 2022 in the *Ribnica* (A=108 km^2, q_{max}=1.66 m^{3}s^{-1}km^{-2}, Kolubara river basin), and *Kamenica* (A=201 km^2, q_{max}=1.33 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin);
- on 19 January 2023 in the *Toplica* (A=180 km^2, q_{max}=1.14 m^{3}s^{-1}km^{-2}, Južna Morava river basin); and

- on 15 June 2023 in the *Lopatnica* (A=116 km^2, q_{max}=2.03 m^{3}s^{-1}km^{-2}, Zapadna Morava river basin) [9].

All listed floods exhibited exceptionally high specific maximum discharges (the ratio of peak discharge to watershed area), exceeding 1 m^{3}s^{-1}km^{-2}, indicating their extreme severity.

Temporally, floods with a rapid onset exhibit strong seasonal concentration in late spring and early summer, coinciding with convective rainfall episodes combined with antecedent soil moisture conditions. Rapid snowmelt, when coupled with intense rainfall, represents a compound hydro-meteorological driver of torrential flood generation in late winter.

Table 1 highlights a pronounced peak in May and June, corresponding to maximum rainfall intensity and convective storm activity, while secondary peaks occur in March and April. May and June torrential floods represent 41.6% of all recorded events and account for the majority of fatalities, claiming as many as 130 lives during the observed timeframe.

Table 1. The frequency of recorded torrential floods per month in Serbia

Period	**Relative frequency**
January–February	Moderate
March–April	High
May–June	*Very high*
July–August	Moderate
September–October	Low to moderate
November–December	Low

In examining the temporal variability of the torrential flood phenomenon, it is crucial to trace changes in runoff indicators while accounting for alterations in land use and vegetation cover over the decades. In this context, research [10] shows that runoff and soil erosion decreased over the past three decades in watersheds located in the border areas of south-eastern and eastern Serbia, largely due to depopulation and decreased human pressure. By contrast, an almost opposite trend was observed in the south-western and western regions of the country.

Furthermore, given that torrential floods represent a two-phase flow, the analysis of sediment characteristics as key indicators of torrential flow events in ungauged watersheds should be further encouraged. Deposited materials exhibit complex behavior governed by geological, geomorphological, and hydrological interactions, with parameters such as grain size distribution, shape, and orientation providing valuable insights into flow type, transport dynamics, and energy. In addition, integrating hydrological methods with modern geospatial and photogrammetric techniques offers a robust interdisciplinary approach for investigating watershed responses to both environmental and anthropogenic pressures.

Overall, the insights from the inventory confirm that torrential floods are a persistent and increasing hazard in Serbia. The observed increase in event frequency can be attributed to a combination of climatic variability and anthropogenic factors. Intensification of short-duration rainfall events plays a key role, consistent with broader regional climate trends in Southeast Europe. Land-use changes, including agricultural expansion and deforestation on steep slopes in the upper parts of the river basin, and urbanization in the lower parts, have significantly altered runoff conditions and amplified the flood processes in many watersheds. Inadequate maintenance of torrent control structures and insufficient integration of flood hazard information into spatial planning further exacerbate vulnerability. The inventory results call for work on several key priorities: expansion of automatic rainfall and discharge monitoring in mountainous regions, implementation of integrated watershed management combining technical measures (check dams, channel regulation), biological measures (afforestation, erosion control), land-use planning, and sustainable forestry [11]. For mitigating consequences, improved early warning systems based on real-time rainfall thresholds, enhanced public awareness and education, and community-based risk reduction are needed. Effective mitigation of torrential floods requires an integrated approach that unites a deep understanding of natural hydrological processes with comprehensive socio-economic planning. All in all, the inventory provides the first unified historical database of torrential floods in Serbia, a foundation for spatio-temporal hazard assessment, a platform for risk communication, and a basis for integration into European databases (e.g., EM-DAT, ESWD). It follows the "3W" principle: what happened, when, and where.

The spatial concentration of recorded events within the Morava river system highlights the need for basin-scale approaches to flood risk management. The findings support previous studies that emphasize integrated watershed management, combining structural measures with nature-based solutions and land-use regulation [12].

With respect to data limitations, several challenges remain: incomplete historical records, particularly during the early decades, variability in the quality and content of reports, lack of continuous rainfall intensity data, and sparse hydrological monitoring in small basins. Despite these constraints, in a number of historical records, cross-verification across multiple sources enhanced the reliability.

CONCLUSIONS

Torrential floods represent a persistent and spatially concentrated natural hazard in Serbia. This paper presents a synthesis of key findings derived from the inventory of torrential floods in Serbia. Future research in this field should require improving monitoring networks, incorporating high-resolution data, and further developing multi-purpose databases. Sustainable watershed management, combining technical measures with biological and land-use planning approaches, is essential for mitigating the impacts of future torrential floods. The interaction between climatic extremes and human-induced landscape changes is central to understanding future flood risk in Serbia.

The study emphasizes the importance of systematic data collection and integrated watershed management as key elements for reducing torrential flood risk in Serbia. The comprehensive inventory provides a valuable foundation for understanding long-term trends and spatial patterns. A total of 2,287 torrential flood events were analyzed to identify spatial distribution, temporal trends, seasonal patterns, and material damage data can be employed for the assessment of impacts on the local population and infrastructure. The inventory of torrential floods in Serbia provides an essential scientific and practical tool for hazard analysis, policy formulation, and international data harmonization.

In an era of climatic uncertainty and accelerating land-use change, systematic documentation of past events is not merely archival—it is strategic. Understanding where, when, and why torrential floods occur is fundamental to anticipating their future behavior and reducing societal vulnerability.

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