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HYDROLOGICAL IMPACT OF SEVERE CONVECTIVE STORMS – CASE STUDY: BROSTENI

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Abstract. *Severe convective storms are high-impact meteorological phenomena that develop under conditions of pronounced atmospheric instability and deep convection. These systems are capable of producing extreme weather events, including torrential rainfall, intense lightning activity, large hail, and strong wind gusts, and under certain conditions, even tornadoes or waterspouts. One of the most critical hydrological consequences is the occurrence of flash-floods, which pose a significant threat to infrastructure and vulnerable communities due to their rapid onset and intensity. This study investigates the hydrological impact of a severe convective storm that affected the Brosteni area during 27–28 July 2025. The analysis focuses on the dynamic and thermodynamic atmospheric conditions, mesoscale circulation patterns, and the influence of surface characteristics such as topography, land use, and soil moisture. By integrating synoptic-scale analysis, high-resolution numerical modelling, and radar data, the study aims to improve understanding of the physical mechanisms responsible for storm initiation, persistence, and the generation of associated hydrological hazards. The results contribute to the enhancing forecasting capabilities and risk management strategies related to extreme convective weather events.*

Keywords: deep convection, severe storms, atmospheric instability, flash floods, heavy rain

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1. Introduction

Flash-floods are among the most severe and destructive hydrological hazards. They primarily affect small catchments with steep slopes and are characterized by a sudden and substantial rise in water levels over a short time interval (typically a few hours). Their short response time makes flash floods particularly dangerous; their impacts include significant human and animal losses, damage to infrastructure (roads and bridges), residential buildings, and agricultural land, as well as major environmental changes such as severe erosion, channel modifications, and sediment deposition.

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Many studies emphasize that a key step in flash-flood research is understanding local orographic characteristics and identifying the physical mechanisms responsible for convective initiation and intensification.

From a meteorological perspective, flash-flood events in the mountainous regions of Romania are closely associated with heavy convective precipitation driven by atmospheric instability and orographic forcing (Doswell, Brooks & Maddox, 1996; Wasko & Sharma, 2017). Such torrential rainfall episodes are frequently linked to train-effect convection, a process in which successive convective cells repeatedly develop and move over the same area, leading to rapid and large rainfall accumulation (Schumacher & Johnson, 2006; Peters & Schumacher, 2014). In other cases, extreme hydrological events are produced by Mesoscale Convective Systems (MCS), which are responsible for widespread torrential rainfall, strong winds, and large hail (Houze, 2004). Understanding the atmospheric conditions that drive severe convection, as well as the factors controlling train-effect development, is essential for improving early-warning systems and reducing flash-flood risk.

Recent studies conducted in the Eastern and Southern Carpathians confirm the major role of severe convective systems in triggering rapid flood events, particularly under synoptic conditions characterized by warm and moist air advection and convective development along frontal boundaries (Stan-Sion & Antonescu, 2020).

According to the IPCC AR6, the increasing frequency and intensity of extreme convective precipitation events are linked to climate change through rising temperatures and changes in aerosol concentrations, which affect atmospheric moisture content (IPCC AR6, Chapter 11). Research focusing on flash floods and precipitation trends highlights the importance of integrating high-resolution radar observations and convection-permitting numerical models into early-warning systems (Rossa, 2010; Bournas, 2024). The identification of convective structures responsible for extreme rainfall (using radar and satellite remote sensing), key environmental parameters (moisture availability, synoptic-scale forcing, instability), and surface characteristics such as roughness, geological structure, and soil moisture (Grillakis, 2016; Ye et al., 2021; Blöschl, 2022) is essential for effective nowcasting and impact reduction.

In Romania, flash-flood research has focused on small-catchment hydrological modelling (Calnau et al., 2013; Popescu & Bărbușescu, 2025), the integration of radar and satellite data into hydrological analyses (Hachemi et al., 2022), and assessments of urban and rural vulnerability to intense precipitation (Ghițescu, 2010).

The main objective of this paper is to analyze the atmospheric conditions that favored the development of severe convection leading to flash flooding in the

Brosteni area during 27–28 July 2025. The study aims to identify and characterize the synoptic, mesoscale, and local factors responsible for intense precipitation and to evaluate the geomorphological characteristics that contributed to the hydrological response. The following sections describe the data used, present a detailed analysis of the flash-flood event, and summarize the main conclusions.

2. Data and orographic information used in the study of the Brosteni flash floods (27–28 July 2025)

The analysis of the convective event of 27–28 July 2025 was based on an integrated set of meteorological, hydrological, and orographic data obtained from operational sources and derived products.

2.1 Orography characteristics, geomorphology, and hydrology of the study area

The city of Brosteni is located in the south-western part of Suceava County, near the administrative borders with Neamț and Harghita counties. It extends over an area of approximately 600 km² along the Bistrița River valley (Fig. 1). The study area lies in a predominantly mountainous region, at the contact between the Bistrița Mountains and the Stânișoarei Mountains, with elevations ranging from about 650 m to 1700 m a.s.l. (INS, 2023; Brosteni City Hall, 2024).

Mountainous terrain occupies approximately 85% of the area and is characterized by steep slopes, locally exceeding 40%, pronounced ridges, and deep, narrow, and rugged valleys (Geography of Romania, 1987; Posea et al., 2005). These morphological features contribute to highly dynamic hydrological conditions, favoring torrent formation and flash-flood occurrence, particularly during episodes of intense convective precipitation (Bălteanu et al., 2010).

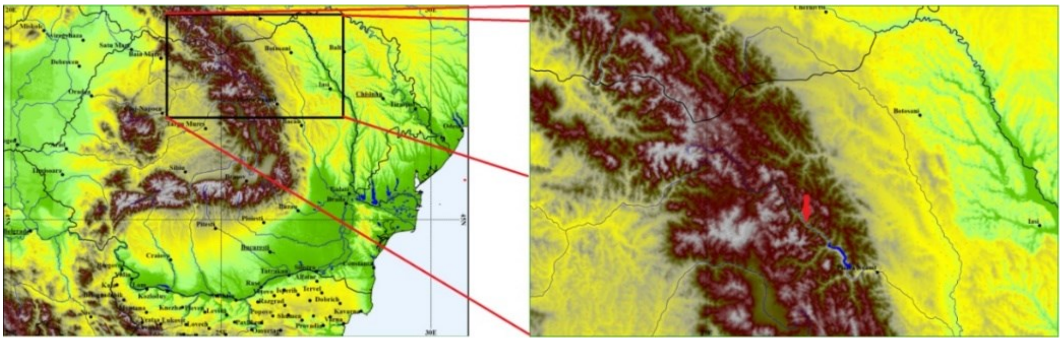


Fig. 1. *Brosteni city (red arrow) and surrounding mountains*

From a geological perspective, the Brosteni area is situated at the contact between the crystalline and flysch units of the Eastern Carpathians (Săndulescu, 1984). The crystalline belt consists mainly of compact metamorphic rocks—

granites, gneisses, and crystalline schists—with low permeability, allowing infiltration only through fissured zones and at limited rates (Mutihac & Ionesi, 1974; Posea et al., 2005). In contrast, the flysch belt, composed of sandstones, marls, and clays, exhibits higher infiltration capacity, enabling water storage within more permeable sedimentary layers. This lithological alternation strongly influences surface runoff and flash-flood generation, as crystalline areas tend to produce concentrated runoff, while flysch areas favour infiltration and slower drainage (Bălteanu et al., 2010).

The Brosteni area is crossed by the Bistrița River, which drains a typical mountainous hydrographic network characterized by steep slopes and deeply incised valleys in its upper reaches, gradually widening downstream (Posea et al., 2005). The dense hydrographic network and fragmented relief give watercourses high specific energy and a strong capacity for solid-material transport (Geography of Romania, 1987). Runoff is rapid and highly concentrated, driven by steep slopes and the relatively low permeability of bedrock (Bălteanu et al., 2010). These geomorphological and hydrological characteristics explain the high susceptibility of the area to torrential processes, slope erosion, and flash flooding during intense convective precipitation events (Romanescu & Stoleriu, 2017; Romanescu & Cojocaru, 2019).

2.2 Meteorological data used

Large-scale atmospheric conditions were analyzed using synoptic charts provided by the Deutscher Wetterdienst (DWD), based on the ICON global model with a horizontal resolution of 0.25°. These products allowed the identification of pressure systems and frontal structures affecting Romania during the analysed period.

Mesoscale dynamic and thermodynamic processes were investigated using the ALARO numerical weather prediction model, operationally implemented by the National Meteorological Administration (ANM), with a horizontal resolution of 4 km and a temporal resolution of 1 hour. Relevant convective parameters, including convective available potential energy (CAPE), convective inhibition (CIN), relative humidity, wind speed, vertical wind shear in the 0–6 km layer, divergence, and potential vorticity, were extracted and analyzed.

Radar observations from the Romanian national radar network operated by ANM were used to examine deep convection evolution. The analysis was primarily based on data from the Iași (Bârnova) Doppler radar, located approximately 100 km east of the study area. Column maximum reflectivity (composite reflectivity), the temporal evolution of convective cells, and the structural characteristics of the convective system at different development stages were investigated.

To quantify the hydrological impact, precipitation data from rain gauges operated by the National Administration "Apele Române" were collected. These included precipitation amounts recorded at the nearest stations, Gura Humorului and Stulpicani, which allowed the estimation of rainfall accumulations and their relationship with basin hydrological response. The integrated analysis of synoptic conditions, convective parameters, and local orography made it possible to identify the physical mechanisms responsible for severe convective development and the resulting flash-flooding in the Brosteni area (Fig. 2).

Fig. 2. *Flash flood event in Brosteni area, 27-28 July 2025*

3. Results

During 27–28 July 2025, Romania was affected by the eastward passage of an active cold front (Fig. 3). At 00:00 UTC on 28 July 2025, the synoptic configuration was dominated by an extensive anticyclone over the North Atlantic and Western Europe, with its center located in the Azores region. Over Central and Eastern Europe, an active cold front associated with a cyclonic system situated over northern Scandinavia extended along a north–south axis, crossing central Romania.

The study area (Brosteni) was located within the warm prefrontal sector, where an unstable atmospheric environment developed as a result of south-westerly warm air advection. These conditions were favourable for convective initiation and the development of organized convective structures such as squall lines (Markowski & Richardson, 2010; Antonescu & Bell, 2015). The organization and persistence of convection were further supported by pronounced vertical wind shear and by the strong thermal contrast between the warm prefrontal air mass and the colder postfrontal air mass. This synoptic and mesoscale configuration favored organized convection capable of producing severe weather phenomena, including hail, strong wind gusts, and torrential rainfall (Bluestein, 2013; Stan-Sion & Antonescu, 2020). At the synoptic scale, southern Europe was influenced by a weak cyclonic system (1005–1010 hPa) affecting the Black Sea and the Aegean Sea, contributing to the maintenance of relatively low pressure over the Balkans, while slightly higher pressure prevailed over eastern Europe.

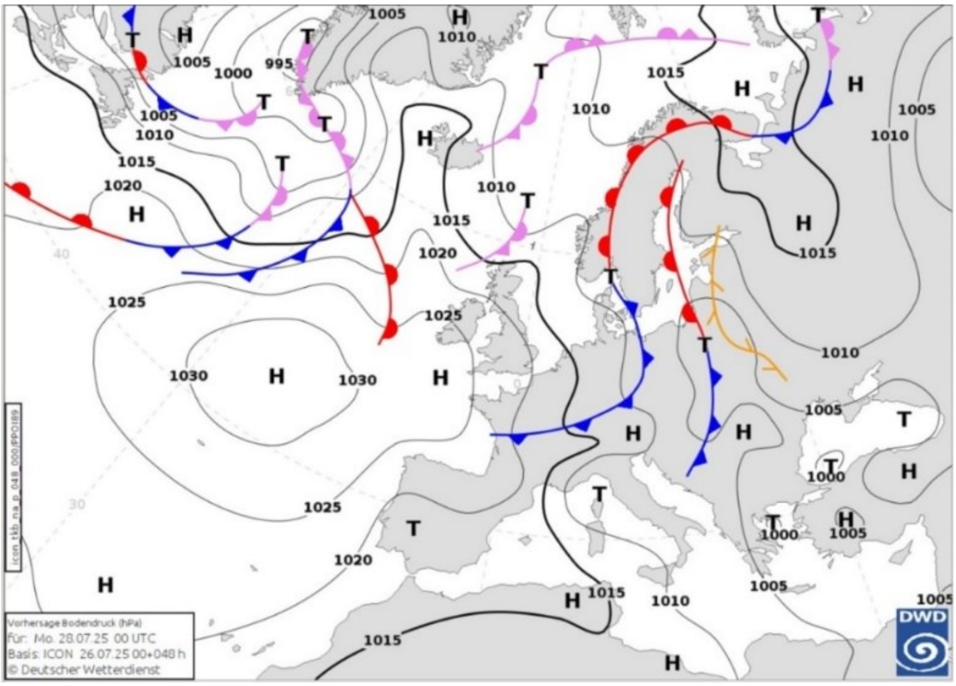


Fig. 3. *Synoptic-scale chart of surface pressure systems and frontal structures over Europe (DWD model ICON)*

The upper-tropospheric configuration at the 300 hPa level was characterized by a well-defined short-wave trough, which favoured positive vorticity advection (PVA) in its anterior sector and led to the intensification and persistence of atmospheric instability over the study area (Fig. 4). PVA is a dynamic process associated with upper-level divergence, which induces upward motion within the air column and enhances ascent under conditions of conditional instability (Markowski & Richardson, 2010).

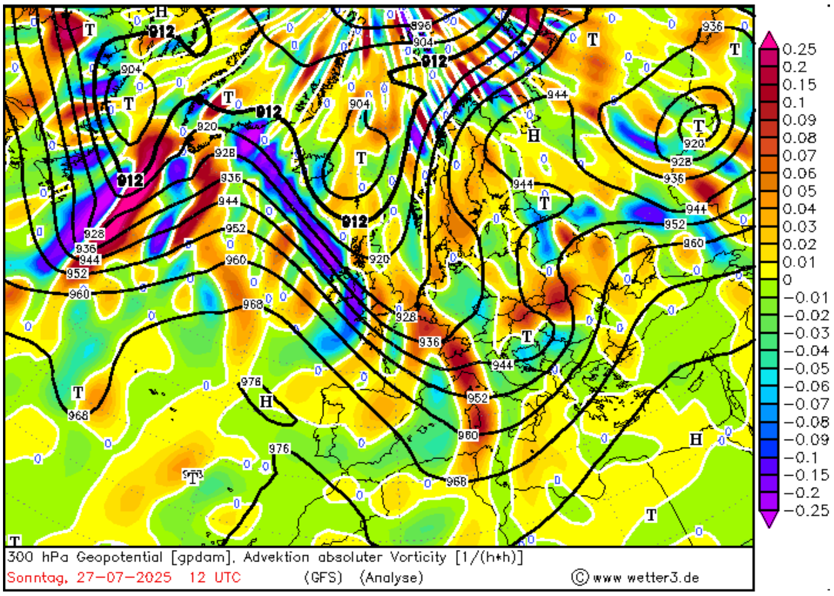
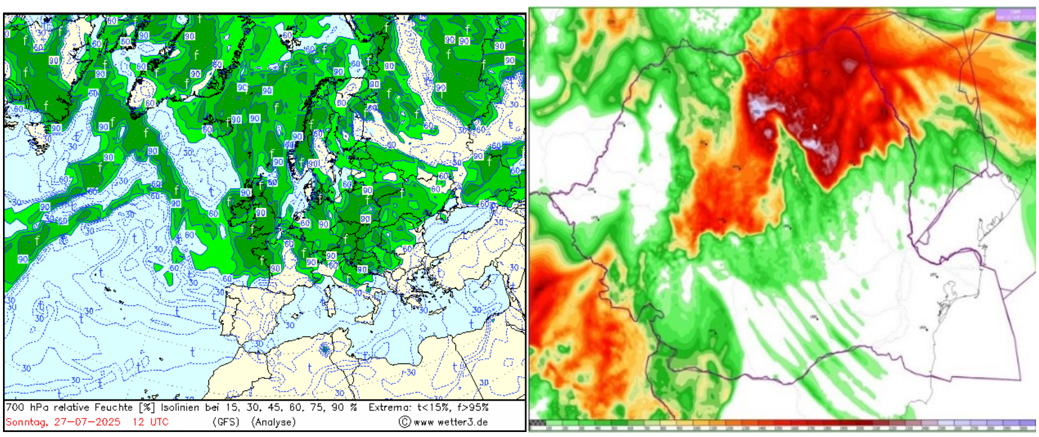
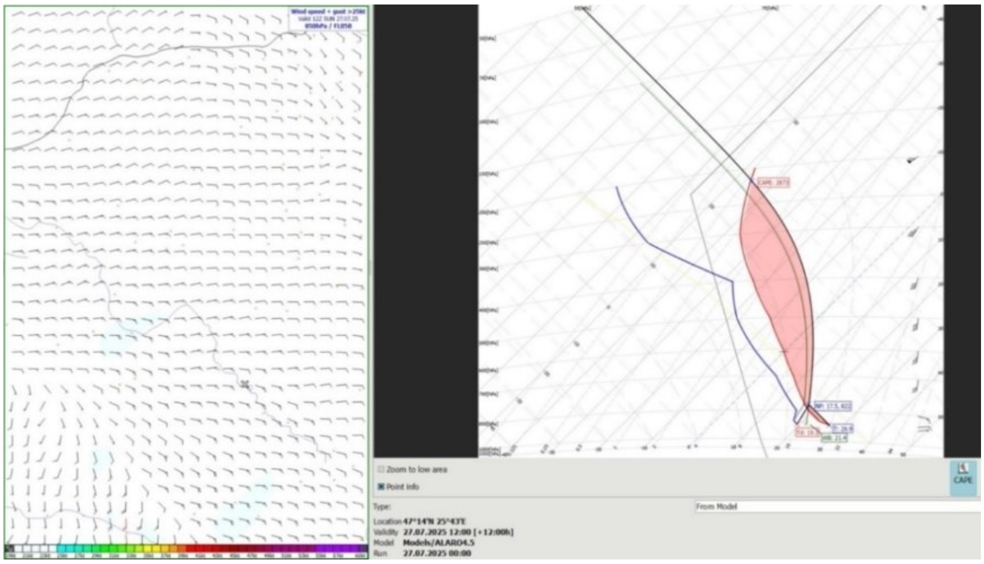


Fig. 4. *300 hPa geopotential high (contour lines), and potential vorticity advection (colours) (wetter3.de)*

In the lower troposphere, relative humidity at the 700 hPa level (approximately 3000 m a.s.l.) reached values of around 90% (Fig. 5a), indicating a substantial moisture supply favourable for condensation and latent heat release. Convective available potential energy (CAPE) values of approximately 3000 J kg^{-1} (Fig. 5b) indicated a high potential for severe convection, supporting the development of strong updraughts and organized convective systems. The vertical wind profile (Fig. 5c) revealed pronounced vertical wind shear, with magnitudes between 15 and 25 m s^{-1} in the 0–6 km layer, characteristic of environments conducive to the persistence and organization of severe convection (Markowski & Richardson, 2010).



(a) *(b)*



(c)

Fig. 5. *Relative humidity at 700hPa(a), CAPE (b), and vertical profile (c) (ALARO)*

Low-level convergence and upper-level divergence associated with severe convective storms can be analysed using Doppler radar observations (e.g. Burgess & Lemon, 1990), although direct detection of near-surface convergence is often limited by radar geometry, beam blockage, and signal attenuation. Consequently, divergence aloft is generally considered a more reliable indicator of severe storm development. In this case, upper-level divergence (Fig. 6) favoured low-level convergence in accordance with the principle of mass conservation, commonly referred to as the Dines model (Dines, 1919). Orographic effects and differential surface heating further enhanced convergence at low levels. Positive vorticity advection in the upper troposphere contributed to the intensification of upward motion and the enhancement of rotation within the updraught. The observed damage path was associated with the development of secondary convective cells, likely triggered by gust-front outflows generated by earlier storms. From an operational perspective, these results indicate that early detection of mid-level rotation may improve nowcasting of severe wind events.

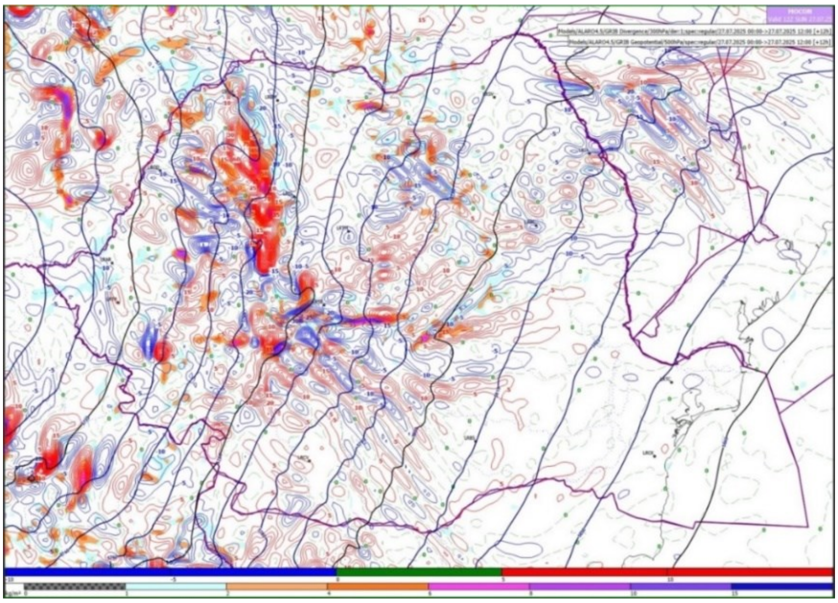


Fig. 6. Convergence (blue), and divergence (red) at 300hPa (ALARO)

Convective initiation occurred after 12:00 UTC and persisted until approximately 18:00 UTC, with radar reflectivity values frequently exceeding 60 dBZ (Fig. 7), indicating extremely intense precipitation and/or hail (Ștefan & Barbu, 2018).

As the cold front approached the Brosteni area, convective precipitation continued throughout the night. Total precipitation amounts were estimated at approximately 70 mm, while observations from nearby hydrometric stations operated by Apele Române recorded 78.7 mm at Gura Humorului and 66.8 mm at Stulpicani.

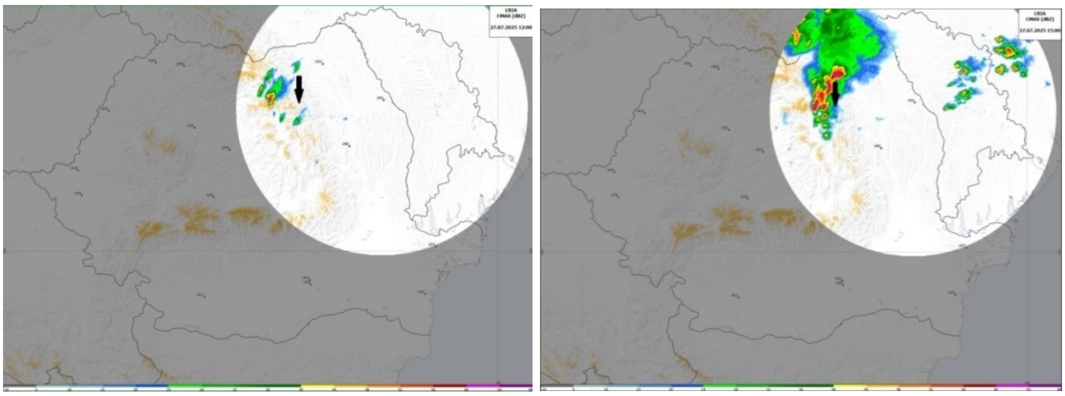


Fig. 7. Column maximum reflectivity from Iasi (Barnova) meteorological radar (black arrow indicates Brosteni city)

According to the General Inspectorate for Emergency Situations, the flash floods that occurred between 27 and 28 July 2025 in the Brosteni area resulted in three fatalities and affected approximately 650 houses, of which about 250 were totally or partially destroyed. Losses of livestock, poultry, and beehives were also reported. In addition, bridges were destroyed, roads were blocked by alluvial deposits and fallen trees, agricultural land was flooded, and freshwater supply infrastructure was severely affected.

Conclusions

The flash-flood event analyzed in this study was generated by severe convective activity that developed within the warm sector ahead of an active cold front, under a prevailing south-westerly circulation. The atmospheric environment was characterized by high instability and elevated moisture content in the lower troposphere, creating favorable conditions for sustained and organized convective development.

As initial convective cells propagated north-eastwards, successive cells repeatedly developed along the same trajectory, resulting in a convective train-type organization. This configuration led to highly localized yet extreme precipitation accumulation over a short time interval.

The persistence of convective activity exceeded 5–6 hours, during which intense rainfall exceeded soil infiltration capacity. Additional precipitation associated with the frontal passage further enhanced surface runoff and catchment response.

The observed event is consistent with the conceptual model of a quasi-stationary "back-building" convective system, in which new convective cells continuously form on the south-western flank of the system while mature cells propagate downstream (Schumacher & Johnson, 2005). Such configurations commonly develop under south-westerly flow interacting with complex orography, which promotes forced ascent of warm and moist air masses.

Local geomorphological characteristics, including steep slopes, narrow valleys, and low soil permeability, significantly amplified surface water accumulation and rapid runoff generation. These factors contributed to the formation of torrents and a sudden increase in discharge within small catchments, ultimately leading to severe flash-flooding in the Brosteni area.

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