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Risk of Natural Hazards Caused by Extreme Precipitation in Poland in 1951–2020

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Abstract: Extreme precipitation of a minimum daily value of >30 mm often initiates natural hazards such as floods, which in turn may not only lead to property damage but also present a danger to people's health and lives. This paper mainly focuses on examining the trends and frequency of extreme daily precipitation (EDPr) in Poland. Also, it determines natural risk zones caused by EDPr of >30 mm, >50 mm, >70 mm, and >100 mm. In Poland, a significant positive trend was found for EDPr > 30 mm, >50 mm, and >70 mm in September, and for EDPr >100 mm in May. The most frequently recorded EDPr in Poland was >30 mm, the frequency of which ranged from 0.04% in February to nearly 3% in July. EDPr of >100 mm was recorded in 4 months, from May to August. An increase in the frequency of monthly EDPr in Poland occurred mainly in the southwestern and western parts. In Poland, three hazard zones of various frequencies of EDPr events were determined. In Zone III, which is in the southwestern and southern parts of the country, EDPr events occurred far more often than in Zone I; on average, four times more in the spring–summer season and slightly more than five times more in the autumn–winter season. The obtained results may help in the building of modern management and monitoring systems for the prevention of natural hazards caused by extreme precipitation.

Keywords: climatic risks; climate change; precipitation variability; type and level of natural hazard; meteorological event

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Citation: Kalbarczyk, R.; Kalbarczyk, E. Risk of Natural Hazards Caused by Extreme Precipitation in Poland in 1951–2020. *Water* **2024**, *16*, 1705. https://doi.org/10.3390/w16121705

Academic Editor: Francesco De Paola

Received: 11 May 2024
Revised: 7 June 2024
Accepted: 14 June 2024
Published: 15 June 2024

1. Introduction

In the climatology literature, many studies are devoted to pluvial conditions and their variability [1–5], whereas there are far fewer studies on the frequency and variability of extreme daily precipitation (EDPr) analyzed in the context of climate change and natural hazards [6–12]. Extreme daily precipitation (EDPr) is characterized not only by spatial and temporal variability, but also by a positive trend and an increase in intensity [12–18]. This increase in the frequency of extreme daily precipitation is on average twice as high on land than over the ocean [19]. In Scandinavia, daily and multi-day intense precipitation are likely to rise by 60% in 2071–2100 according to the RCP4.5 scenario, or even by 100% according to the RCP8.5 scenario [20]. On the other hand, by the end of the present century, in the north of Turkey the frequency of storms will have risen on average by 29% according to the RCP4.5 scenario, and by about 37% according to RCP8.5 [21]. In Central Europe, the biggest increase in intense precipitation by the year 2100 will occur in the winter season. Most probably, this increase will be caused by a positive trend of air temperature in winter due to climate change [20]. EDPr is becoming more intense due to higher levels of carbon dioxide in the atmosphere and a resulting increase in mean global temperatures, and due to the relationships described by the Clausius–Clapeyron equation [12,22]. EDPr events in Poland are observed most frequently during advection from western sectors [23,24]. In both the cold and warm seasons of the year, such events are related to increased water vapor in the air [23].

Wet periods in southern Poland, including EDPr events, occur mainly with a cy-clonic circulation during advection from N to NE in the lower part of the troposphere [25–27]. In southern Poland, heavy precipitation and massive airflows from the N–NE are often accompanied by mid-tropospheric advection from the sector S [28]. High precipitation over plains may only be caused by cell storms with high water content [29]. In rising humid air, latent heat is released when the dew point is reached, which is additionally reinforced by updraughts. In the mature stage of a storm cell, a clearly separated zone of precipitation with a downburst occurs. The same amount of precipitation and sometimes even the same intensity lead to different natural hazards, such as floods [30], in different geographical regions of the world. EDPr may also negatively impact people's lives and damage their property [12,31]. Therefore, various criteria that determine the level and type of hazard are adopted in relation to the amount of extreme daily precipitation. For example, to assess the risk of flood in South Yorkshire in Great Britain, a daily precipitation threshold of over 50 mm was chosen [22]. Also, Ma et al. [32] adopted a threshold of ≥50 mm/day for very heavy precipitation in China. In turn, Goswami et al. [13] and Roxy et al. [16] assessed the frequency of extreme daily precipitation in India at a threshold of ≥150 mm. Wypych et al. [28] analyzed extreme daily precipitation events in the Polish Carpathians that exceeded 30 mm, 50 mm, and 100 mm. For Poland, Lorenc et al. [33] used EDPr thresholds equal to or exceeding 30 mm, 50 mm, 70 mm, and 100 mm. Exceeding these precipitation thresholds may have a negative effect on society, economy, and the environment. Natural hazards caused by exceeding the determined thresholds are described in Table 1. Extreme precipitation is also defined as a daily sum exceeding the 95th or 99th percentile of a given time series, calculated separately for each station with a daily sum of ≥1 mm [14,34–36].

Table 1. Criteria and characteristics of natural hazards caused by extreme daily precipitation.

Hazard Level	Hazard Type	Criterium	Selected Effects of Activity *
I	Waterlogging	>30 mm/day	There are local floods of low-lying terrain and facilities. Standing water collects in the streets and on non-porous surfaces, erosion and surface run-off occur, pedestrian and road traffic disruptions take place.
II	Threatening flood	>50 mm/day	Rainwater starts to form "streams" in certain places. There are surface floods of terrain and low-lying facilities. First considerable infrastructure damage in towns and villages occurs, ponds are formed on farmland, soil around tree roots is washed away, and there are possible mudslides.
III	High flood risk	>70 mm/day	Water absorption by the ground is limited. Storm drains and sewer systems in cities do not manage to drain water. Torrents are formed on steeply sloping terrain, destroying everything in their way, soil under railway and tramway tracks is washed away and landslides and mudslides occur.
IV	Catastrophic flood	>100 mm/day	Intense, uncontrolled flow of rainwater into rivers occurs. The area around watercourses is flooded and whole infrastructure elements are destroyed, including bridges. These are natural disasters during which people lose their lives. Help from organized rescue units is required. Care for victims from government administration bodies is necessary.

Note: * According to Lorenc et al. [33].

Estimation of the number of extreme daily precipitation events is of great importance for prevention and management of floods, design of hydraulic structures (e.g., dams, spillways, and embankments) and municipal sewage systems [9,17,20,31,37,38]. EDPr may also play a significant role in the occurrence of other natural hazards, e.g., hydric erosion caused by storm precipitation, which may increase in Europe by 18% by 2050, landslides, and mudslides [39].

The study puts forward a working hypothesis that the frequency of extreme daily precipitation exceeding the adopted thresholds of 30 mm, 50 mm, 70 mm, and 100 mm will increase due to climate change, which is highly likely to contribute to a higher risk of natural hazards in Poland. The aim of the study is to learn about the variability of extreme daily precipitation (EDPr) in Poland, including its trends and frequency, and to determine the natural risk zones caused by EDPr events.

2. Materials and Methods

The study uses daily precipitation sums from January to December in 1951 to 2020. The precipitation data were collected at 74 meteorological posts and stations (Figure 1) and were made accessible by the Institute of Meteorology and Water Management, State Research Institute, Warsaw (acronym: IMGW-PIB, https://www.imgw.pl/instytut/imgw-pib, accessed on 24 April 2023). Weather monitoring, including precipitation conditions, was conducted according to the rules accepted by the World Meteorological Organisation. The time unit selected to analyze the amounts of daily precipitation was 'standard day' (24 h from 0600 hrs to 0600 hrs, according to Coordinated Universal Time (UTC)). Gaps in the input data were completed using measurements from the closest station that provided a full series of data. The missing values were calculated on the basis of available data from the three closest meteorological stations using interpolation based on inverse distance weighting [40]. The reliability of the results of this data completion was checked by comparing the statistical values of the original and the completed data, and their homogeneity was checked using the Browne–Forsythe test.

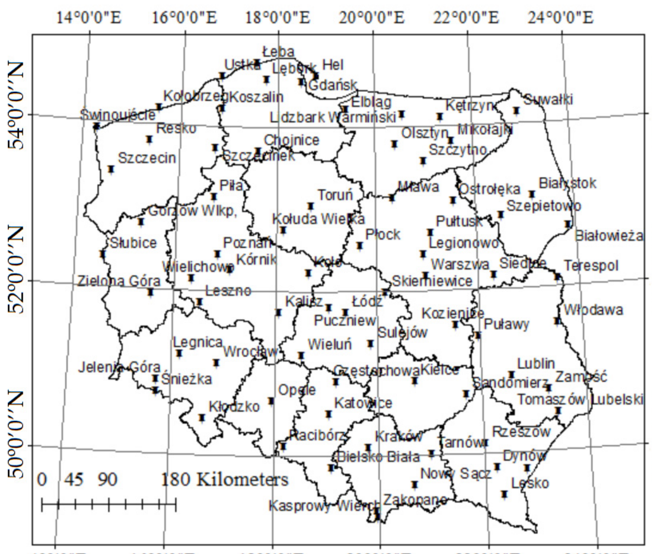

Figure 1. Location of meteorological stations used in the study.

To determine the possible risk of natural hazards caused by extreme daily precipitation (EDPr), the following thresholds were selected: >30 mm (Hazard Level I—waterlogging), >50 mm (Hazard Level II—threatening flood), >70 mm (Hazard Level III—high flood risk), and >100 mm (Hazard Level IV—catastrophic). Exceeding the precipitation thresholds can but does not always lead to the negative results described in Table 1. The adopted criterion is pragmatic in its nature and is in line with the thresholds determined by Lorenc et al. [33]. The thresholds described by Lorenc et al. [33] were specified based on the results observed with a certain amount of precipitation. To determine the thresholds, the researchers analyzed materials that characterise the intensity of precipitation on a similar scale and the effects which it causes in the climatic conditions.

Precipitation (Pr, mm) in the successive months of the analyzed multi-year period, 1951–2020, was characterized on the basis of two indices, the frequency of days with precipitation (% days a month) and the number of days with precipitation $\geq$ 0.1 mm (NDPr, day). On the other hand, daily precipitation sums amounting to $\geq$0.1 mm (dPr, mm) were examined by means of basic statistics, the mean (dPrx, mm) and the absolute maximum value (dPrmax, mm). The dPr trend in 1950–2020 as well as the number of days with extreme precipitation at the four selected thresholds (>30 mm, >50 mm, >70 mm and >100 mm) were determined with the use of the Mann-Kendall test at significance levels of 0.1, 0.05, and 0.01.

The potential risk of natural hazard (Table 1) was examined based on the frequency of extreme daily precipitation (>30 mm, >50 mm, >70 mm, and >100 mm), taking into account days with precipitation. The analysis was carried out not only for the whole multi-year period, 1951–2020, but also for particular years. The analysis of the multi-year period was based on months. On the other hand, the analysis of particular years was based on a whole year and on meteorological seasons. The following seasons were adopted in the study: winter (from 1 December to 28/29 February), spring (from 1 March to 31 May), summer (from 1 June to 31 August), and autumn (from 1 September to 30 November).

The zones exposed to the risk of natural hazard caused by heavy precipitation in Poland were determined on the basis of the number of days with extreme daily precipitation. The number of days with extreme precipitation was calculated for the four adopted thresholds. In Poland, three zones of different risk intensity were determined; low intensity was Zone I, medium intensity was Zone II, and high intensity was Zone III. The number of analyzed events at particular stations varied from 56 to 915. The data set of these events was divided into three groups with the use of geometrical interval classification. Each group of data represented one of the three determined zones of risk. Zone I included all the meteorological stations where the number of days on which extreme daily precipitation occurred in 1951–2020 did not exceed 81 (30th percentile). Zone II encompassed stations where the number of days with extreme daily precipitation ranged from 82 to 167. Finally, Zone III consisted of stations with at least 168 heavy precipitation events (90th percentile).

The spatial distribution maps of all the examined indices, statistics, the number of days with extreme daily precipitation in relation to the four adopted thresholds, and the zones at risk of natural hazards were prepared by means of inverse distance weighting using ArcGis 10.8.1. The spatial resolution of maps showing the administrative division grid of the 16 Polish Provinces (NUTS 2 in the Nomenclature of Territorial Units for Statistics) was 4×4 km.

Statistical analyses were conducted in STATISTICA 13.3 and Excel 2010 spreadsheet.

3. Results

3.1. Temporal and Spatial Distribution of Precipitation (Pr) and Number of Days with Precipitation of ≥0.1 mm (NDPr)

In Poland in 1951–2020, precipitation (Pr) was recorded least frequently in April and August, at frequencies of 40.4 and 40.7% days a month, respectively (Table 2). Pr occurred more often, i.e., >50%, in the autumn–winter period (from November to February), with a maximum in December (≈54% days a month).

Table 2. Characteristics of precipitation in Poland (on the basis of 74 stations). Years 1951–2020.

Statistics	Month											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
frequency of days with precipitation (%)	52.7	50.5	43.8	40.4	43.1	45.0	46.0	40.7	41.9	41.6	50.5	53.7
number of days with precipitation of ≥0.1 mm (day)	14.6	13.9	17.4	17.8	17.6	16.5	16.7	18.3	17.4	18.1	14.8	14.3

The variation in Pr frequency was also related to particular regions of Poland (Figure 2). Least often, at a frequency of <40% days a month, precipitation took place mainly in northern and central Poland in April and May, and in central-eastern and central Poland from August to October. Most frequently, at a frequency of >60% days a month, Pr was usually recorded only locally in some regions of Poland. Precipitation of a frequency of >60% days a month was observed locally in the southwestern part of the country in November, and also in the southwestern, southern, and northern parts in December. Pr of a frequency of >55% days a month was recorded in January and December, mainly in the north–west and west of the country.

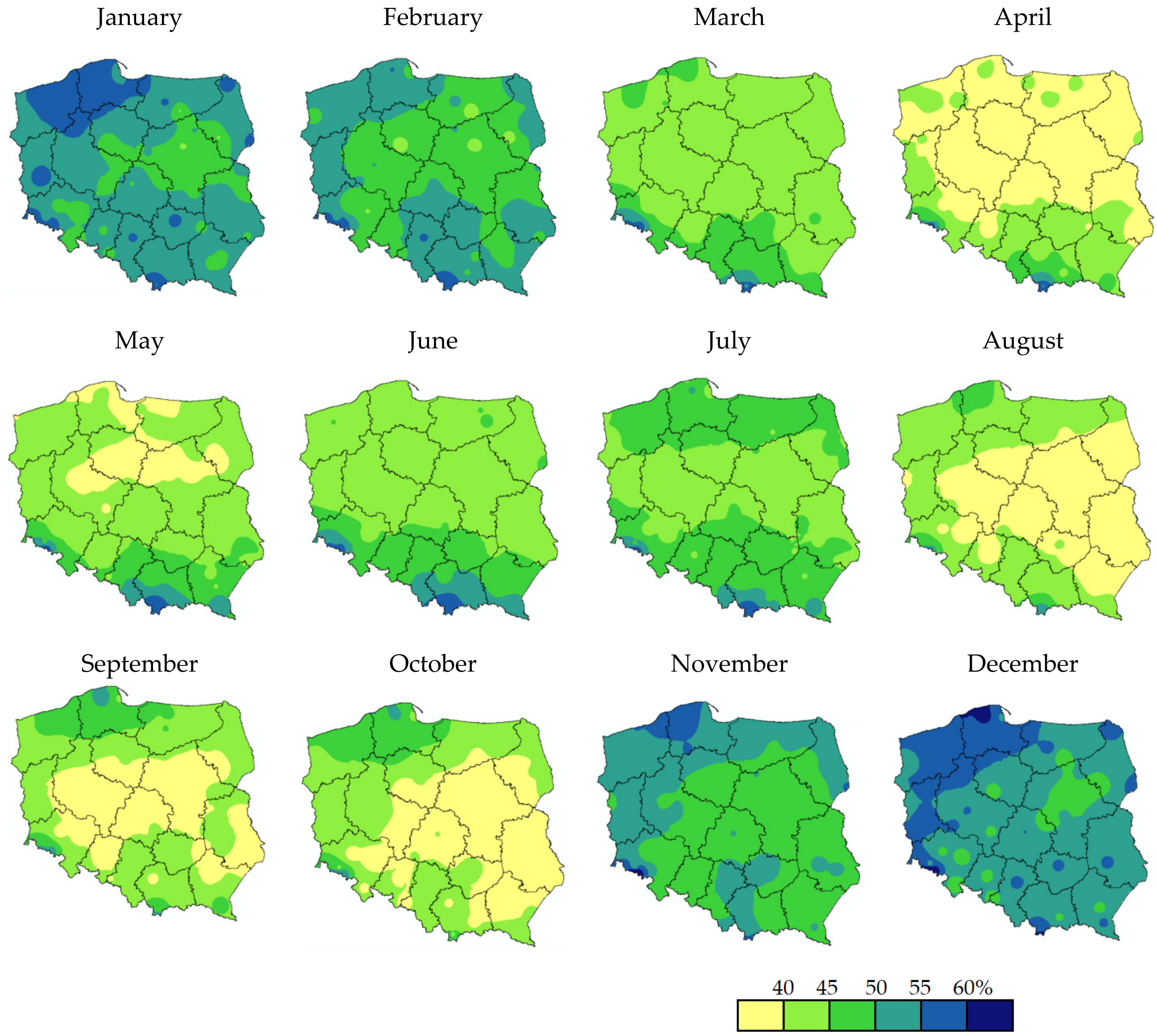

Figure 2. Spatial distribution of the frequency of days with precipitation in Poland. Years 1951–2020.

In Poland, the number of days with precipitation of ≥0.1 mm (NDPr) fluctuated on average from less than 14 days in February to more than 18 days in August and October (Table 2). The lowest NDPr, <10 days and <12 days, was observed predominantly in the northwestern, western, and southern parts of Poland from November to December (Figure 3). In the remaining months, that is from March to October, the lowest NDPr was recorded in the southwestern and southern parts of Poland; the highest NDPr, >18 days, was observed mainly in the central part of the country in March and September, but also in northern and central Poland in April and May, and in eastern and central Poland in August and October.

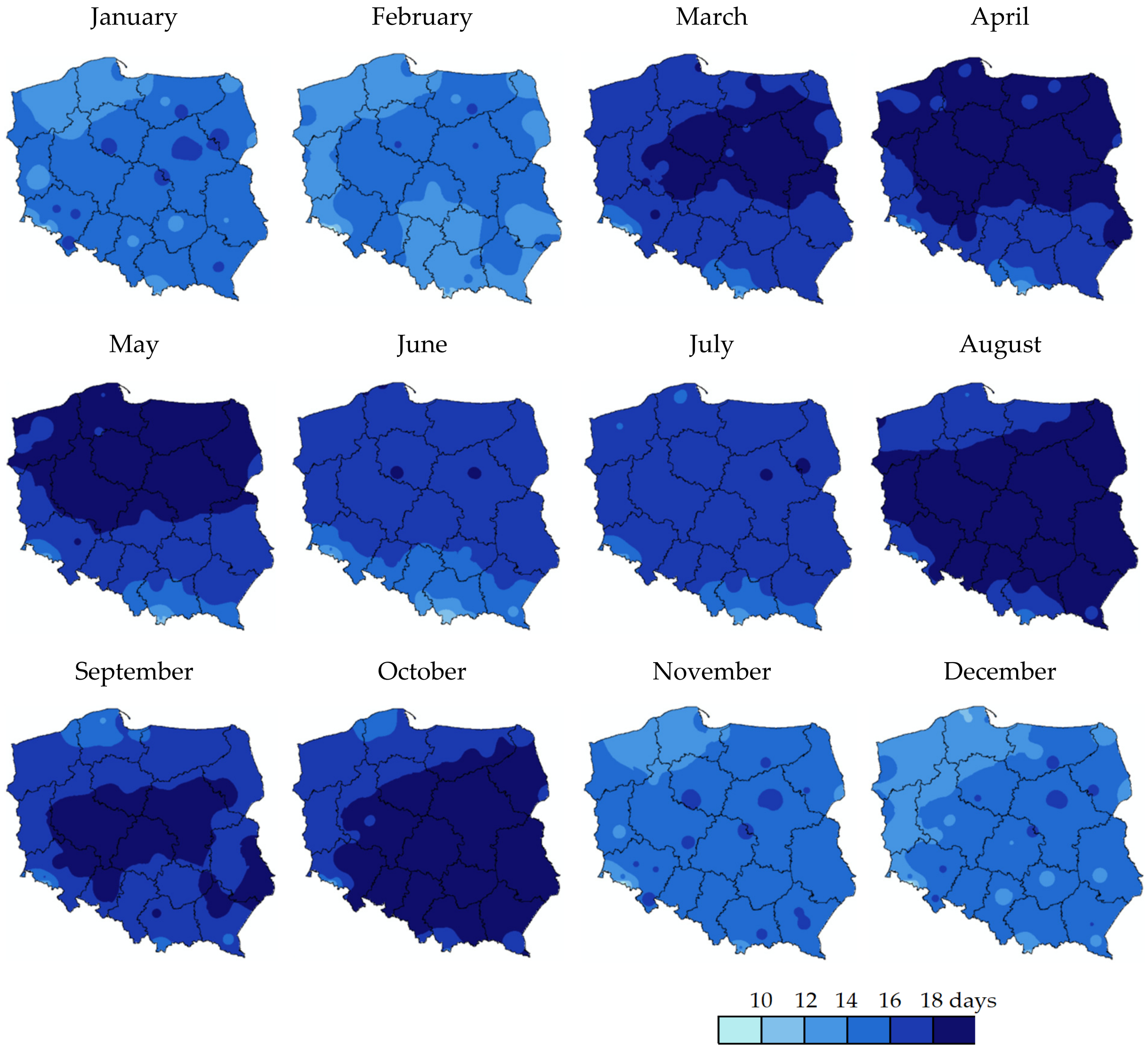

Figure 3. Spatial distribution of the number of days with precipitation in Poland. Years 1951–2020.

3.2. Characteristics of Average Daily Precipitation (dPrx) and Absolute Maximum Daily Precipitation (dPrmax)

Average multi-year daily precipitation (dPrx) in Poland, calculated for values of ≥0.1 mm, varied from 2.2 mm in January and February to 6.2 mm in July (Table 3). The lowest mean values of the dPrx index, amounting to <2 mm, occurred mainly in January and February in central-eastern and central Poland (Figure 4). The highest average values of the dPrx index, amounting to >11 mm, were recorded in the southern part of the country, mostly from June to August.

Table 3. Descriptive statistics of daily precipitation amounting to ≥0.1 mm in Poland (on the basis of 74 stations). Years 1951–2020.

Statistics	Month											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Average (mm)	2.2	2.2	2.6	3.3	4.7	5.6	6.2	5.7	4.5	3.6	2.9	2.6
Absolute maximum (mm)	65.3	76.4	53.2	81.6	162.7	232.0	167.6	147.4	100.5	93.1	70.8	59.4

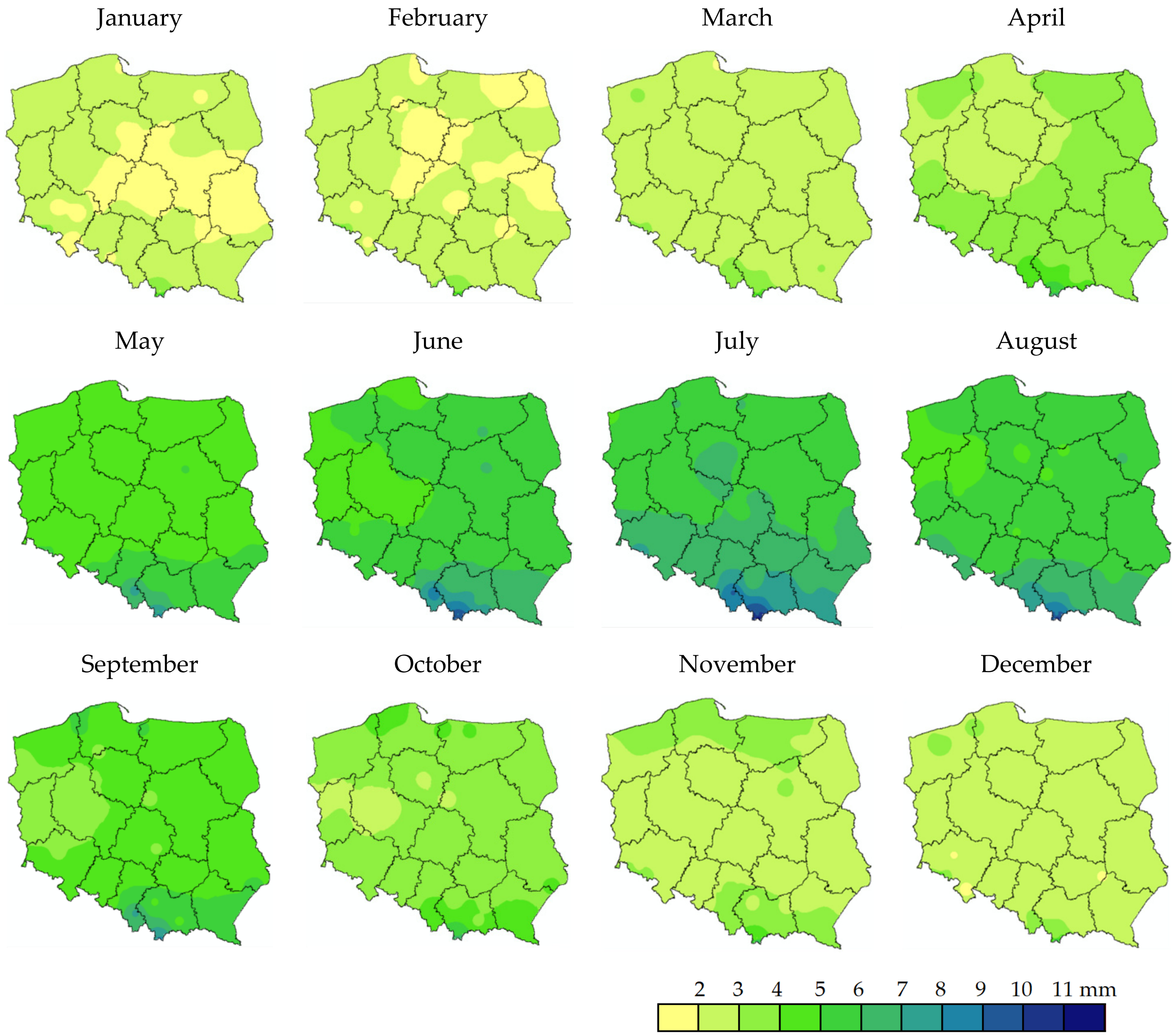

Figure 4. Spatial distribution of the average daily precipitation in Poland amounting to ≥0.1 mm. Years 1951–2020.

Absolute maximum daily precipitation (dPrmax) in Poland calculated only for values of ≥0.1 mm ranged from 53.2 mm in March to 232.0 mm in June (Table 3). As in the case of temporal distribution, the spatial distribution in Poland was very diverse (Figure 5). Absolute maximum dPrmax values of ≤20 mm were observed in various parts of the country; in central Poland in January, in eastern and central Poland in February, in central-eastern Poland in March, and in central and northeastern Poland in December. On the other hand, absolute maximum dPrmax values of >160 mm were recorded at meteorological stations located mainly in the southern part of the country from May to July, with dPrmax in June even exceeding 200 mm.

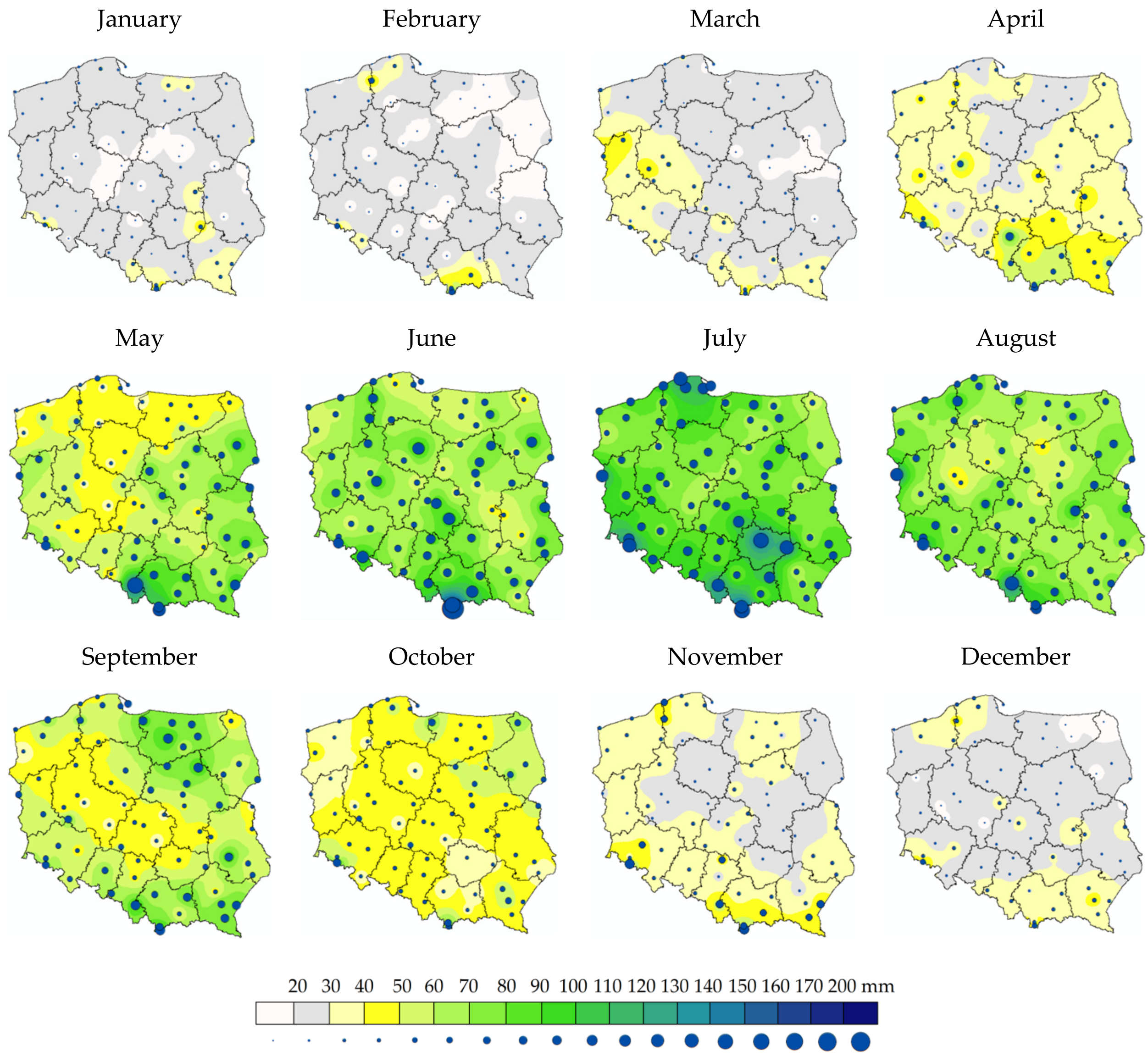

Figure 5. Spatial distribution of absolute maximum daily precipitation in Poland. Years 1951–2020.

3.3. Trend of Daily Precipitation (dPr) and Extreme Daily Precipitation (EDPr)

A negative trend of daily precipitation (dPr) for the whole country at a level of $p < 0.01$ was found with the use of the Mann-Kendall test only in the months of April and November, whereas a positive trend of dPr was proven only in October ($p < 0.1$) (Table 4). Due to the analysis of dPr at the level of individual meteorological stations, the largest number of significant negative trends was found in April, chiefly in western Poland, and in November in central and southern Poland, i.e., in similar months as for the whole country (Figure 6). On the other hand, a significant positive dPr trend at many meteorological stations was found not only for October, as for the whole of Poland, but also in January and March.

Table 4. Trend of daily precipitation (dPr) in Poland (on the basis of 74 stations). Years 1951–2020.

dPr (mm)	Month											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	n.s.	n.s.	n.s.	− ***	n.s.	n.s.	n.s.	n.s.	n.s.	+ *	− ***	n.s.

Note: n.s.—insignificant, ***—significant at a level of 0.01, *—significant at a level of 0.1, −/+—negative/positive trend.

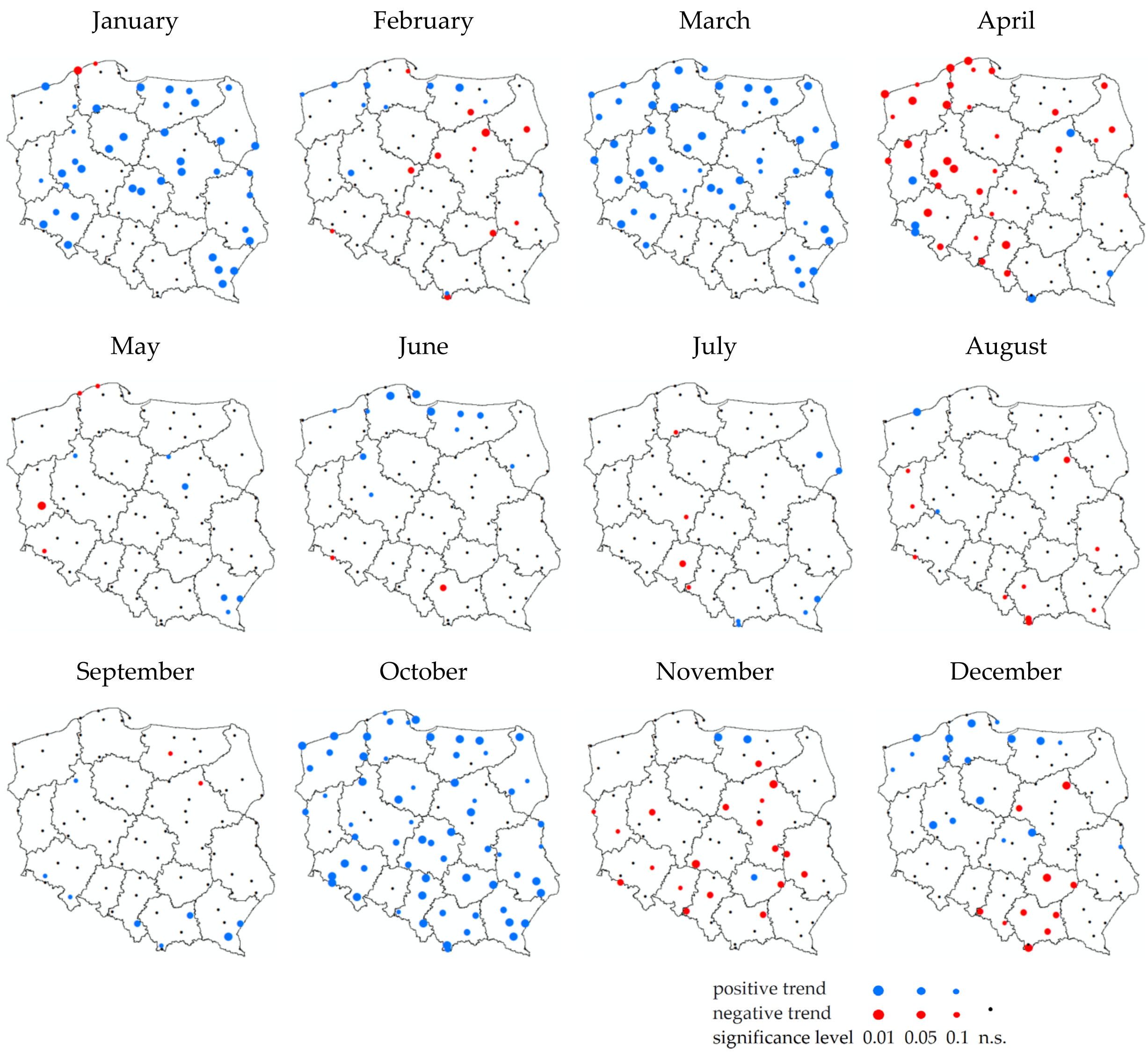

Figure 6. Spatial distribution of the trend of daily precipitation in Poland. Years 1951–2020.

A significant negative trend of extreme daily precipitation (EDPr) of >50 mm for the whole of Poland was found in three months, January, February, and November, whereas a negative trend of EDPr of >30 mm was found only in February (Table 5). A significant positive trend was statistically proven for EDPr of >100 mm in May, whereas a significant positive trend was proven in September for EDPr of >30 mm, >50 mm, and >70 mm.

Table 5. Trend of the number of days with extreme daily precipitation (EDPr) in Poland. Years 1951–2020.

EDPr (mm/day)	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
>30	n.s.	− *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+ ***	n.s.	n.s.	n.s.
>50	− **	− **	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+ ***	n.s.	− **	n.s.
>70	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+ **	n.s.	n.s.	n.s.
>100	n.s.	n.s.	n.s.	n.s.	+ **	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Note: n.s.—insignificant, ***—significant at a level of 0.01, **—significant at a level of 0.05, *—significant at a level of 0.1, −/+—negative/positive trend.

3.4. Frequency of Extreme Daily Precipitation (EDPr)

The frequency of extreme daily precipitation (EDPr) in Poland according to the selected thresholds (>30 mm, >50 mm, >70 mm, and >100 mm) was temporally (Figures 7 and 8) and spatially diverse (Figures 9–12). In 1951–2020, EDPr exceeding 30 mm, which can pose a flood risk, occurred with a frequency from 0.04% days with precipitation in February to about 3% days with precipitation in July (Figure 7). The frequency of days with extreme daily precipitation of >50 mm (with a potential risk of floods) on average amounted to 0.2% days with precipitation and varied from 0% in January, March, and December to approx. 0.7% in July. EDPr of >70 mm and >100 mm is much less frequently recorded in Poland. These levels may respectively lead to floods and natural disasters, with a frequency of 0.04% days with precipitation and 0.01% days with precipitation on average. EDPr of >70 mm was recorded in February and from April to November, whereas EDPr of >100 mm was observed only from May to September.

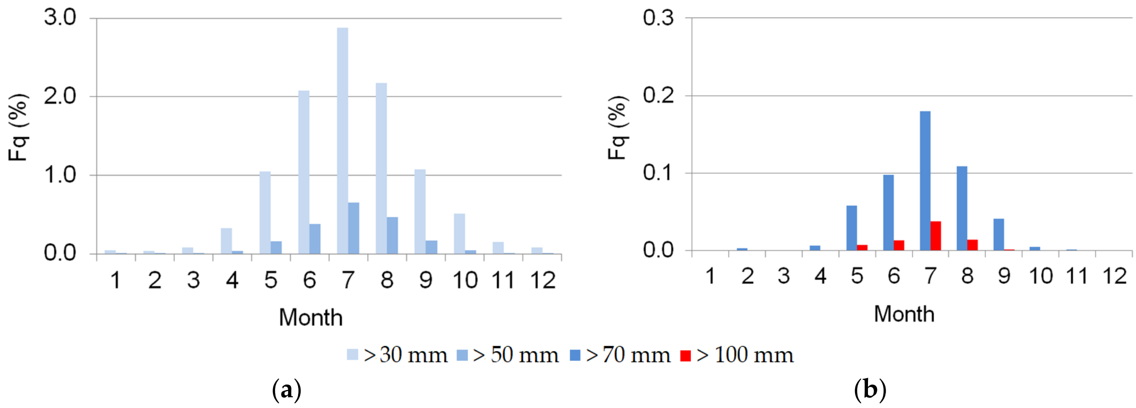

Figure 7. Frequency (Fq, %) of extreme daily precipitation, taking into account days with precipitation (**a**) >30 mm, >50 mm, (**b**) >70 mm, and >100 mm in Poland by months (on the basis of 74 stations). Years 1951–2020.

At the analyzed meteorological stations, in particular years of the examined multi-year period, extreme daily precipitation of >30 mm was most frequently recorded in 2010 (247 events, 1.82% days with precipitation), 1966 (177 events, 1.33%), 1980 (166 events, 1.19%), 1974 (165 events, 1.26%), and 1997 (161 events, 1.28%) (Figure 8a). EDPr of >50 mm was most frequently recorded in 2010 (65 events, 0.48% days with precipitation), 1966 (42 events, 0.32%), 2001 (41 events, 0.29%), 1970 (37 events, 0.25%), and 2016 (36 events, 0.28%). EDPr of >70 mm occurred most often in 2010 (19 events, 0.14% days with precipitation) and in 2001 (17 events, 0.12%), while EDPr of >100 mm occurred most frequently in 2001 and 1970 (four events in each year, 0.03% days with precipitation).

Out of the four analyzed seasons, EDPr events were most often observed in summer (on average, with a frequency of 3.05% days with precipitation), then in autumn (on average, with a frequency of 0.61% days with precipitation), in spring (on average, with a frequency of 0.57% days with precipitation), and least often in winter (on average, with a frequency of 0.06% days with precipitation) (Figure 8b–e). In summer, EDPr of >30 mm, >50 mm, >70 mm, and >100 mm was most often recorded in the following years, respectively; 2010 (155 events >30 mm, 5.30% days with precipitation), 2010 and 2001 (40 events in each year >50 mm, 1.37% and 1.17%), 2001 (16 events >70 mm, 0.47%), and 1970 (four events >100 mm, 0.15%) (Figure 8d). In autumn, EDPr according to the adopted thresholds was most often recorded in the following years: 1992 (>30 mm—55 events, 1.59% days with precipitation; >50 mm—16 events, 0.46%; >70 mm—six events, 0.17%) and 2001 (>100 mm—one event, 0.03% days with precipitation) (Figure 8e). In this season, EDPr of >30 mm also was frequently recorded in 1952 (51 events, 1.15% days with precipitation), 1974 (50 events, 1.37%), and 2020 (49 events, 1.59%). In spring, EDPr events were most often observed in 2010 (>30 mm—58 events, 1.62% days with precipitation; >50 mm—16 events, 0.45%; >70 mm—seven events, 0.20%; >100 m—two events, 0.06%) (Figure 8c). In winter, EDPr events of >30 mm occurred most frequently in 1966 and 1974 (eight times each, 0.23%) (Figure 8b). EDPr > 50 mm was recorded only in individual cases (0.02–0.04% days with precipitation). One event with EDPr > 50 mm per season was recorded in the following years: 1952, 1956, 1957, 1962, 1966, 1973, 1974, 1981, 1982, and 1985. Also, EDPr of >70 mm was observed only in individual cases (0.03% days with precipitation) in 1962 and 1973. In winter, EDPr events of >100 mm were not recorded in any of the analyzed years.

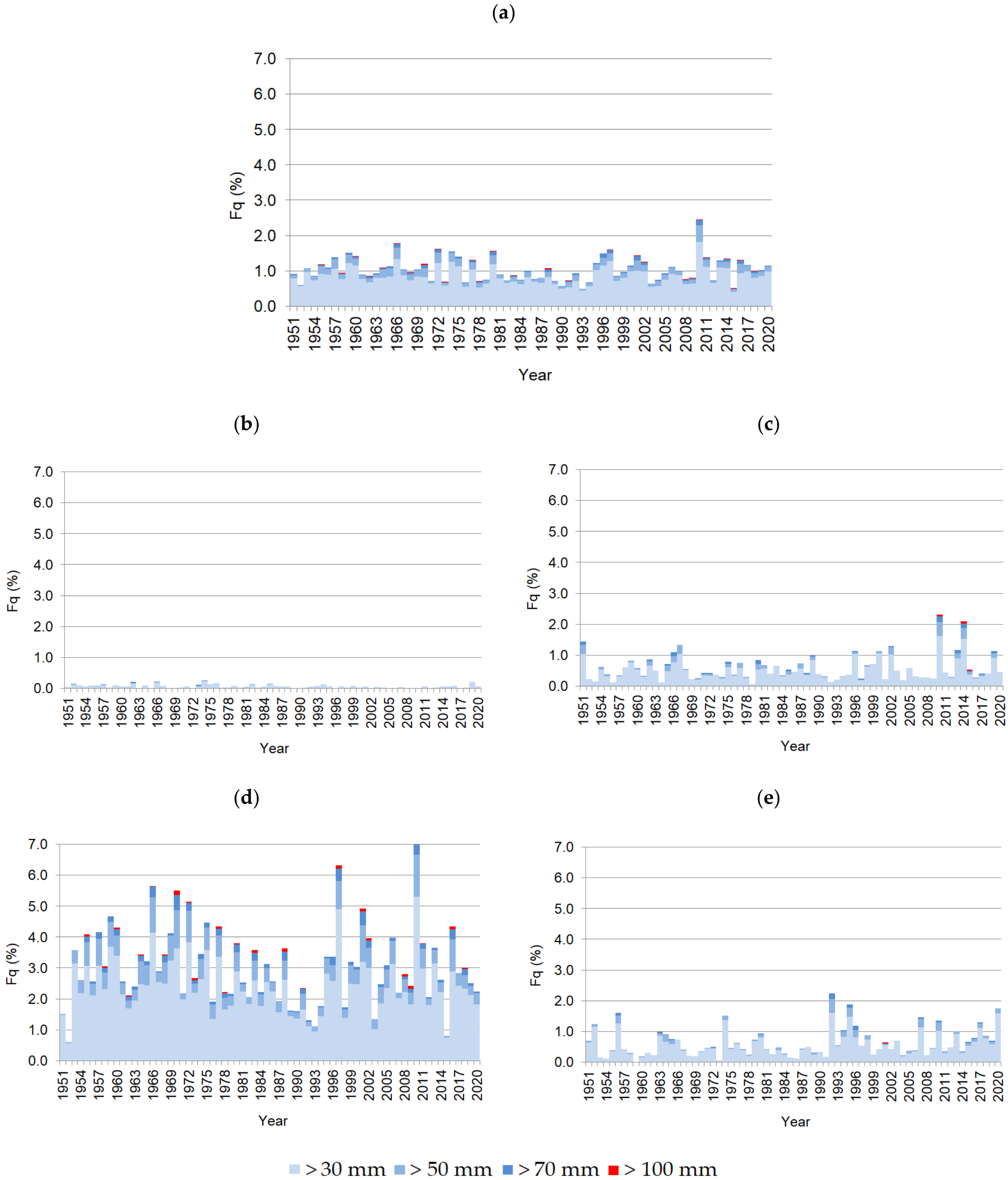

Figure 8. Frequency (Fq, %) of extreme daily precipitation in Poland in the successive years of the multi-year period 1951–2020, taking into account days with precipitation; year (**a**), winter season (**b**), spring season (**c**), summer season (**d**), and autumn season (**e**).

The spatial distribution of the number of days with extreme daily precipitation of >30 mm (potentially generating Hazard Level I) in Poland was very diverse (Figure 9). The number of days with such events varied from 0 to slightly >110. Days with extreme daily precipitation of >30 mm did not take place from January to March and in December in most parts of Poland, also in April in northern and central Poland, and in November in central and northeastern Poland. Slightly more than 110 days with extreme daily precipitation of >30 mm were recorded only in July in southern Poland. The number of EDPr events of >30 mm noticeably increased from April to July, mainly in southern Poland. In August, the number of events with EDPr of >30 mm was smaller in comparison with the number of such events in July, fluctuating from <10 events in northern and central Poland to 90 events in southern Poland. In September and October in most parts of Poland, there were from 1 to 10 events with EDPr of >30 mm; however, there were slightly more in September, as from 11 to 20 events were recorded in northern and southwestern Poland. In addition, 21 to 60 events with EDPr of >30 mm were observed in September in the southern part of the country. On the other hand, 21 to 30 events with EDPr of >30 mm were recorded in October in south Poland.

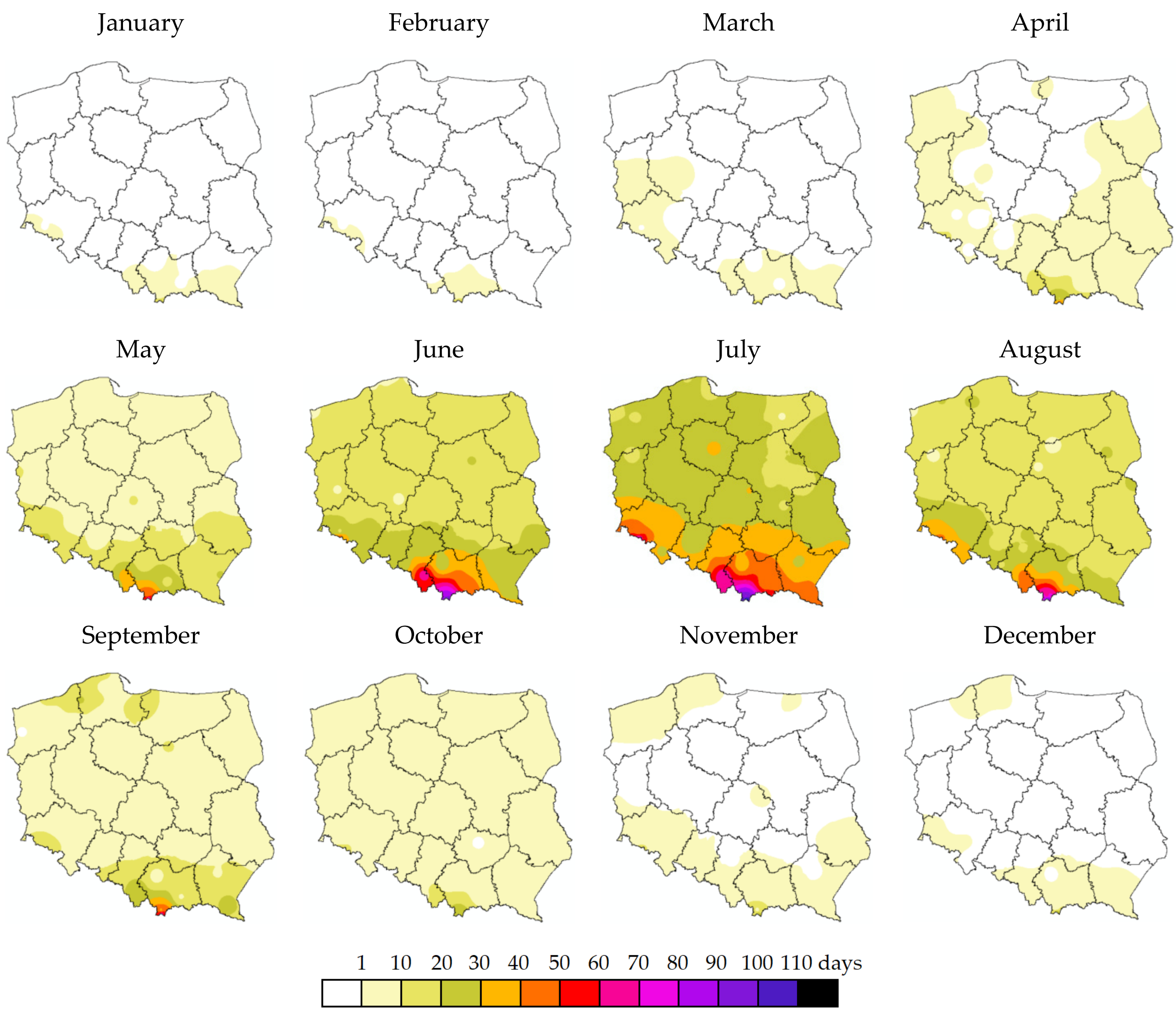

Figure 9. Spatial distribution of the number of days with extreme daily precipitation of >30 mm (Hazard Level I) in 1951–2020.

EDPr of >50 mm (events of potential Hazard Level II) was not recorded in any of the analyzed IMGW-PIB stations in March and December (Figure 10). From 1 to 10 events with

EDPr of >50 mm were recorded in four months, January, February, October, and November, but in January and February they were observed at only one station located in the south. From June to August, events with EDPr of >50 mm most often took place 1 to 10 times in most parts of the country. In the same period, up to 50 events with EDPr of >50 mm were observed in southern Poland. In May and September, the number of events with EDPr of >50 mm varied from 0 to 20. A bigger number of such events, not only >1 but also >10, occurred in southern Poland. On the other hand, more than 1 event with EDPr of >50 mm was also recorded in central-western and central-eastern Poland in May and in northern and northeastern Poland in September. EDPr of >70 mm (potential Hazard Level III) was observed in eight months, mainly in spring and summer (Figure 11). Events with EDPr of >70 mm took place 20 times in total in the examined multi-year period. Most often, they occurred in southern Poland. The biggest area of the country affected by such events in July covered the southern, northern, and central-western parts. In August, events with EDPr of >70 mm were chiefly observed in southern and south-western Poland, whereas in June and May they occurred in a smaller area, mainly in the south.

EDPr of >100 mm (potential Hazard Level IV) was recorded only in four months of the warm season, i.e., May to August (Figure 12). The number of such events did not exceed ten. In the period from May to August, they were recorded predominantly in southern Poland, and additionally in July and August, also in southwestern Poland.

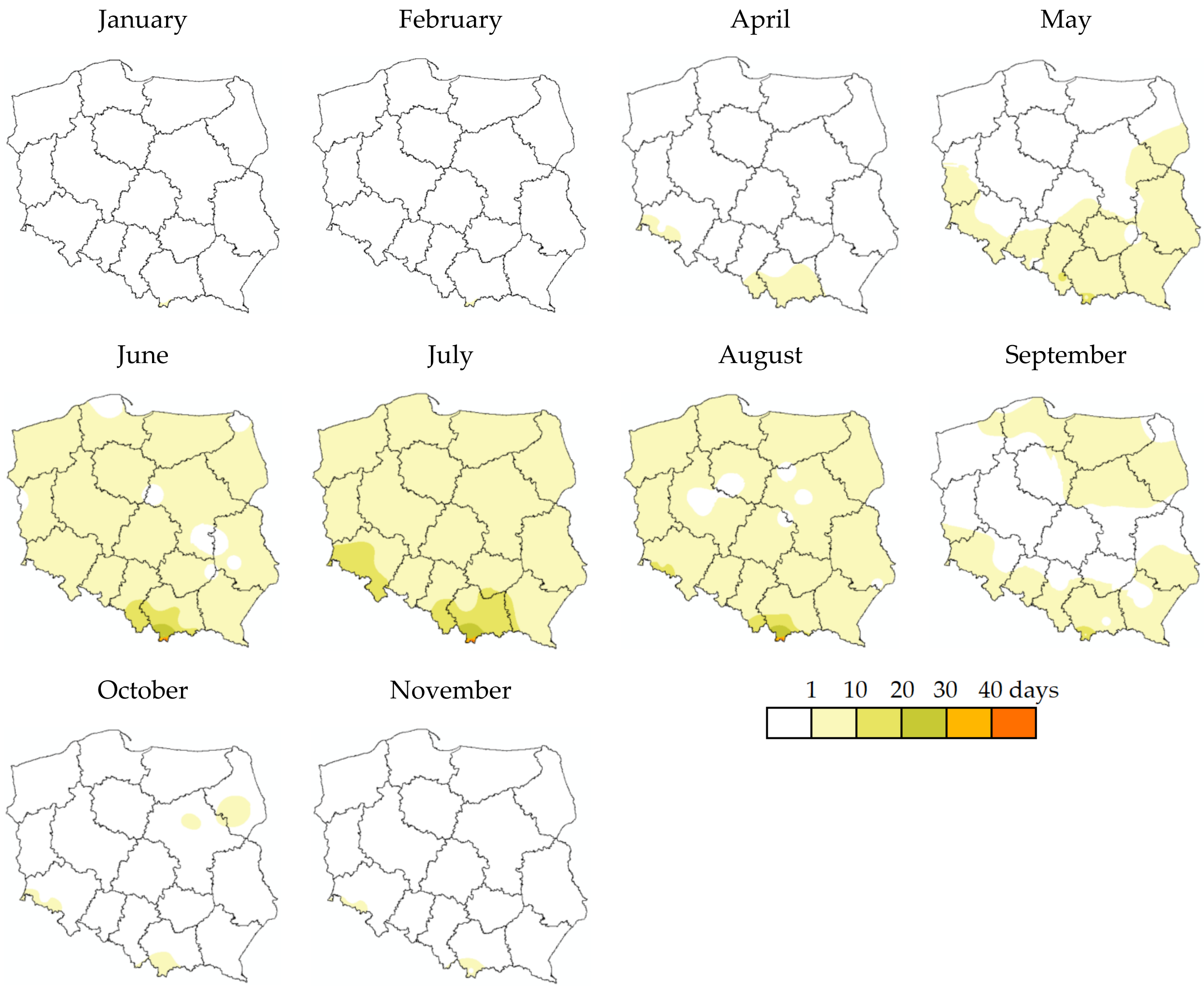

Figure 10. Spatial distribution of the number of days with extreme daily precipitation of >50 mm (Hazard Level II) in 1951–2020.

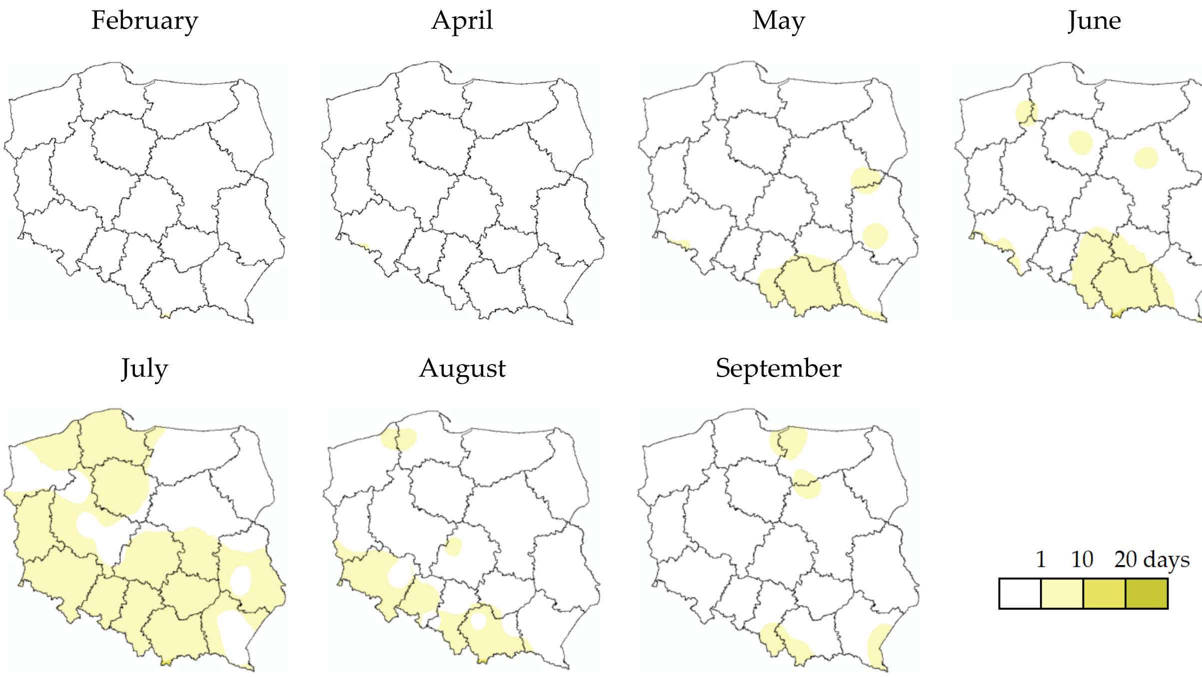

Figure 11. Spatial distribution of the number of days with extreme daily precipitation of >70 mm (Hazard Level III) in 1951–2020. In the months of January, March, October, November, and December, only single EDPr events > 70 mm occurred.

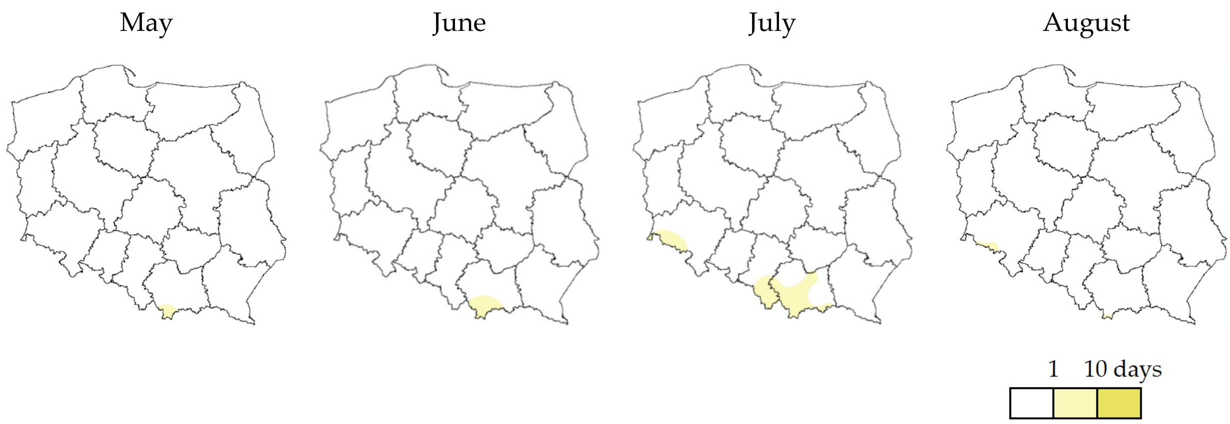

Figure 12. Spatial distribution of the number of days with extreme daily precipitation of >100 mm (Hazard Level IV) in 1951–2020. In the months from January to April and from September to December, only single EDPr events > 100 mm occurred.

In March and December, only a few EDPr events > 50 mm occurred.

3.5. Extreme Daily Precipitation (EDPr) Hazard Zones

Three hazard zones caused by extreme daily precipitation (EDPr) were determined for Poland (Figure 13). The zone of Hazard Level I, i.e., low risk, covered approx. 25% of Poland, mainly the northwestern, northeastern, and central parts. Hazard Level II, that is, medium risk, covered up to 62.5% of the country. The smallest area, encompassing approx. 12.5%, was Hazard Level III, i.e., high risk. Hazard Level III covered the southwestern and southern parts of the country. The average multi-annual sum of days in the spring–summer season for the whole country amounted to 80.9 for a threshold of >30 mm, 16.2 for >50 mm, 4.3 for >70 mm, and 0.7 for >100 mm (Table 6). On the other hand, in the autumn–winter season, the average multi-year sum of days with EDPr events amounted to

17.6 for a threshold of >30 mm, 2.1 for >50 mm, 0.4 for >70 mm, and 0.0 for >100 mm. In the three determined risk zones, the average number of days with EDPr of >30 mm in the spring–summer season varied from 50.2 in Zone I to 181.8 in Zone III. In the autumn–winter season, the average number of days with EDPr of >30 mm fluctuated from 9.8 in Zone I to 49.2 in Zone III. At higher thresholds of EDPr, i.e., >50 mm and >70 mm, the average number of days with such events was also higher. The average sum of days with EDPr of >50 mm and >70 mm was observed to be on average just over nine times higher in the spring–summer season than in the autumn–winter season. Events with EDPr >50 mm in the spring–summer season were from six times more often in the case of Zone III to approx. 11 times more often in the case of Zone I than the same type of events in the autumn–winter season. Events with EDPr of >70 mm in the spring–summer season were from nine times more frequent in the case of Zone III to nearly 14 times more frequent in the case of Zone II than these events in the autumn–winter season. The average number of days with EDPr of >100 mm ranged from 0.1 in Zone I to 3.5 in Zone III in the spring–summer season and from 0.0 in Zones I and II to 0.1 in Zone III in the autumn–winter season.

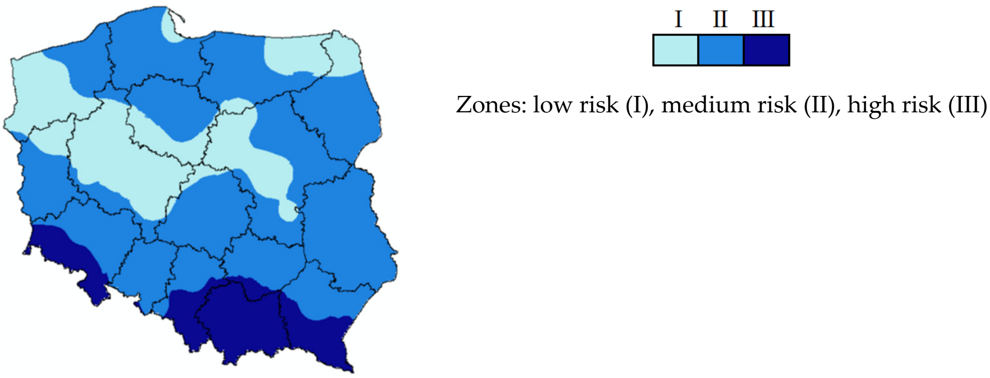

Figure 13. Zones of natural hazard caused by extreme daily precipitation in Poland. Years 1951–2020.

Table 6. Characteristics of the natural hazard zones caused by extreme daily precipitation in Poland. Years 1951–2020.

Natural Hazard Zone	Country's Area	Average Sum of Days with Precipitation in the Spring–Summer Season (from March to August)				Average Sum Days with Precipitation in the Autumn–Winter Season (from September to February)			
	(%)	>30 mm	>50 mm	>70 mm	>100 mm	>30 mm	>50 mm	>70 mm	>100 mm
I—low	25.0	50.2	8.0	1.7	0.1	9.8	0.7	0.2	0.0
II—medium	62.5	70.9	12.3	2.7	0.3	13.4	1.3	0.2	0.0
III—high	12.5	181.8	47.6	15.3	3.5	49.2	8.2	1.7	0.1
∑ or x̄	100.0	80.9	16.2	4.3	0.7	17.6	2.1	0.4	0.0

4. Discussion

Natural hazards caused by forces of nature that affect people and their environment include weather anomalies like extreme daily precipitation (EDPr) [12,33,41]. EDPr events may lead, for example, to floods and mudslides. As a consequence of these events, technical failures and disasters may occur, which in turn often give rise to big losses for society and the economy [9,12,17,20,31,37,38]. Scientific reports show an increased risk caused by extreme meteorological phenomena in recent years in different regions of the world, including intense precipitation [13,15,21,39,42]. Nevertheless, there are still not enough publications on the temporal and spatial variability of EDPr in different climatic zones, particularly in the warm temperate transitional zone to which the present study is dedicated.

Various indices are used to assess extreme precipitation in the context of natural hazards, e.g., a daily sum exceeding the 95th or 99th percentile of a given time series, calculated separately for each station with a daily sum of ≥1 mm [14,34–36], or various amounts of precipitation; ≥30 mm/day, ≥50 mm/day, ≥70 mm/day, and ≥100 mm/day [13,16,22,28,32,33], i.e., with thresholds similar to these of the present study. As pointed out by some scientists [43–45], EDPr events could be characterized much better if researchers had at their disposal not only the amount of precipitation, but also its duration. However, acquisition of such data covering long multi-year periods of at least 70 years from several dozen stations in the whole country is almost impossible.

In the specialist literature, extreme daily precipitation (EDPr) events are often explained by synoptic situations [33]. EDPr has different origins but also different ranges, spatial distributions, durations, and intensities [46]. These characteristics can affect the extent and type of natural hazard in a given place or region, as has been shown in many research papers, e.g., Vörösmarty et al. [47], Panagos et. al. [39], Blenkinsop et al. [48], Wang and Nguyen [49].

On the basis of data from 1951–2020, the present paper shows a positive trend of events with EDPr of >30 mm/day, >50 mm/day, and >70 mm/day in September and >100 mm/day in May. These results are partially confirmed in the research study by Lorenc et al. [33]. According to Lorenc et al. [33], in 1991–2002 there was an increase in the number of days with precipitation of ≥50 mm/day in southern Poland. Lorenc et al. [33] also found the highest frequency of events with EDPr of ≥30 mm/day, ≥50 mm/day, ≥70 mm/day, and ≥100 mm/day in southwestern and southern Poland, i.e., similar to the present study.

Over the 70 examined years, the largest number of the analyzed EDPr events occurred in summer, as much as ≥4.9% of all precipitation days. EDPr events took place most frequently in summer in 2001 (4.9% days with precipitation), 1972 (5.2%), 1970 (5.5%), 1966 (5.7%), 1997 (approx. 6.3%), and 2010 (approx. 7%). Similarly, a large number of EDPr events in 2001 and 2010 was also shown by Lorenc et al. [33]. The years 2001 and 2010 were classified as the so-called wet years in Poland also by Bednorz [50]. On the other hand, in the research study by Kalbarczyk and Kalbarczyk [5], the highest monthly precipitation was shown in the same months and years in which most of the EDPr events identified in the present study occurred in 1951–2020. In the years 1966, 1970, 1972, 1997, 2001, and 2010 in Poland there were floods whose range covered vast areas of the country [51–53]. In most cases, these floods were caused by above average precipitation. For example, the floods in July 2001 and May and June 2010 occurred after heavy precipitation in the Vistula basin (eastern Poland). On the other hand, in 1997 after heavy precipitation in July, the Millennium Flood occurred in the Oder basin (western Poland). An example of a flood that had a different cause than precipitation was the flood in the spring of 1966 caused by an ice jam and the flood of 1970 caused by snowmelt. The hazard zones caused by EDPr events in Poland determined in the present study partly overlap with the spatial distribution of yearly precipitation sums [50] and their yearly variability [5].

A limitation of the conducted research is the lack of unambiguously defined trends of precipitation variability in Poland until the end of the 21st century [54]. Furthermore, possible spatial differences in the predicted variability of meteorological elements by 2030 are indicated [55]. Therefore, it is undoubtedly necessary to carry out further studies on the variability of precipitation, including extreme precipitation in Poland. The designated risk zones may already need to be verified and updated in the next decade.

5. Conclusions

Meteorological data sourced from the Polish network of ground-based weather monitoring stations show that, from 1951–2020, precipitation (Pr) in the whole of Poland occurred on about 46% of days in the year on average, least often in April (approx. 40% of days in the month) and most frequently in December (approx. 54% of days in the month). In the period from November to January, Pr was mostly recorded in the northern part of the country and in December in western Poland.

The absolute maximum value of daily precipitation (dPrmax) in Poland varied from 53.2 mm in March to 232.0 mm in June. In summer, dPrmax values at all the analyzed IMGW-PIB stations exceeded 40 mm. The highest dPrmax values, from >140 mm in August to >200 mm in June, were recorded in southern Poland and in August in central-western Poland.

A significant trend of daily precipitation (dPr) for the whole country was found in only three months; in April and November a negative trend of daily precipitation, and in October a positive trend of daily precipitation. A significant increase in dPr was also recorded at some stations located in various parts of the country in January, March, and October. A significant increase in EDPr events for the whole country was found in September for thresholds of >30 mm, >50 mm, and >70 mm. An increase in the number of EDPr events was also found in May, but only for a threshold of >100 mm.

Out of all the four analyzed hazard levels in Poland, the most frequent was EDPr of >30 mm, which was most often recorded in the summer season, then in autumn and spring, and least frequently in winter. In summer, events with EDPr of >30 mm, >50 mm, >70 mm, and >100 mm, taking into account days with dPr, were most frequent in 2010, 2001, and 1970.

An increased frequency of EDPr events at the analyzed threshold values mainly occurred in the southwest and the south. The spatial distribution of the number of days with extreme daily precipitation was diverse; from 0 to just over 110 days in the case of >30 mm, from 0 to just over 40 days for >50 mm, from 0 to just over 20 days for >70 mm, and from 0 to just over 10 days only for >100 mm.

In Poland, three hazard zones caused by EDPr events were determined and characterized by means of the adopted thresholds; >30 mm, >50 mm, >70 mm, and >100 mm. Hazard Zone I, i.e., low risk, was located mainly in the northwestern, northeastern, and central parts of Poland, covering approx. 25% of the country. Hazard Zone II, i.e., medium risk, covered the largest area, 62.5% of Poland, mainly in the northern, central-eastern, and central parts. The smallest area was covered by Hazard Zone III, i.e., high risk, in the southwestern and southern parts of the country, 12.5% of Poland.

In Hazard Zone III, EDPr events occurred on average 4–5 times more often than EDPr events in Hazard Zone I. It is worth noting that in the spring–summer season, EDPr events were recorded on average five times more frequently than in the autumn–winter season.

Due to rapid changes occurring in the atmosphere as a consequence of human activity and a high probability of an increased frequency of EDPr events resulting from this, it would be advisable to continue this research on the trends and risk assessment of such events in Central Europe.

Author Contributions: Conceptualization, R.K.; methodology, R.K. and E.K.; formal analysis, R.K.; investigation, E.K.; data curation, R.K.; writing—original draft preparation, R.K.; writing—review and editing, E.K. and R.K.; visualization, R.K.; supervision, E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Publicly available datasets were analyzed in this study. These data can be found here: https://danepubliczne.imgw.pl/apiinfo (accessed on 24 April 2023); https://dane.imgw.pl/ (accessed on 24 April 2023).

Conflicts of Interest: The authors declare no conflicts of interest.

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