EXTREME RAINFALL INTENSITIES AT SUB-HOURLY TEMPORAL SCALE IN DOBRUDJA (ROMANIA)

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DOI: 10.21163/GT_2024.191.08

ABSTRACT:

This study presents a statistical analysis of maximum precipitation amounts at different time intervals in Dobrudja - a historical region in Romania, with semi-arid mid-latitude climate, spanning over the entire historical period of measurements available for each weather station taken into consideration. The data provided by the National Meteorological Administration have different time spans for each weather station, starting with 1948 (at Constanța weather station). Two methodologies were used for data recording: the pluviographs being used during the last century, and the automatic weather sensors, which have been introduced into general use starting with 2008. In this study, a sub-hourly temporal scale was used to estimate extreme rainfalls: 5, 10, 15, 20, 25, 30 minutes. Then, the corresponding evolution trends were calculated over the entire period of reference (1948-present day), with Mann-Kendall and Sen's slope tests being applied (cases with p-level < 0.05 have been considered statistically significant). The probability for extremely high rainfall amounts to occur in very short periods of time and consequently, the resulting rainfall intensities have also been computed by means of Gumbel distribution. Our findings show that, despite rather scarce rainfall amounts, mostly due to the prevalent mid-latitude semi-arid conditions (the annual rainfall amounts in Dobrudja hardly exceed 400 mm/year), when occurring, they turn into downpours, mounting up to 21 mm in 5 minutes (two events exceed 20 mm) and sometimes 10 mm in one minute (one event).

Key-words: *extreme precipitation, rainfall intensity, trend analysis, Gumbel, IDF curves, Dobrudja (Romania).*

1. INTRODUCTION

According to a previous Romanian study, Dobruja's territory is mainly characterized by a semi-arid mid-latitude climate, with either inland continental or maritime influences (Ciulache & Ionac, 2004), but which according to to the Köppen-Geiger classification, carried out in Romania in a more recent study (Cheval et al., 2023), it displays specific features falling into three distinct types of climates: **Cfa** (warm temperate humid with hot summers) in most of the region, **Cfb** (warm temperate humid with warm summers) on the peaks of Măcin mountains and **BSk** (cold semi-arid) in the Danube Delta.

The mean annual temperature in Dobrudja varies between 10 and 12°C over most of its territory and falls below 10°C only on the peaks of the Măcin mountains and over the Babadag Plateau; thus, turning it into one of the warmest regions in the country (**Fig. 1**).

By analyzing the spatial distribution of rainfall amounts over Romania's territory, it becomes obvious that the Dobrudjan Tableland and the Bărăgan steppe-like Plain areas record the lowest annual precipitation amounts (generally below 500 mm) (**Fig. 2**). In fact, Dobruja's easternmost areas, and especially the Danube Delta, represent the country's most arid areas in terms of precipitation, with accumulated annual amounts below 300 mm on its easternmost parts (National Meteorological Administration, 2008).

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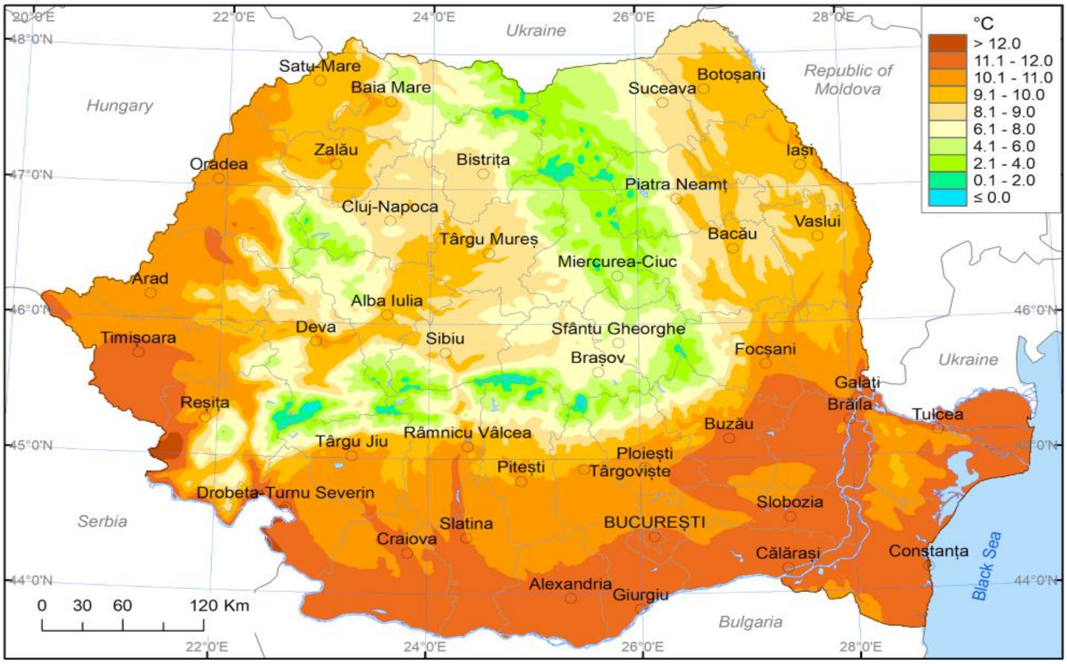

Fig. 1. Mean annual air temperature in Romania (1961-2020).

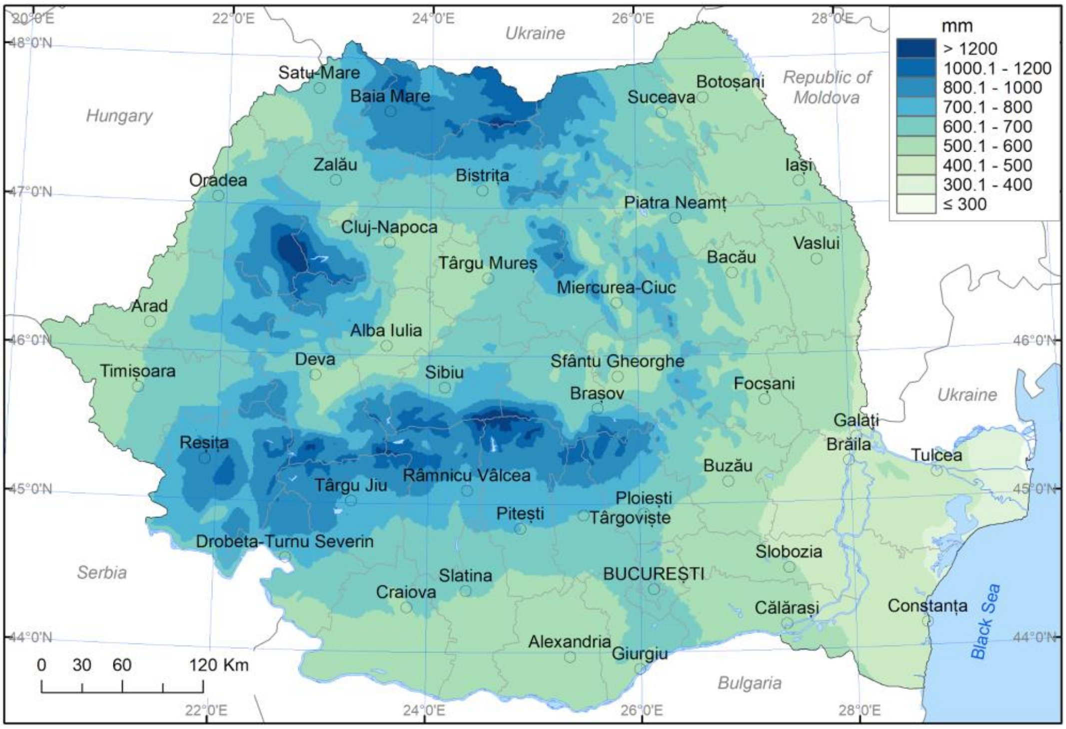

Fig. 2. Mean annual precipitation amount in Romania (1961-2020).

Dobrudja has always been a region of interest for Romanian researchers, due to its climatic particularities. Many authors have studied this region due to its mostly arid character, by calculating several aridity indices used worldwide (Lungu et al., 2011a; Prăvălie & Bandoc, 2015; Tișcovschi et al., 2013). This aspect was also highlighted in country-scale studies (Croitoru et al., 2013; Dobri et al., 2021; Păltineanu et al., 2007; Păltineanu et al., 2007). Many papers have been dedicated to the analysis of variability, trends and changes in rainfall extremes, both on a regional (Croitoru et al., 2013; Deguenon & Bărbulescu, 2011; Maftei et al., 2011) and national scale (Ciulache & Ionac, 1993, 2000, 2004; Croitoru et al., 2015, 2018; Dragotă, 2006). In most of the studies, indices of rainfall extremes such as the ETCCDI indices were calculated. Other studies have been focused on the bioclimatic stress (Chiotoroiu, 1993; Grigore, 2013; Ionac, 2007a, 2007b; Ionac & Grigore, 2012a, 2012b), torrential rains (Lungu et al., 2011b) or the desertification phenomenon in Dobrudja (Vorovencii, 2015). The land degradation and desertification in Dobrudja were highlighted in country-scale studies as well (Onțel at al., 2023). At the same time, the agricultural sector was also of interest, with many researchers studying the favorable climatic conditions for certain crops (Lungu et al., 2010b; Panaitescu et al., 2011, 2012; Prăvălie et al., 2014), the drought phenomenon (Lungu et al., 2010b; Angearu et al., 2018) and the fires' occurrence (Angearu et al., 2018).

The present study makes an analysis of the sub-daily evolution and trend of extreme rainfall amounts in Dobrudja, based on a dataset with a very fine temporal resolution, up to 1 minute. These precise data were used in the past only in a few studies carried out by researchers from the National Meteorological Administration (Busuioc et al., 2015, 2017; National Meteorological Administration, 2008). At the same time, this study also makes an accurate analysis of some indices of extremes (and their trends) that have never been used in Romania before, such as the maximum rainfall amount recorded in a 5-minute interval. Other indices such as the maximum intensity of the rain related to a 5-minute interval or the return period of the rainfall extremes recorded in various time intervals, from 5 minutes to 24 hours, were nevertheless highlighted only for a few weather stations in the country, in some studies published by the National Meteorological Administration (*Climate of Romania*, 2008).

2. STUDY AREA

The study area includes the historical region of Dobrudja and the Danube Delta, both located in the South-East of Romania (**Fig. 3**), being bounded to the North by Ukraine through the natural border created by the Danube River; to the East by the Black Sea; to the South by the border with Bulgaria and to the West, by the two Danube's floodplains and the Romanian Plain.

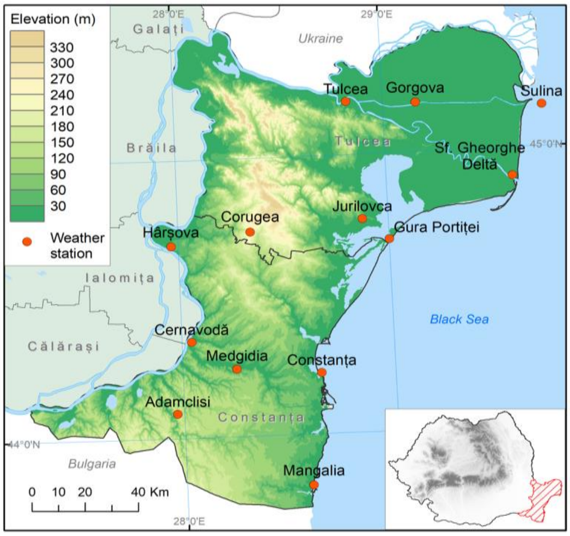

Fig. 3. Study area - location and topography.

The elevation in this area varies between 0 and 467 m and the landforms are very diverse: strongly eroded Hercynian mountains in the North, plateau landforms in the South and center, delta landforms in the North-East, as well as shorelines with beaches, cliffs, sandbars and lagoons all along its eastern border to the Black Sea. Besides the Danube River, the hydrographic network in Dobrudja is very poorly represented, being limited to a few tributary rivers to the Black Sea through many lagoons (Institutul de Geografie, 1983). The resident population in Dobrudja is 849,352 people (National Institute of Statistics, 2022), representing 4.5% of Romania's population.

3. DATA AND METHODS

In this paper, sub-hourly precipitation data were used. As provided by the National Meteorological Administration (NMA) the observation data about rainfall amounts recorded in 1 minute could be identified only for 13 weather stations in the research area (**Fig. 3** and **Table 1**).

Table 1.

List of the weather stations being taken into consideration in Dobrudja.

No	Station	Station Code	Latitude (Deg.)	Longitude (Deg.)	Elevation (m)	Time range of dataset	No. of years with data	Missing data	
								Years	%
1	Adamclisi	15479	44.0883	27.9656	158.0	1965-2021	50	1995, 2008-2011, 2013, 2017	12.3
2	Cernavodă	15445	44.3456	28.0437	87.2	1985-2021	32	1987, 2011-2014	13.5
3	Constanța	15480	44.2138	28.6455	12.8	1948-2021	70	2008-2011	5.4
4	Corugea	15408	44.7343	28.3420	219.2	1958-2021	50	1960, 1962, 2000-2011	21.9
5	Gorgova	15336	45.1769	29.1568	2.8	1987-2022	35	2015	2.8
6	Gura Portiței	15428	44.6898	28.9989	2.0	1992-2022	28	2009, 2013, 2014	9.7
7	Hârșova	15406	44.6917	27.9635	37.5	1964-2021	46	1982-1987, 2006-2011	20.7
8	Jurilovca	15409	44.7661	28.8764	37.7	1963-2021	41	1989-1996, 2009-2017, 2020	30.5
9	Mangalia	15499	43.8161	28.5874	6.0	1964-2021	48	2002-2011	17.2
10	Medgidia	15462	44.2432	28.2514	69.5	1957-2021	59	1961, 1962, 2009-2011, 2015	9.2
11	Sf. Gheorghe Deltă	15387	44.8976	29.5991	1.4	1992-2022	15	2000-2015	51.6
12	Sulina	15360	45.1485	29.7589	12.7	1961-2021	57	2009-2012	6.6
13	Tulcea	15335	45.1905	28.8241	4.4	1963-2021	55	1965, 2009-2011	6.8

These precise data were recorded by using two instruments: the Union of Soviet Socialist Republics (USSR)-type pluviographs, until 2007-2008, and the precipitation sensors of the automatic weather stations (with tipping cups or weighing system) after this period on.

The length (time-span) of the sub-daily dataset (in number of years with recorded data) varies between 15 (at Sf. Gheorghe Deltă) and 70 years (at Constanţa). The weather stations are located at elevations between 1.4 and 219.2 meters.

The statistical processing and the spatial distribution maps of the analyzed indices were based on the R programming language. The maximum rainfall amounts were calculated through the running sum (moving sum) method (Ciulache & Ionac, 1993) and not by using a fixed time interval (the climatological or synoptic day). Accordingly, the maximum value related to an absolute quantity can be obtained from rainfall amounts recorded during two consecutive calendar days. The rainfall intensities were obtained by dividing the maximum rainfall amounts to the duration in which they were recorded.

For the weather stations with long data series, the trends of maximum rainfall amounts recorded in time intervals between 5 minutes and 24 hours were calculated, provided that the data series had less than 20% missing values. The trends were obtained by applying the non-parametric Mann-Kendall test, with a statistical significance threshold of 95% (p-level < 0.05). The slope of the trend, defining the magnitude of change expressed in mm/decade, was calculated by applying the Sen's slope test which, like the Mann-Kendall test, is based on Kendall's Tau correlation coefficient. The trend analysis was then performed by using the R-package *trend* (Pohlert, 2015).

The return probability of these maximum rainfall amounts was estimated by means of *extRemes* R-package (Gilleland & Katz, 2016). For the available data at the weather stations in Dobrudja, two different methods to estimate resulting probabilities were tested, namely, the Gumbel distribution and the Generalized Extreme Value (GEV) distribution. As the Gumbel distribution actually proved more fit for the observed frequency of the data than the GEV distribution, therefore only the Gumbel distribution was used further in this study.

The Gumbel distribution, also known as *The Type I Extreme Value distribution* or the *double exponential distribution*, is widely used to estimate the extreme values, either maximum or minimum, of a large sample of independent elements from an initial distribution ending up into a tail of an exponential type. The values of the initial cumulative distribution increase/decrease towards the zero point at least as fast as the exponential distribution approaches it (Haan, 1977). Most often, this distribution is used for maximum rainfall amounts and flashflood peaks estimations. Thus, by using the annual maxima for 32 time-span intervals (between 5 and 1440 minutes) as main input data and by applying the Gumbel distribution (Gumbel, 1935), estimates were obtained for return periods of 2, 3, 5, 10, 20, 50 and 100 years.

The cumulative probability function, F(x), of the Gumbel distribution is:

$$F(x) = exp[-exp(-\frac{x-\mu}{\alpha})] \quad (1)$$

where:

- x - precipitation amount;
- α - parameter of the Gumbel distribution (for scale);
- μ - parameter of the Gumbel distribution (for location).

The Gumbel distribution can be used to calculate the maximum probable rainfall amounts (X_T) corresponding to any return period (T), by using equation (2) (Amin et al., 2016):

$$X_T = \bar{X}(1 + C_v K_T) \quad (2)$$

$$K_T = \frac{\sqrt{6}}{\pi}[0.5772 + ln\{ln(\frac{T}{T-1})\}] \quad (3)$$

where:

- $\bar{X}$ - mean of the maximum probable rainfall amounts;
- C_v - coefficient of variation;
- K_T - frequency factor, which is dependent on the return period and the probability distribution.

In the end, the intensities coresponding to the estimated maximum values were calculated and plotted on a double-log chart, representing the Intensity-Duration-Frequency (IDF) curves for all the 13 stations in the study area.

4. RESULTS

This study outlines the characteristics of the rainfall extremes in Dobrudja (Romania) both by analyzing the maximum amounts recorded in different time intervals, the intensity of these maximum amounts and the decennial trends observed in the time-distribution of the pluviometric extremes, and by also estimating the probability of occurrence of some extreme rainfall amounts in the future by using the Gumbel distribution.

4.1. Maximum precipitation amounts

The maximum 24 hours' precipitation amounts recorded at the weather stations in Dobrudja during the 1948-2022 period varies from 76.1 mm in the Danube Delta (Sulina) to 206 mm in the southern extremity of the shoreline (Constanța) (**Fig. 4**).

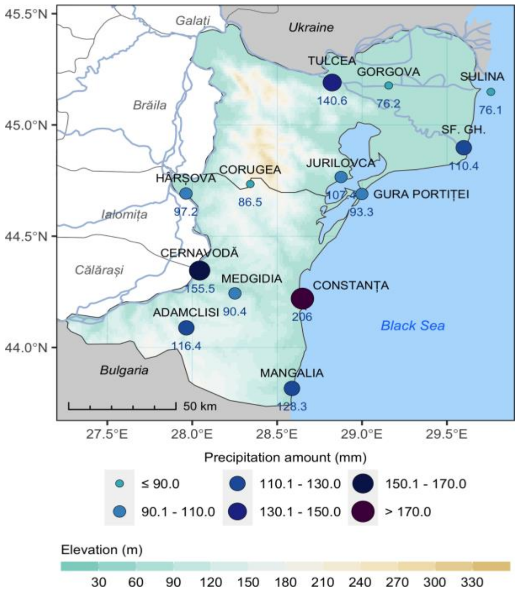

Fig. 4. Maximum 24 hr precipitation amounts in Dobrudja (1948-2022).

The maximum precipitation amount recorded at Constanța station, on August 28, 2004, is higher than the amount resulting from climatological days, namely 201 mm (https://www.meteoromania.ro/clim/caracterizare-multianuala/cc_1961_2021_08.html), and at the same time, it is also a value close to the absolute maximum amount of precipitation that has ever fallen in 24 hours in Romania, respectively 224 mm, recorded at Drobeta-Turnu Severin on July 12, 1999 (https://www.meteoromania.ro/clim/caracterizare-multianuala/cc_1961_2022_07.html).

The highest rainfall amounts were mainly recorded in Dobrudja's southern parts, where the long-wave troughs of the polar vortex and the cut-off low systems can generate atmospheric instability and heavy downpours due to the steep thermal gradient that occurs between the warm air on the surface and the colder air from middle and upper troposphere (Dobri et al., 2017). Moreover, the Black Sea has a thermoregulatory effect, giving off a part of its heat to the land, especially during night time (Ionac & Ciulache, 2004), and combined with the high air-humidity and atmospheric instability, it favors cyclogenesis or the deepening of the Mediterranean cyclones over the western part of the Black Sea (Chiotoroiu, 1998). On the contrary, the lowest amounts were recorded in the Danube Delta, where the extended area of water usually inhibits the development of convective systems by its colder surface (Dobri et al., 2017; Porcù et al., 2007).

The Danube Delta is known as the most arid area in the country (Lungu et al., 2011a), which is visible in the spatial distribution of the annual averages of rainfall amounts. However, as far as the sub-daily precipitation regime is concerned, it can be observed that, in certain situations, the highest values were recorded in the Danube Delta or in its immediate vicinity (Razim-Sinoe Lagoon System). Thus, the absolute maximum amount of precipitation recorded in one hour in Dobrudja (85.4 mm) occurred at Jurilovca on September 16, 2008 (**Fig. 5**). The next maximum amount (81.8 mm) was recorded on August 3, 2019, at Sf. Gheorghe Deltă. The absolute maximum in 3 hours (108.1 mm) was recorded at Tulcea weather station (w.s.) on July 27, 1997, followed by Jurilovca w.s. (106 mm /September 16, 2008). Regarding the amounts recorded in 6 hours, the highest values occured at Cernavodă (144.2 mm/July 28, 2017) and Constanța w.s. (127.1 mm/August 28, 2004). However, in the North-East of the region, more than 100 mm were recorded at half of the weather stations as well.

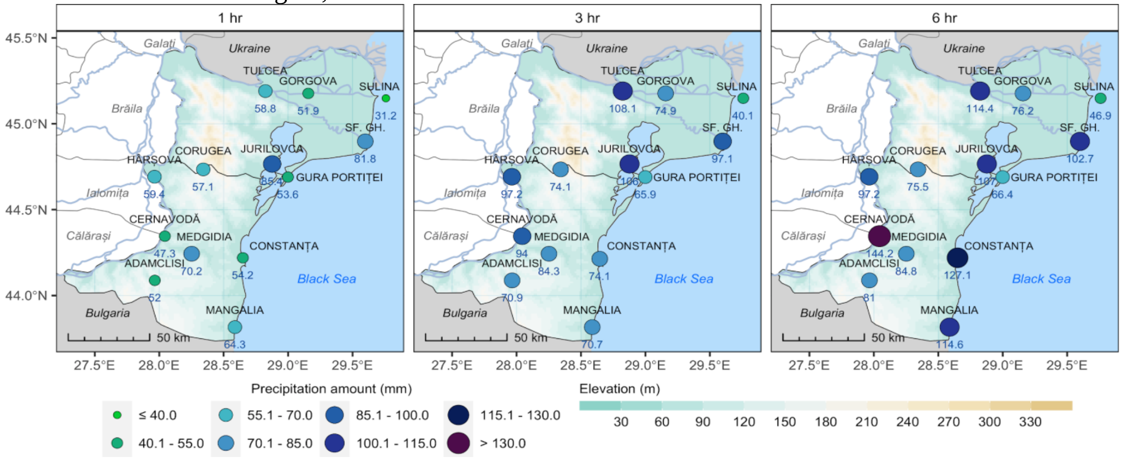

Fig. 5. Maximum rainfall amounts in Dobrudja, at different time spans (1, 3 and 6 hours) (1948-2022).

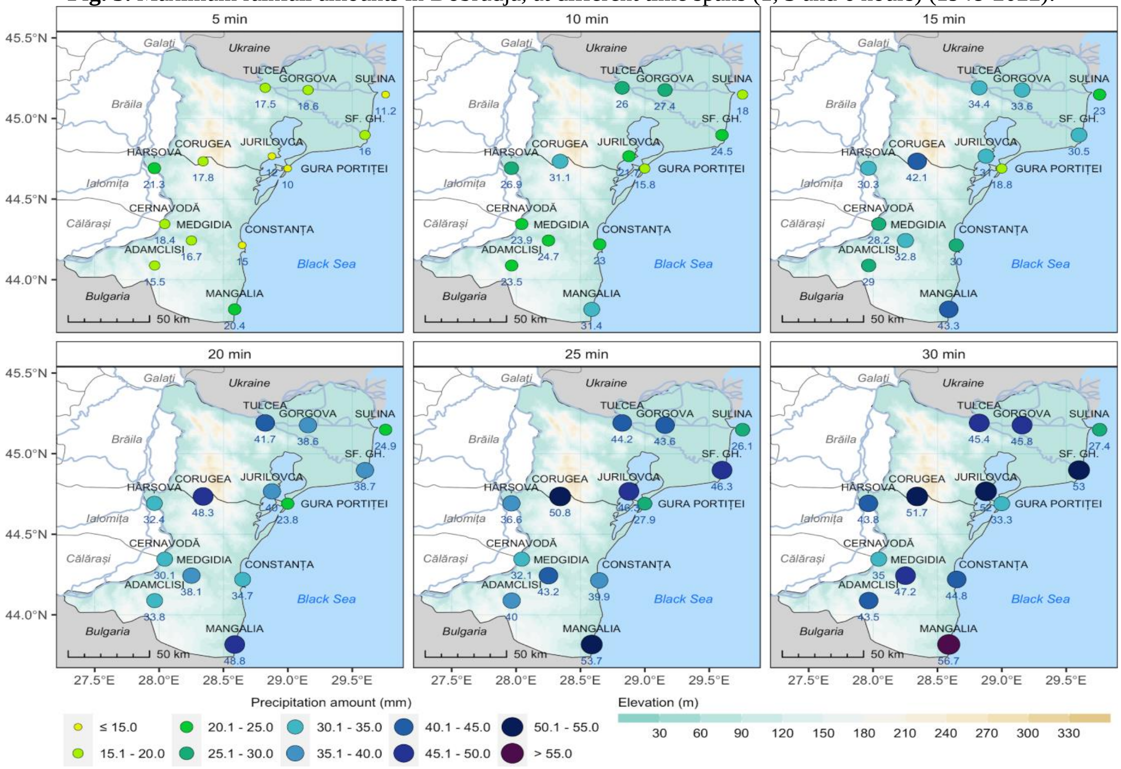

Fig. 6. Maximum rainfall amounts in Dobrudja, at time spans: 5, 10, 15, 20, 25, and 30 minutes, (1948-2022).

The lowest rainfall amounts recorded on 1, 3 and 6 hours occured at Sulina w.s., located in Romania's easternmost border, in a region with mid-latitude climate but strong eastern-continental influences and where the predominant direction of the wind is northerly. Furthermore, the weather station is not located quite on the land shore, but off the Black Sea coast and this might be a cause for these lower amounts, as colder underlying surfaces are known to inhibit convection. The higher wind speed values during storms, specific to larger water bodies with no rough surfaces, might also be a (technical) cause for the lower precipitation amounts that have been recorded with the rain gauges.

At a sub-hourly temporal scale, the highest rainfall amounts were mainly recorded in the southern part of the region (**Fig. 6**). The highest rainfall amount recorded in a 5-minute interval (21.3 mm) occured at Hârșova w.s., on July 11, 1967, with an intensity of 4.26 mm/min. In the first minute of the rain, 10 mm of precipitation were recorded. More than 20 mm in 5 minutes were also recorded at Mangalia w.s. on 22 June 1983. On the same day, maximum amounts in 10 and 15 minutes were also recorded at both stations, the values at Mangalia being the highest in the region. The lowest value of a 5 minutes' rainfall amount (10 mm) was recorded at Gura Portiței w.s. In 20, 25 and 30 minutes, the maximum amount was recorded at Mangalia, on August 27, 2021, but high amounts were also recorded at Corugea, Jurilovca and Sf. Gheorghe Deltă w.s.

4.2. Extreme rainfall intensities

Rainfall intensity is defined by the World Meteorological Organization (WMO) as the amount of precipitation collected per time unit interval (WMO, 1992, 2006). Depending on its intensity, a rain can be considered weak, moderate, heavy or violent (**Table 2**). The rainfall intensity at the weather stations in Dobrudja was analyzed on the same time scale as in the case of maximum rainfall amounts (24 hours, 6 hours, 3 hours, 1 hour, 5, 10, 15, 20, 25 and 30 minutes).

Table 2.

Rainfall intensity (i) classification according to the WMO's *Guide to Meteorological Instruments and Methods of Observation* (World Meteorological Organization, 2008).

Intensity range (mm h^{-1})	Intensity range (mm min^{-1})	Rain classification
$i < 2.5$	$i < 0.04$	Slight
$2.5 \leq i < 10.0$	$0.04 \leq i < 0.17$	Moderate
$10.0 \leq i < 50.0$	$0.17 \leq i < 0.83$	Heavy
$i \geq 50.0$	$i \geq 0.83$	Violent

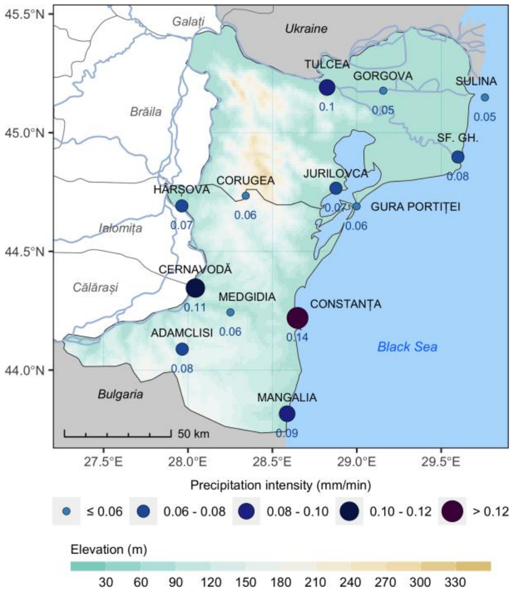

Fig. 7. Rainfall intensities of the maximum 24 hr precipitation amounts in Dobrudja (1948-2022).

The maximum rainfall intensity in Dobrudja, in 24 hours (**Fig. 7**), varied from 0.05 mm/min in the Danube Delta (Sulina and Gorgova w.s.) to 0.14 mm/min in the southern part of the shoreline (Constanța w.s.); at all weather stations the rain was moderate for this duration, according to the WMO's classification. After Constanța w.s., the highest intensities were recorded at Cernavodă, Tulcea and Mangalia w.s. Thus, from a statistical point of view, the highest intensities recorded in 24 hours are specific to the southern parts of the research area (Constanța county).

The highest rainfall intensity in only one hour, namely 1.42 mm/min, was recorded at Jurilovca w.s., followed by Sf. Gheorghe Deltă with 1.36 mm/min (**Fig. 8**).

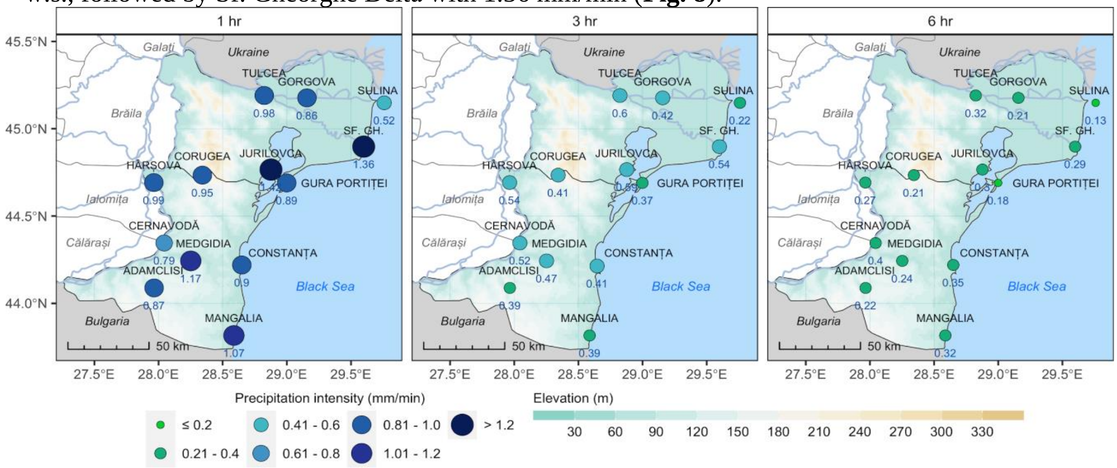

Fig. 8. Rainfall intensities of maximum precipitation amounts at time spans: 1, 3 and 6 hours, (1948-2022).

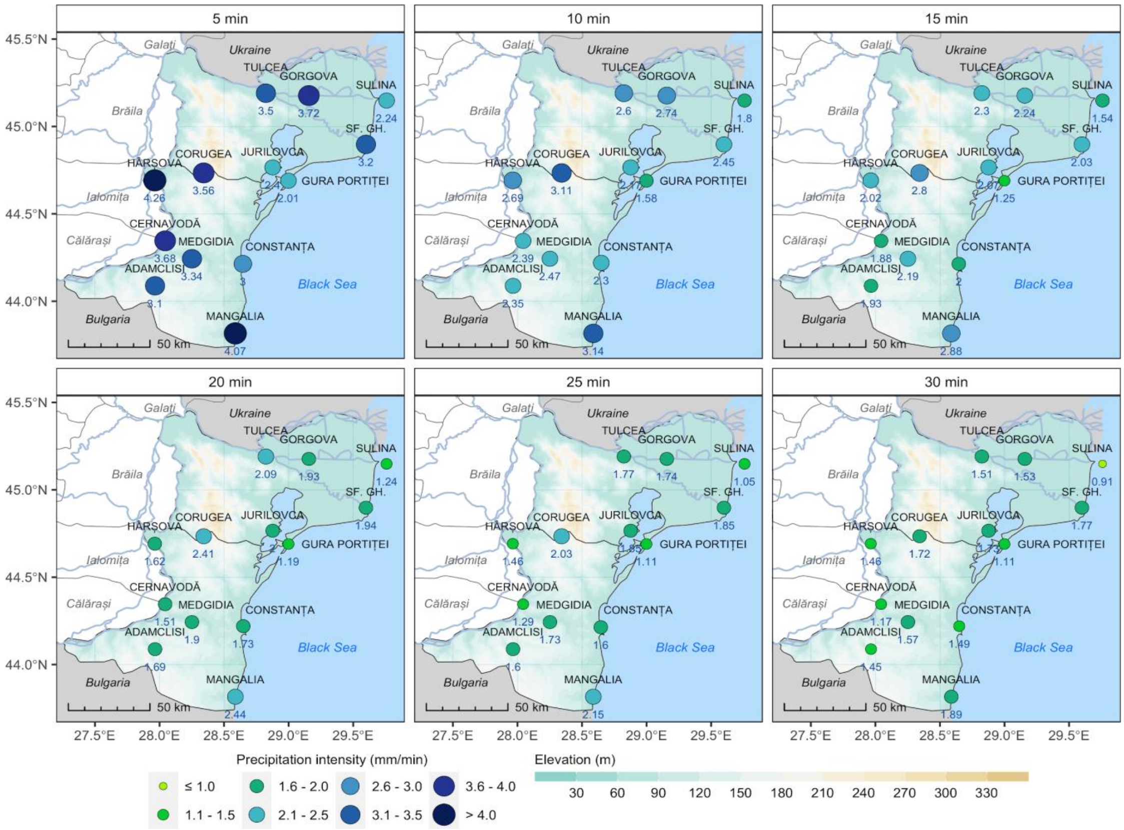

Fig. 9. Rainfall intensities of maximum precipitation amounts at time spans: 5, 10, 15, 20, 25, 30 min.(1948-2022).

The lowest maximum intensity (0.52 mm/min) occurred at Sulina w.s. Excepting Cernavodă and Sulina w.s., all the other weather stations recorded at least one rainfall episode that could be classified as violent/extreme within an hour. The rainfall intensities related to durations of 3 and 6 hours define the respective rains as heavy at almost all stations, with the exception of the Sulina w.s., where the respective rain may be considered as moderate if relating it to the duration of 6 hours. The highest intensity in 3 hours occurred at Tulcea, and in 6 hours, at Cernavodă w.s. It should also be noted that all these maximum intensities are directly correlated with the maximum rainfall amounts. Thus, the weather station with the highest rainfall amount is also the station where the rainfall intensity reached the highest value. However, the intensity of a rain is a good indicator to classify rain types in terms of their specific features.

In the time intervals from 5 to 30 minutes, the rainfall intensity values place all rains into the violent/extreme class (**Fig. 9**). The highest values in 5 minutes, of more than 4 mm/min, occurred at Hârșova and Mangalia w.s., exceeding by more than 3 times the threshold chosen by the WMO for a rain to be considered violent. At most stations, the intensity was at least 3 mm/min. In Hârșova, 10 mm of precipitation fell on the first minute of the rain, as it was retrieved from that day's pluviogram. Although Dobrudja is known as Romania's scarcest region in annual rainfall amounts from the historical data, we could observe that extremely high rainfall amounts can nevertheless occur on a sub-hourly basis, in a very short time.

In time intervals of 10, 15, 20 and 25 minutes, the most intense rains occurred in Mangalia and Corugea, exceeding by far the minimum intensity characteristic of an extreme rain. In 30 minutes, high intensities were recorded at Mangalia, Sf. Gheorghe Deltă, Jurilovca and Corugea w.s. The lowest values for all durations occured at the Gura Portiței and Sulina stations.

4.3. Observed trends in maximum precipitation amounts

Most of the previous studies relating to the pluviometric regime in Dobrudja were based on the ETCCDI indices and also include trend analyses. Consequently, the evolution trends of some indices such as: R10 (number of heavy precipitation days), R20 (number of very heavy precipitation days), Rx1day (maximum 1-day precipitation amount), SDII (simple daily intensity index) and PRCPTOT (annual total wet-day precipitation) etc. were also analysed (Croitoru et al., 2013; Croitoru et al., 2015; Deguenon & Bărbulescu, 2011). In this study, according to the described methodology, the trends of maximum sub-daily rainfall amounts were calculated. By comparing our results those presented in other papers, a certain similarity can be observed between the indices computed in this study and the ETCCDI indices. So, the trends calculated by Croitoru et al. (2013) have the sign of the slope almost identical to those of the trends presented in the **Fig.s 10, 11 and 12** (at Constanța, Mangalia and Sulina w.s.), although the input data and the analyzed indices were substantially different, highlighting the fact that the trends in the precipitation regime are similar for both analyzed time scales. The trends of the maximum rainfall amounts recorded in 24 hours are positive (upward) at 5 weather stations out of the 9 considered in total (**Fig. 10**).

The weather stations with an increasing trend are located both on the Southern Dobrudjan Plateau and in the Danube Delta, possibly because even if rains are not so frequent as on the shoreline of the Black Sea, they have higher intensities over shorter periods of time, so when summed up over 24 hrs, they display a seemingly increasing trend. In general, the negative (downward) trends overlap the Black Sea coast, basically because the colder waters of the sea may greatly impede upward air-movements and condensation processes, despite the activity of the breeze fronts that usually develop in summer. The only station with a statistically significant trend is Constanța (p-value = 0.001) and the station with the highest magnitude is Cernavodă (7.03 mm/decade). For all analyzed time scales, the trend is upward at Constanța and Gorgova w.s. and downward at Medgidia and Sulina.

The trends of the maximum rainfall amounts recorded in one hour and in 3 hours are quite similar (**Fig. 11**), being positive at 5 weather stations. In one hour, they are statistically significant at two weather stations: Cernavodă (p-value = 0.033) and Mangalia (p-value = 0.044). In 3 hours, the statistical significance of the positive change is characteristic only for Cernavodă w.s. (p-value = 0.008). Statistically significant negative trends appear only at Sulina w.s. (p-value = 0.015 in one hour, respectively 0.024 in 3 hours). The maximum rainfall amounts recorded in 6 hours have increasing trends at ⅔ of the analyzed stations, with statistical significance at Cernavodă (p-value = 0.019) and Constanța (p-value = 0.006). For all the three analyzed durations, the highest magnitude was recorded at Cernavodă w.s.

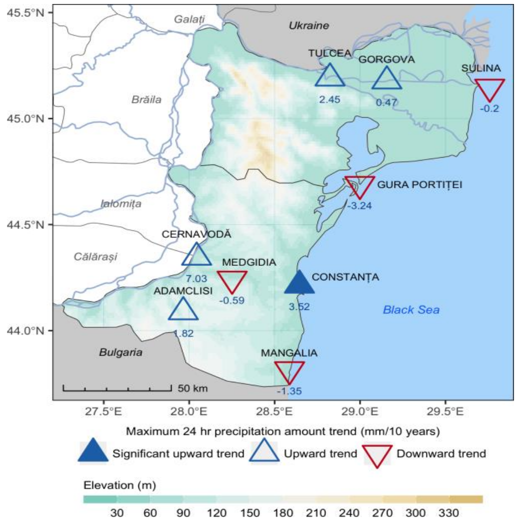

Fig. 10. Trends of the maximum 24 hr precipitation amounts in Dobrudja. (*The values below the triangles represent the magnitude of the rainfall amounts trend, expressed in mm/decade*).

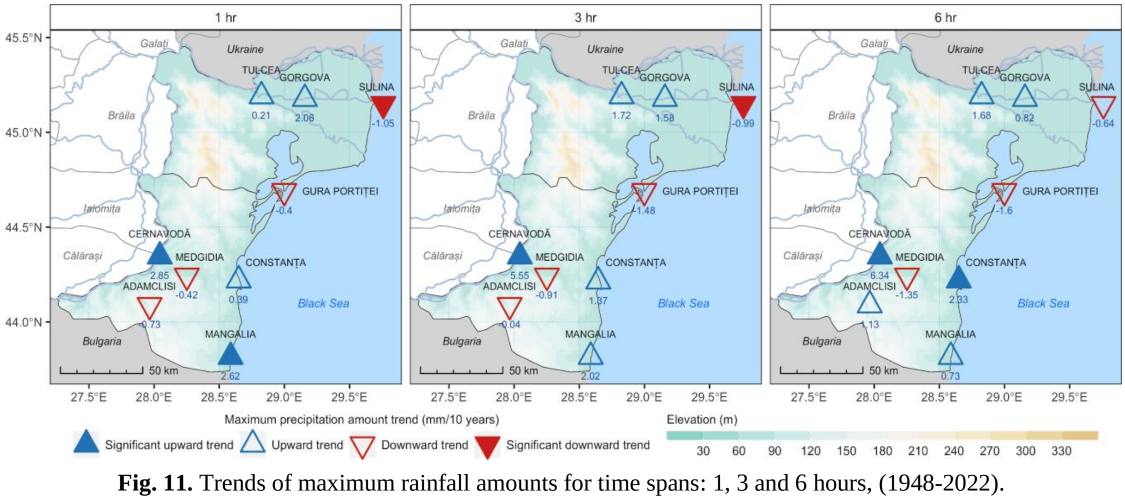

Fig. 11. Trends of maximum rainfall amounts for time spans: 1, 3 and 6 hours, (1948-2022). (*The values below the triangles show the magnitude of the rainfall amount trend, expressed in mm/decade*).

In the case of sub-hourly maximum rainfall trends, they are exclusively increasing at the Constanța, Gorgova, Gura Portiței and Mangalia stations, with a statistical significance only at Gorgova and Mangalia (**Fig. 12**). At Adamclisi, Medgidia, Sulina and Tulcea w.s. the trends are only negative for all durations, yet they are statistically significant only at Medgidia and Sulina for certain durations. At Cernavodă w.s., the trends are mainly positive, except for the 5 minutes' (when it is negative) and the 10 minutes' durations (when the slope of the trend is 0).

For all 6 durations, the highest magnitude was recorded at the Gorgova w.s. This indicates that torrential rains greatly increase in intensity at this station (generally by more than 2 mm/decade for durations ≤ 30 minutes), although it is located in the driest area of the country, namely the Danube Delta.

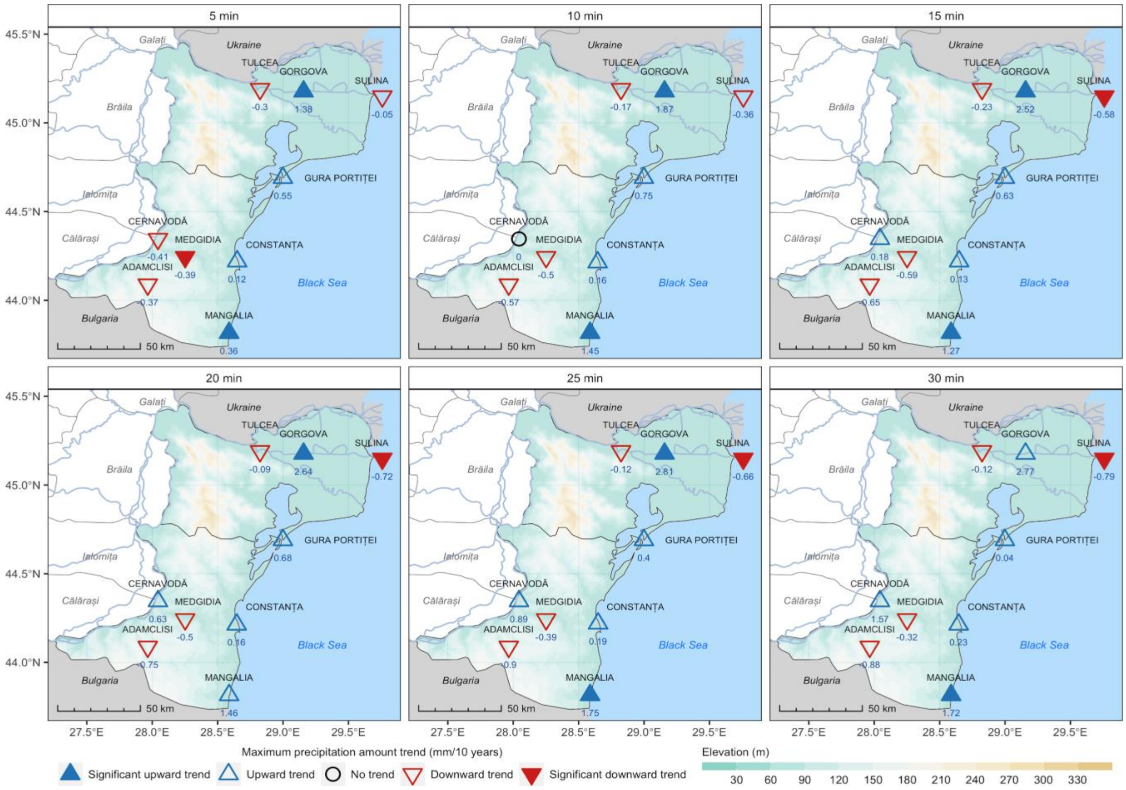

Fig. 12. Trends of the maximum rainfall amounts for time spans: 5, 10, 15, 20, 25, 30 min., (1948-2022). (*The values below the triangles show the magnitude of the rainfall amount trend, expressed in mm/decade*).

4.4. Probability of occurrence of extreme rainfall amounts in the future

The Intensity-Duration-Frequency (IDF) curves are graphical representations of the probability that a given rainfall intensity might occur in a given time period (Dupont & Allen, 1999). These charts are currently used in water resources engineering to create/develop urban water drainage systems, to assess the strength of hydraulic structures (dams, bridges, etc.) and flood vulnerability (Keifer & Chu, 1957). In this study, the IDF curves were constructed for all the analyzed stations, by using Gumbel's extreme values distribution (**Fig. 13**).

A comparative assessment of Gumbel estimates was also performed by analysing the values retrieved from the IDF curves, briefly summarized in **Table 3**. So, the highest rainfall intensities (1.4 mm/min) for a 5 minutes' duration and 2 yrs' return period are specific for the Medgidia, Corugea, Tulcea and Cernavodă weather stations. If multiplying the intensity by the duration, the most probable rainfall amount is retrieved, which is 7 mm in this case. Within this distribution of values, the intensity increases directly proportional to the return period. Thus, for the same duration and a return period of 100 years, the intensity reaches the value of 4.3 mm/min at Corugea, corresponding to a precipitation amount of 21.5 mm. Once every 100 years, the second highest intensity characterizes Hârșova w.s. (4.1 mm/min).

According to the Gumbel distribution, it is evident that the highest values generally overlap with the plateau area for small return periods. For a return period of 100 years, high intensities are also estimated on the Danube Delta (3.9 mm/min at Sf. Gheorghe Deltă and 3.5 mm/min at Tulcea w.s.) or on the Black Sea coast (3.7 mm/min at Mangalia w.s.).

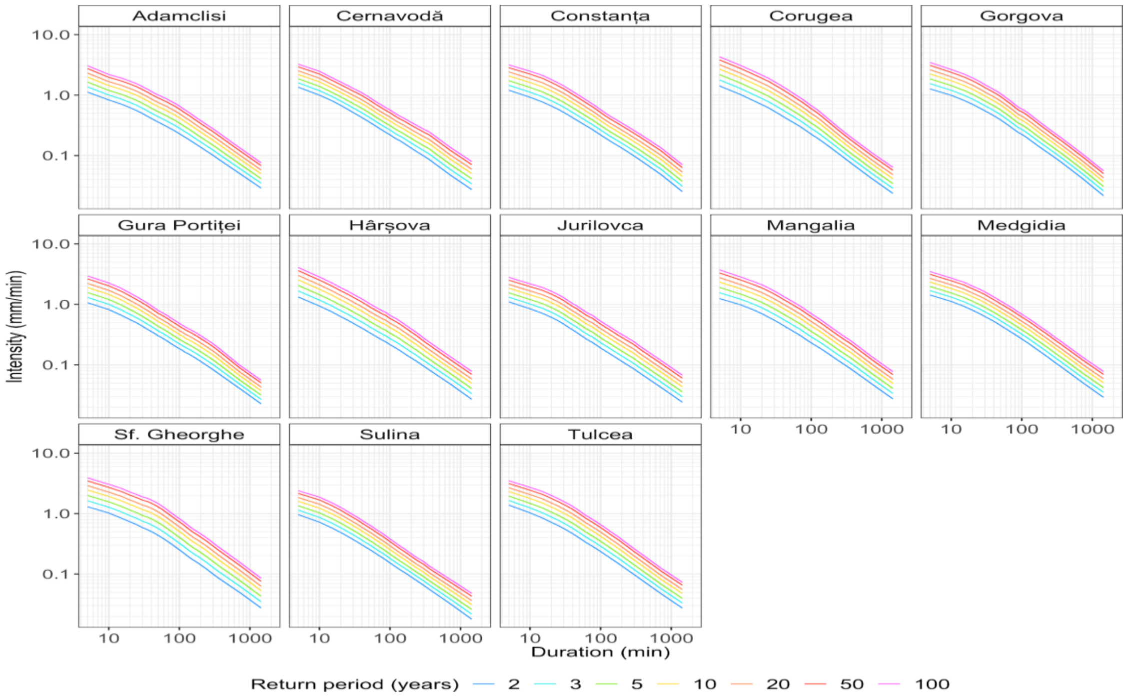

Fig. 13. The Intensity-Duration-Frequency (IDF) curves of maximum rainfall amounts (logarithmic scale).

Table 3.

The maximum rainfall intensity (mm/min) in Dobrudja, according to Gumbel distribution.

Weather station	Duration						Return period (years)
	5 min	10 min	30 min	1 hr	3 hr	24 hr	
Adamclisi	1.120	0.832	0.496	0.320	0.149	0.029	2
Cernavodă	1.355	0.998	0.516	0.318	0.144	0.027	
Constanța	1.205	0.922	0.518	0.319	0.143	0.025	
Corugea	1.420	1.019	0.540	0.335	0.141	0.024	
Gorgova	1.267	0.992	0.549	0.337	0.138	0.022	
Gura Portiței	1.065	0.819	0.434	0.269	0.124	0.023	
Hârșova	1.325	0.938	0.488	0.305	0.140	0.027	
Jurilovca	1.100	0.844	0.472	0.277	0.123	0.024	
Mangalia	1.246	0.982	0.546	0.339	0.149	0.027	
Medgidia	1.429	1.116	0.629	0.391	0.167	0.029	
Sf. Gheorghe	1.298	1.022	0.585	0.383	0.155	0.027	
Sulina	0.964	0.721	0.373	0.227	0.097	0.018	
Tulcea	1.383	1.029	0.566	0.342	0.149	0.027	
Adamclisi	1.986	1.437	0.888	0.582	0.266	0.050	10
Cernavodă	2.199	1.655	0.861	0.537	0.249	0.051	
Constanța	2.077	1.616	0.920	0.557	0.245	0.045	
Corugea	2.704	1.942	1.042	0.635	0.253	0.041	
Gorgova	2.248	1.729	0.966	0.590	0.235	0.037	
Gura Portiței	1.903	1.459	0.764	0.463	0.215	0.037	
Hârșova	2.544	1.781	0.926	0.581	0.268	0.050	
Jurilovca	1.854	1.440	0.836	0.494	0.220	0.043	
Mangalia	2.346	1.807	1.042	0.649	0.278	0.049	
Medgidia	2.343	1.829	1.065	0.663	0.285	0.050	
Sf. Gheorghe	2.459	1.922	1.165	0.778	0.309	0.053	
Sulina	1.600	1.233	0.633	0.382	0.159	0.031	
Tulcea	2.320	1.778	1.019	0.616	0.264	0.048	
Adamclisi	3.066	2.192	1.378	0.908	0.411	0.076	100
Cernavodă	3.252	2.474	1.292	0.810	0.379	0.079	
Constanța	3.165	2.481	1.421	0.855	0.371	0.071	
Corugea	4.306	3.093	1.667	1.009	0.392	0.064	
Gorgova	3.472	2.649	1.486	0.905	0.357	0.056	
Gura Portiței	2.948	2.258	1.175	0.706	0.328	0.056	
Hârșova	4.065	2.832	1.474	0.924	0.427	0.078	

Weather station	Duration						Return period (years)
	5 min	10 min	30 min	1 hr	3 hr	24 hr	
Jurilovca	2.794	2.183	1.290	0.764	0.341	0.067	
Mangalia	3.718	2.835	1.661	1.036	0.438	0.077	
Medgidia	3.483	2.719	1.609	1.001	0.432	0.077	
Sf. Gheorghe	3.907	3.044	1.887	1.271	0.502	0.085	
Sulina	2.393	1.871	0.957	0.575	0.236	0.048	
Tulcea	3.490	2.712	1.584	0.958	0.409	0.073	

For durations of 30, 60 and 1440 minutes (24 hrs), the highest probable intensity in return periods of 10, 20, 50 and 100 years is specific to the Danube Delta, respectively the Sf. Gheorghe Deltă w.s. It should also be noted that the other extreme (the lowest) intensity has also been estimated in this area, at Sulina station.

A summary of the results obtained in this paper is shown in **Table 4**.

Table 4.

Summary of extreme sub-daily rainfall amounts in Dobrudja, Romania (1948-2022).

No	Weather station	Maximum rainfall amounts (mm) and their trend[1] for each duration							
		5 min	10 min	30 min	1 hr	3 hr	6 hr	24 hr	24 hr CD[2]
1	Adamclisi	▼ 15.5	▽ 23.5	▽ 43.5	▽ 52.0	▼ 70.9	△ 81.0	△ 116.4	83.3
2	Cernavodă	▼ 18.4	◯ 23.9	△ 35.0	△ 47.3	△ 94.0	△ **144.2**	△ 155.5	155.5
3	Constanța	▲ 15.0	▲ 23.0	▲ 44.8	▲ 54.2	△ 74.1	△ 127.1	△ **206.0**	201.0
4	Corugea	17.8	31.1	51.7	57.1	74.1	75.5	86.5	86.8
5	Gorgova	△ 18.6	△ 27.4	△ 45.8	△ 51.9	△ 74.9	△ 76.2	▲ 76.2	87.0
6	Gura Portiței	△ 10.0	△ 15.8	▲ 33.3	▼ 53.6	▽ 65.9	▽ 66.4	▽ 93.3	69.0
7	Hârșova	**21.3**	26.9	43.8	59.4	97.2	97.2	97.2	96.7
8	Jurilovca	12.0	21.7	52.0	**85.4**	106.0	107.0	107.4	79.9
9	Mangalia	▲ 20.4	△ **31.4**	△ **56.7**	△ 64.3	△ 70.7	△ 114.6	▽	127.7
10	Medgidia	▼ 16.7	▼ 24.7	▼ 47.2	▼ 70.2	▽ 84.3	▽ 84.8	▽ 90.4	84.6
11	Sfântu Gheorghe Deltă	16.0	24.5	53.0	81.8	97.1	102.7	110.4	121.8
12	Sulina	▼ 11.2	▼ 18.0	▽ 27.4	▽ 31.2	▽ 40.1	▽ 46.9	▼ 76.1	84.9
13	Tulcea	▼ 17.5	▼ 26.0	▼ 45.4	▲ 58.8	△ **108.1**	△ 114.4	△ 140.6	134.5

[1]*The precipitation amount trend is shown as follows: △ - upward trend, ▲ - significant upward trend, ◯ - no trend, ▼ - significant downward trend, ▽ - downward trend*

[2]*24 hr CD = the maximum 24 hr precipitation amount according to the WMO's calculation methodology (by using the Climatological Day); the shown results are calculated for the same time range, excluding the missing years in the sub-hourly dataset.*

5. DISCUSSION

The data used in this paper allowed a detailed analysis of rainfall extremes through a different methodological approach, i.e. the calculation of sub-daily and sub-hourly running rainfall amounts. If compared to the classical method of calculating the precipitation amounts, being used worldwide according to WMO's regulations (collected rainfall amounts in fixed time intervals), the method used in this study highlighted, in case of 8 out of 13 weather stations, higher amounts of precipitation, especially referring to maximum rainfall amounts that can be recorded in 24 hours (**Table 4**). At 3 weather stations, the difference between the two methods exceeded 20.0 mm (33.1 mm at Adamclisi, 27.5 mm at Jurilovca and 24.3 mm at Gura Portiței w.s.). Therefore, we can state that this method better describes extreme rainfall events from a quantitative point of view.

In fact, any automated measurement instrument may get out of service at some moment and because of this, there may appear situations when the sub-hourly dataset is really affected by technical issues. So, the data about certain rain episodes that have been recorded with the pluviograph or the automatic weather station can be lost, yet they can still be recorded with the classical rain gauge. The cases when the maximum rainfall amounts obtained through the running window method are lower than those obtained through the standard method are generally caused by the gaps in the database series and not by the method being used.

As regards the synoptic context in which the maximum rainfall amounts were recorded, it was observed that most events mentioned in the previous chapter usually occurred under the influence of cyclones located in the north of the continent and by their long-wave troughs or cut-off low systems extendeing towards or over Romania's territory and the western coast of the Black Sea. All these rainfall extremes were recorded during the summer months, when the greater atmosphere's instability favored the convective development of hot and humid air-masses. Moreover, the orientation of the troughs in the NW-SE direction at the 500 hPa level was facilitating the transport of moist air from the Black Sea to the inland coast, thus creating a favorable context for the development of cumulonimbus clouds with great vertical extent.

6. CONCLUSIONS

This study provides a different approach in analyzing extreme rainfall events, by taking into consideration a new dataset and methodology (the running rainfall sums on continuous specific durations), so that our results could better highlight the apparently paradoxical contrast between the scarcer annual rainfall amounts and the extreme sub-daily rain intensities in Dobrudja, Romania. In this respect, the NMA's database was an invaluable resource for this research, in shaping the sub-daily regime of extreme rainfall amounts. Thus, the pluviograph recordings showed that heavy rainfalls / downpours can occur in Dobrudja with intensities exceeding 4 mm/min only at sub-hourly temporal scale. Moreover, in certain synoptic contexts, when there is a great thermal gradient between air masses (such as the long-wave troughs or the cut-off low systems), the maximum rainfall amount ever recorded in Dobrudja from 1948 to 2022 reached as high as 10 mm in 1 minute, despite the fact that Gumbel's extreme value distribution showed that such extreme intensities are expected only once in a century.

The trend analysis has been performed for a number of 9 out of 13 weather stations, but the results are pretty uncertain. Four weather stations have a clear trend, upward or downward respectively, while at five other stations the trend varies, depending on the duration. It has been observed that the precipitation trend is mainly upward on the Black Sea coast for sub-hourly durations and downward for the maximum 24 hrs amount. However, at Constanța weather station, the trend is only upward. In recent years, the surroundings of the weather stations got intensely urbanized, thus the station has currently become more representative of the urban climate. This might be a logical reason for this station to have a different precipitation trend, as compared to the other coastal stations.

Certainly, this hypothesis should be subject of further research in order to be validated. Similarly, other trends could also be explained on the grounds of the local conditions in which the the weather stations are sited. It might also be the case of Sulina, as the station is located off the Black Sea shore.

Overall, this study aimed to be a useful information tool for the authorities of the Constanța and Tulcea counties, namely for rainwater management and flood vulnerability assessment, in order to improve resilience during extreme rainfall events. Our results might also be of interest to the water resources engineering sector, regarding feasibility studies on the development of water drainage systems or hydraulic structures. The IDF curves charts, as a product of Gumbel's estimates, are a valuable support for the latter mentioned sector.

ACKNOWLEDGEMENTS

The completion of this research paper would not have been possible without the support of Romania's National Meteorological Administration, which provided the dataset used for our analysis. We are grateful for all the informational and technical support that we received. In addition, we would like to thank to all the colleagues in the Department of Climatology who contributed to the digitization and the quality control process of the analysed dataset. We would also like to express our gratitude to Assoc. Prof. PhD Lucian Sfîcă (Alexandru Ioan Cuza University of Iași) for his advice, guidance and support throughout the research process.

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