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Climatology of intense rainfall in Bulgaria in the recent decades

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Abstract: The intense rainfall, according to the accepted in the National Institute of Meteorology and Hydrology at the Bulgarian Academy of Sciences (NIMH-BAS) terminology, is relatively short-lived (from a few to 60 or more minutes) heavy rainfall with an intensity not less than 0.18 mm/min. The large variability of this phenomenon in both time and space scales complicates assessing of its spatiotemporal characteristics by point data. However, statistical analysis of long time series from a large number of stations makes it possible to reveal some basic peculiarities of intense rainfall, such as average and maximum precipitation amount for different time intervals, maximum intensity and duration, frequency distribution by months, and average annual number of cases. In the present study, the main features of intensive rainfall in the period 1976-2015 are analyzed on the basis of digitalized archive information from paper strip pluviograph charts. An attempt to summarize the spatial and intra-annual distribution of intense rainfall in that period, as well as a comparison with some results of studies for earlier periods, is made.

Keywords: intense rainfall, homogeneity tests, spatiotemporal characteristics

1. INTRODUCTION

During the last decades, the study and the evaluation of changes in global climate have been a major task for the scientific community. The increasing of rainfall variability and frequency of heavy rainfall events has a significant impact on the hydrologic regime, which affects the ecological, economic and social structures. Climate assessment and monitoring of intense rainfall provide the scientific basis for reducing uncertainty and unfavorable impacts in the risky areas. Irrespective of the sharp intensification in the development and use of new automated measuring techniques and instruments in the recent years, the pluviograph records remain basic for climate researches. Precipitation intensity is defined as the amount of precipitation, collected per unit time interval

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(WMO-No 8, 2010). In that sense, precipitation intensity is a secondary parameter, derived from the precipitation amount, which can be measured with pluviograph or ordinary rain-gauge.

The intense rainfall differs from the abundant rain (with large 24-hour quantity) and from prolonged rain (with duration more than 24 hours). Torrential rains with greater intensity are relatively short-lived, whereas the heavy prolonged rains reach small or medium intensity. From a meteorological point of view, the distinction between rainfall events is determined by the vertical distribution of thermodynamic features of atmospheric processes under the influence of land surface peculiarities. The great variety of definitions of heavy rainfall events arises from the difficulty to accept generally applicable quantitative thresholds for precipitation amount and intensity. There is a few number of fundamental researches on the meteorological conditions and processes of formation of intense rains in Bulgaria (L. Krastanov, 1939; P. Hristov and A. Pisarski, 1956). In the case of pluviograph based measurements, R. Kalcheva (1962) considered as risky the rains with intensity greater than or equal to 0.18 mm/min.

Seasonal and monthly distribution of intense rains corresponds to the precipitation regime in the different climatic regions of the country. The territory of Bulgaria is divided into two climatic areas (European-Continental and Continental-Mediterranean), four subareas (Moderate-Continental, Transition-Continental, South-Bulgarian, and Black-Sea – shown on Fig. 1), and twenty-five climatic regions (Sabev&Stanev, 1959). The differences in the circulation conditions between the northern and the southern parts of the country determine the peculiarities in the annual course of rainfall in the relevant lowland and mountain areas.

In the European-Continental climatic area, the annual precipitation minimum is in February, with the exception of the southernmost part of the Thracian lowland. The number of rainy days and the precipitation amount, as well as the number of convective storms, increase sharply in May. The annual precipitation maximum is in June (about 30% of the annual precipitation amount), as the largest rainfall quantities are observed on the northern and western mountain slopes and relevant hilly areas. The maximum of 24-hour heavy rainfall (over 25 mm) is clearly expressed in the summer. Frontal rainfall predominates in October and November. In the Continental-Mediterranean climatic area, the precipitation maximum is observed in November and the beginning of winter, due to the strong influence of Mediterranean cyclones. In June, there is a secondary precipitation maximum. Autumn is the rainiest season in the Black Sea climatic subarea, as the seasonal rainfall amount is smallest in the coastal part and largest in the southern parts of the Strandzha region. The largest 24-hour precipitation quantities are registered also in this season.

In the present study, the main features of intense rainfall for the period 1976-2015 on the basis of digitalized archive information from pluviograph charts are analyzed. An attempt to summarize the spatial and intra-annual distribution of intense rains in that period, as well as a comparison with some results of studies for earlier periods (Kyuchukova et al., 1986), is made.

Fig. 1. Climatic subareas on the territory of Bulgaria (Sabev&Stanev, 1959). The bold line separates European-Continental and Continental-Mediterranean climatic areas

2. DATA AND METHODOLOGY

In the meteorological network of NIMH-BAS for measuring and registering of heavy rainfalls during the warm half year (from April to October or November in the southernmost parts of the country), are used mechanical recorders (pluviographs). The meteorological stations with installed pluviographs are basic for the establishment of the regime of intense rainfall mostly in the areas up to 800 m a.s.l. and cover relatively evenly the territory of the country. The existing archive information contains the paper-based records of the results of manually processed paper strip pluviograph charts by the method of "maximum intensities" (Hristov, 1962). The advantage of this method consists in extracting of all five-minute intervals in which the intensity remains over the lower limit, and ranking of corresponding precipitation quantities in descending order (from highest to lowest five-minute intensity), which permits a fast quality control of the obtained results. The main disadvantage is the need for enough trained staff. The boundaries of the time intervals for rains with different duration are taken as follow: up to 30 minutes – every five minutes (5, 10, etc.), from 30 minutes up to 1 h – every

10 minutes (30, 40, etc.), and over 1 h – every 30 minutes (90, 120, etc.). The main parameters that characterize the intense rains are precipitation amount H (mm), duration T (min), and intensity of the rain I (mm/min). Herein, for the bottom border of intensity is accepted the limit value defined by Kalcheva (1962): I = 0.18 mm/min, regardless of the rainfall duration.

The original idea of the present study comprised in updating the main results of the "Climate Guide–Intense rains in PR Bulgaria" (Kyuchukova et al., 1986) by extending the analysis over the period till 1990, and subsequent comparison with the key features of the intense rainfall in the period 1991-2015. In this connection, the available archive information from 95 stations (84 stations, listed in the Climate Guide, plus 11 other with a sufficiently long observation period after 1976) was processed. Data from each station for the whole observational period (up to 2015) are digitized and investigated by the developed for the purposes of this specific task automated procedures for quality control and analysis (in Excel environment). Preliminary data analysis (after digitalization and automated quality control) included: 1) checking data periods and gaps due to damage or repairs of instruments or damage of archives, and 2) identifying incorrect values. All inaccurate records were excluded. Time series of precipitation quantity at different durations (specified in the paper-based source) are derived for each station.

Two homogeneity tests – RHtestsV4 (Wang&Feng, 2013) and Mann-Whitney-Pettitt test (Štěpánek, 2008) were applied to the control time series of logarithmically transformed yearly amounts of five-minute quantities of intense rainfall. The software package RHtestsV4 can be used to detect multiple change-points in data series that may have zero-trend or a linear trend throughout the whole period of record and first-order autoregressive errors. The test is based on the penalized maximal t-test and the penalized maximal F-test, which are embedded in a recursive testing algorithm (Wang, 2008). The change-points detection is also possible when a homogenous reference series is not available. In this case, the verification of detected change-points by another test is a good strategy, especially when metadata is insufficient or not available. Mann-Whitney-Pettitt test is a rank-based test for detecting the change in the median of series with an unknown time of change. According to Pettitt (1979), the test is considered to be powerful relative to Wilcoxon-Mann-Whitney test and sensitive to all possible conditions resulting in a stochastic ordering. The outcomes of homogeneity testing and verification for some control time series are shown on the Fig. 2.

Finally, in 63 control time series of the total 95, RHtestsV4 detects from one to three change-points but the test statistic values for the most of them fall in the 95% confidence interval. In 37 cases, the detected change-points are confirmed by the Mann-Whitney-Pettitt test but only in 22 cases, the test statistic values are greater than the respective critical values (in the significance level $p=0.01$). In 12 cases, the inhomogeneity is confirmed by the available metadata. The results obtained by the quality control procedures and homogeneity testing showed an increased number of data gaps and change-points in time series before 1975 (Fig. 3). This fact does not in any way compromise the results of Kyuchukova et al. (1986) and finds its explanation in the data loss due to the late introducing of innovative procedures for storing archive information (Marinova, 2008) and several transformations of the hydro-meteorological service under the management of various ministries (Andreev, 2014).

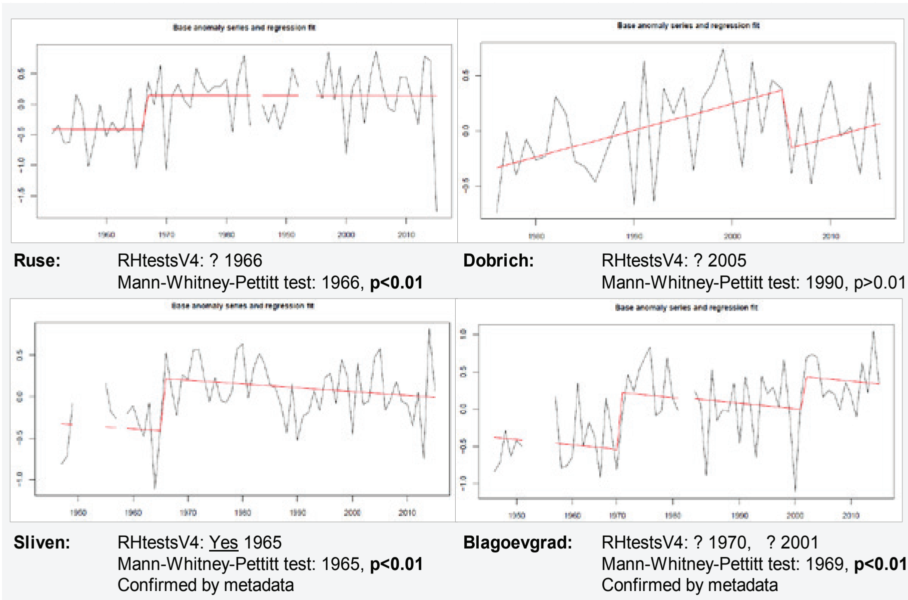

Fig. 2. Homogeneity testing results for some control time series

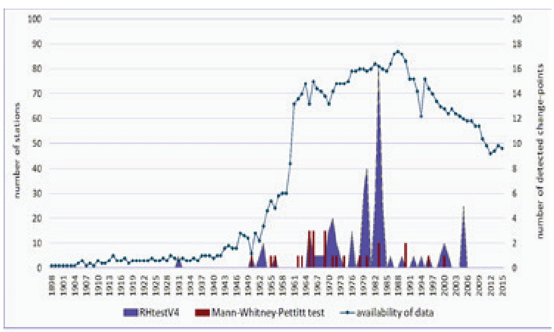

Fig. 3. Graphical representation of the obtained results after data preprocessing (right vertical axes corresponds to marked line – availability of data)

The homogenization of precipitation time series is a difficult task that must be performed carefully, especially when metadata is not available or insufficient as is emphasized in Wang&Feng (2013) and many other studies. An incorrect application of homogenization procedures to the time series with seasonal breaks, such as intense rainfall records, leads to unreliable climate analysis. Taking in mind that the mean values of Quantile Matching (QM)-adjustments calculated by RHtestsV4 for inhomogeneous control time series only in singular cases reach to 10-12% of the respective long-term averages it seems reasonable to specify the scope of the study. First, the 40-year period 1976-2015 was preferred to avoid of many data gaps and inhomogeneity in time series and, second, the number of stations is reduced and only these with available observations in 20 or more years are used (Fig. 4). The stations are situated mainly in no mountainous regions of the country and can be grouped in three altitude zones: up to 400 m – 49 stations, from 401 to 800 m – 19 stations, and from 801 to 1200 m – 5 stations. The selected stations cover relatively evenly the four climatic subareas – 35 of them are located in the Moderate-Continental climatic subarea, 21 in the Transition-Continental climatic subarea, 12 in the South-Bulgarian climatic subarea, and 5 in the Black-Sea climatic subarea. Over 70% of the stations have an observational period of 30 to 40 years. In comparison with the Climate Guide (Kyuchukova et al., 1986) this number is about seven times bigger.

Fig. 4. Spatial distribution of the selected meteorological stations used in the study

The most part of performed calculations follows the methodology described in the Climate Guide. The frequency of intense rains by months in the period 1976-2015, regardless of their intensity and duration, is calculated for each station as a ratio (in %) of the total number of cases in each month from April to October and the total number of cases in the period April-October. The average long-term quantity of intense rainfall for a given duration is obtained, as the total rainfall amount (for this duration) in the observation period is divided by the number of rains with the same duration, and not as an average quantity for the entire duration of the rain. The maximum intensity for all rainfall duration is derived from the respective maximum quantity divided by the duration (in minutes).

Maps for ***visualization*** of the spatial distribution of intense rains and their main characteristics are created using kriging interpolation and the open source software QGIS (version 2.14.20). It is important to note, with accounting for the specific nature of intense rainfall, that the number of used data-point (total 73 and only 5 in areas with altitude above 800 m) is not enough to perform advanced kriging technics, which increases the risk of biased estimates for mountainous areas due to inaccurate interpolation between low-altitude stations.

3. RESULTS

Previous mentioned above studies have shown that intense rains occur mainly in the warmer lowlands and do not coincide with the locations of the largest precipitation amounts, which are mainly in the mountains. However, the long-term annual amount of intense rainfall with small duration (up to 15 minutes) increases with the altitude (Fig. 5). The long-term annual amounts for five-minute duration averaged by the mentioned above altitude zones are: 56 mm (from 38 mm – Kaliakra, to 87 mm – Botevgrad) for altitude up to 400 m; 65 mm (from 45 mm – Gotse Delchev, to 110 mm – Chiflik) for altitude 401-800 m; 72 mm (from 55 mm – dam "Batak", to 96 mm – Smolyan) for altitude 801-1200 m.

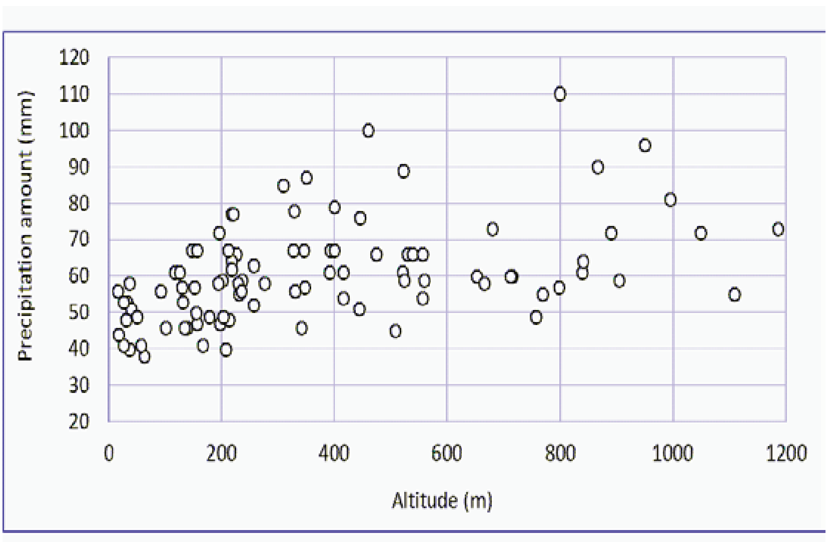

Fig. 5. Variation of long-term annual rainfall amount for five-minute duration with altitude

A key feature of the regime of intensive rains is their average annual number, which varies from 17 to 44 in the period 1976-2015, and its spatial distribution (Fig. 6) obviously corresponds to the described in Sabev&Stanev (1959) peculiarities of the precipitation patterns from April to October in the climatic areas and subareas in Bulgaria. As far as this phenomenon occurs in the warm half year, the largest number of intense rains is observed in the Moderate-Continental climatic subarea – in the hilly areas relevant to the northern and western slopes of Balkan Mountains (39 in Vratsa and Krastets, and 44 in Chiflik). The lowest average number of intense rains is registered in the regions with increased drought in the summer and early autumn.

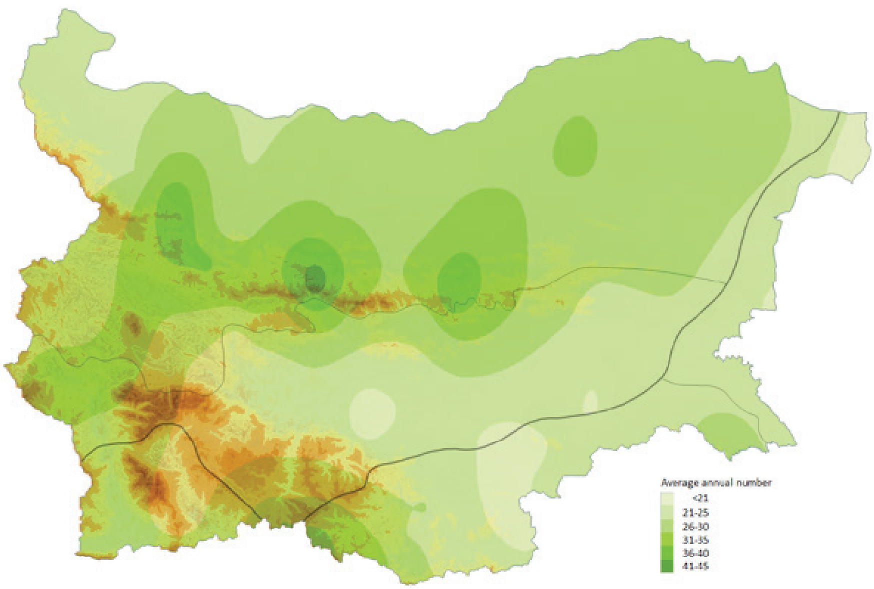

Fig. 6. Average annual number of intense rains in the period 1976-2015

In the most of stations, the highest number of cases is registered in the period 2005-2014 (86 in Razgrad and Vratsa in 2005; 102 in Vratsa in 2014), but the tendency of significant increase in the number of intense rains noted in Kyuchukova et al. (1986) couldn't be confirmed for the period 1976-2015 and, probably, it seems to be a climate variation due to the fluctuations in the atmospheric circulation over Balkan Peninsula and Eastern Mediterranean. The observed decrease in the number of cases during the 1980s and early 1990s in the stations in Western and Southern Bulgaria (Fig. 7) matches approximately with the minimum of Mediterranean cyclones with trajectories through Greece and the Aegean Sea in the considered period.

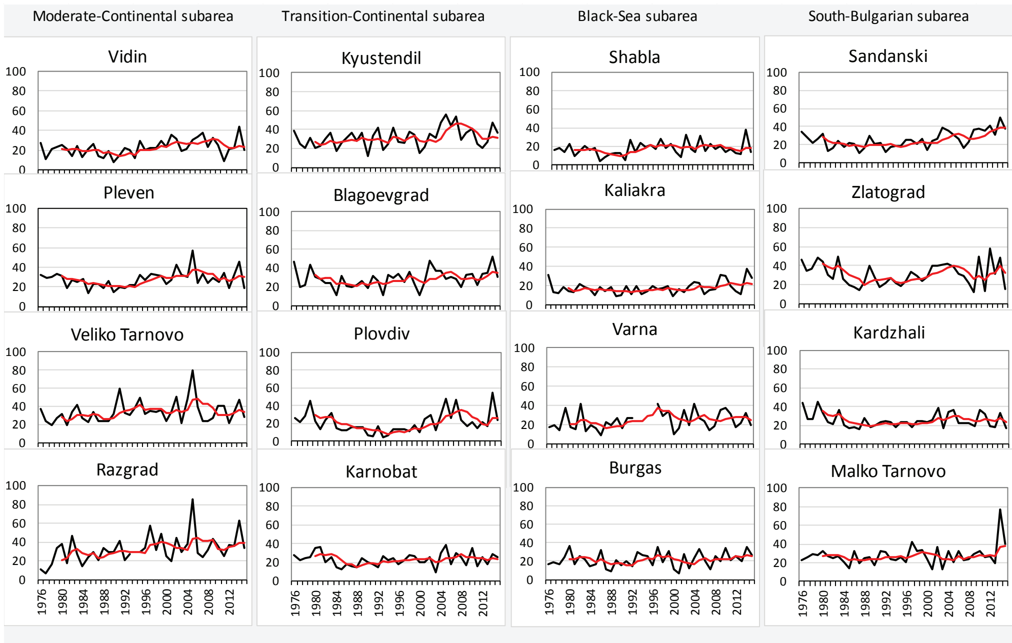

Fig. 7. Long-term variation of the number of intense rains for selected stations in the four climatic subareas

Over 88% of intense rainfall events are those with duration between 5 and 30 minutes. The five-minute rains are about 35% (from 27.2% in Yambol to 46.2% in Ruse). Prolonged rains (over 1 h) occur more frequently in North-Eastern Bulgaria (above 3% in Razgrad, Targovishte, Shumen, and Shabla), as well as in the southern part of Strandzha region (4.1% in Malko Tarnovo). The lower intensity rains (around 0.18-0.20 mm/min) are most frequent, while the unusually heavy rains are relatively rare.

Most frequently intense rains fall during the summer months (June, July, and August), in which occur 49.4-57.6% of the all observed cases from April to October (averaged by climatic subareas). About 20.8-29.5% of intense rains fall in the spring months (April and May) and between 15.7% and 29.8% in the autumn months (September and October) – Fig. 8. The maximum number of cases in the late spring and early summer is related to the increase of solar radiation and moisture transfer, which create conditions for the development of strong upward movements of air masses, powerful convective cloudiness, and short-lived intense rains. Over 22% of the rains fall in June, followed by July. For the greater part of the country, the average number of intense rains is minimal in October (6%) and April (8%), except the southern coastal areas and southeastern part of the country, which are under strong influence of the seasonal regime of Mediterranean cyclones.

The average and maximum quantities of intense rains with different duration represent their main characteristic based on the real measurements. For the whole country, the average five-minute amount is about 2.3 mm (from 1.9 mm in Gotse Delchev to 2.6 mm in Roman, Knezha, Pleven, Lovech, Karlovo, and Yambol) and forms approximately 7-10% of rainfall quantity for a 60-minute duration. The average maximum rainfall quantity for small durations (up to 30 minutes) exceeds 4-7 times the average quantity for the same duration and increases from 18.8 mm in five minutes to 43.3 mm in thirty minutes. Spatial distribution of the average five-minute rainfall quantity (Fig. 9) reveals the specific nature of intense rains. Obviously, the areas of highest five-minute quantity don't coincide to the areas of a highest number of intense rains. This fact finds its explanation in the behavior of short-lived rains, which usually accumulate a small rainfall amount, starting with small five-minute values. In the warm half year, the transfer of Atlantic air masses leads to the formation of intense rainfall with a medium or large (relatively rare) duration, whose five-minute quantity determines the long-term averages.

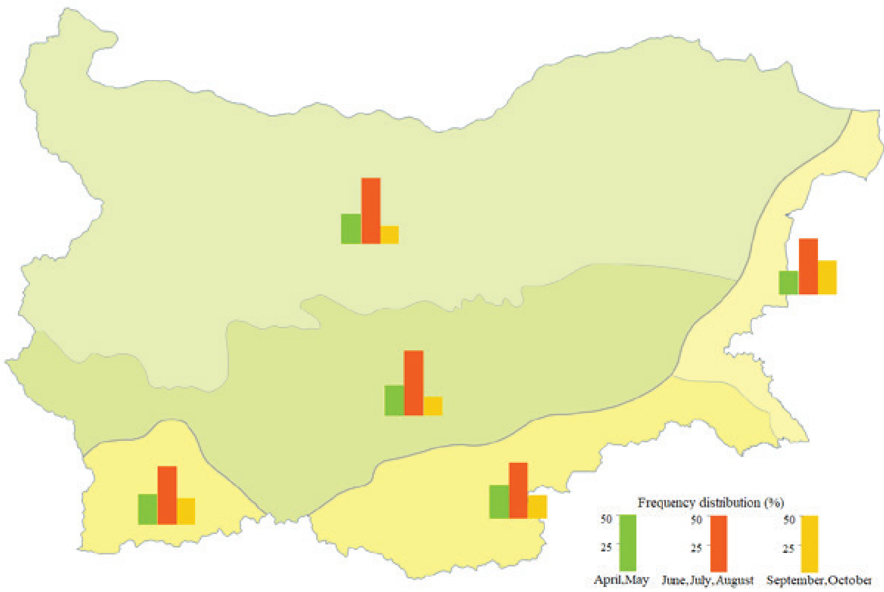

Fig. 8. Seasonal distribution of intense rains in the period 1976-2015

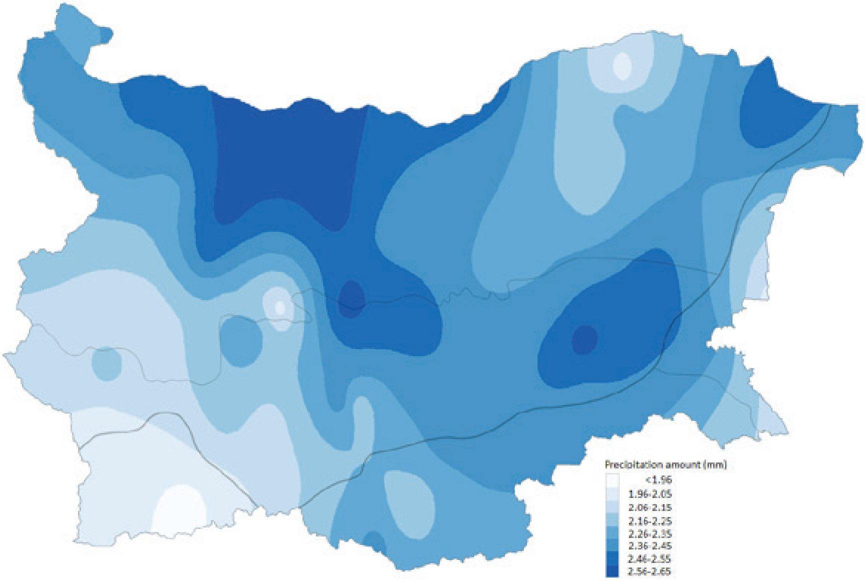

Fig. 9. Average five-minute rainfall quantity in the period 1976-2015

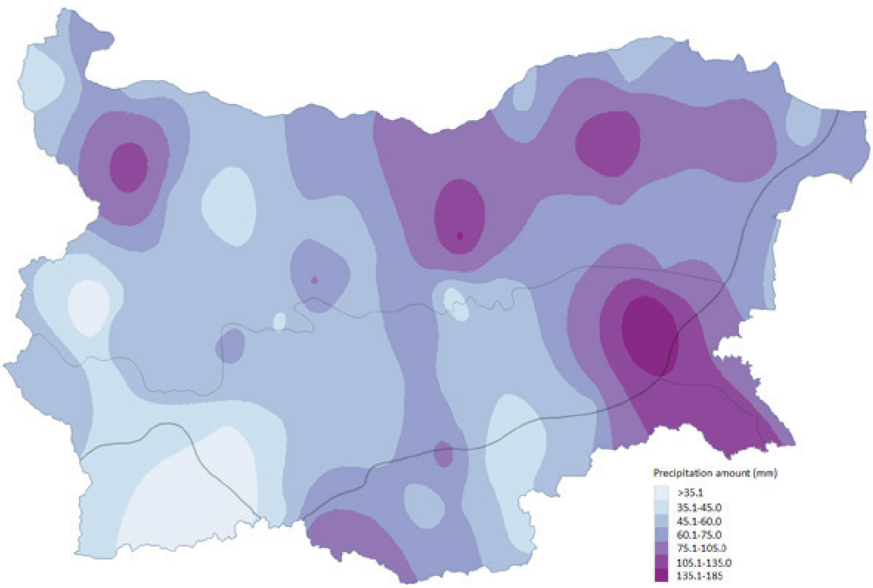

Fig. 10. Maximum quantities of intense rainfall in the period 1976-2015

In the period 1976-2015, the absolute maximum rainfall quantities for all durations to 25 minutes are observed in Lovech (from 40.0 mm in five minutes to 77.8 mm in 25 minutes) during the single heavy rainfall event on 2.VII.1994. The absolute maximum quantities for all durations from 30 to 60 minutes are observed in Pleven (from 79.6 mm in 30 minutes to 122.1 mm in 60 minutes) during the heavy rainfall on 9.VI.1981. The absolute maximum rainfall quantity is recorded in Karnobat (184 mm in 360 minutes) on 20.IX.1983. The absolute minimum quantities for all durations are registered in the region of Pernik. Spatial distribution of maximum quantities observed in the period 1976-2015 reveals the risky regions and dangerous nature of the intense rains (Fig. 10). Besides the mentioned extremely intense rain in Karnobat, a few similar events are registered: Montana (134.3 mm in 210 minutes) on 6.VIII.2007; Veliko Tarnovo (138.8 mm in 240 minutes) on 30.V.2002; Samuil (135.5 mm in 390 minutes) on 1.VII.2006.

Absolute maximum duration of intense rainfall in the considered period is 570 minutes (Isperih, 7.VIII.2002, 112.1 mm), followed by 450-minute duration (Karnobat, 4.IX.1999, 125.9 mm; Dobrich, 19.VI.2014, 82.0 mm) and 420-minute duration (Pavlikeni, 14-15.IX.2005, 91.1 mm). So far as the prolonged heavy rainfall is formed under large-scale circulation conditions, the location of the main risky areas (Fig. 11) relatively coincides with those shown on Fig. 10, except the Montana region.

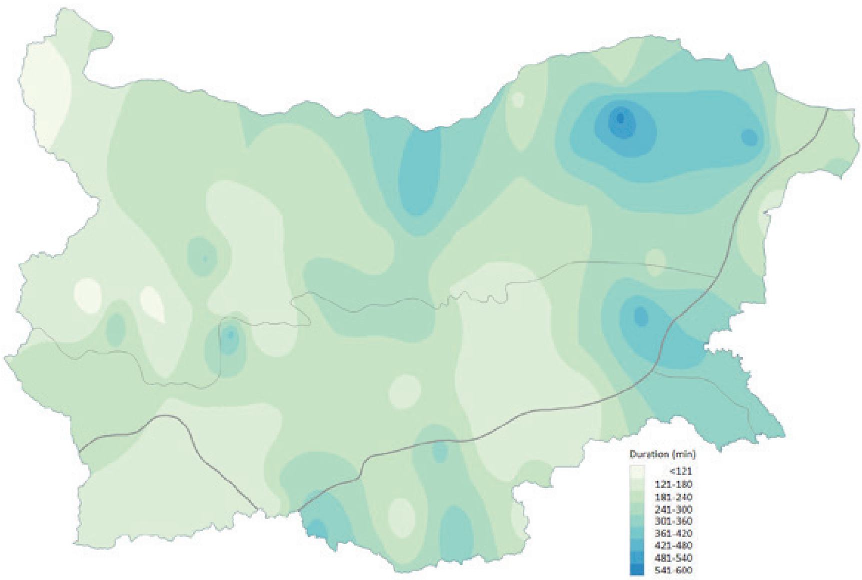

Fig. 11. Maximum duration of intense rainfall in the period 1976-2015

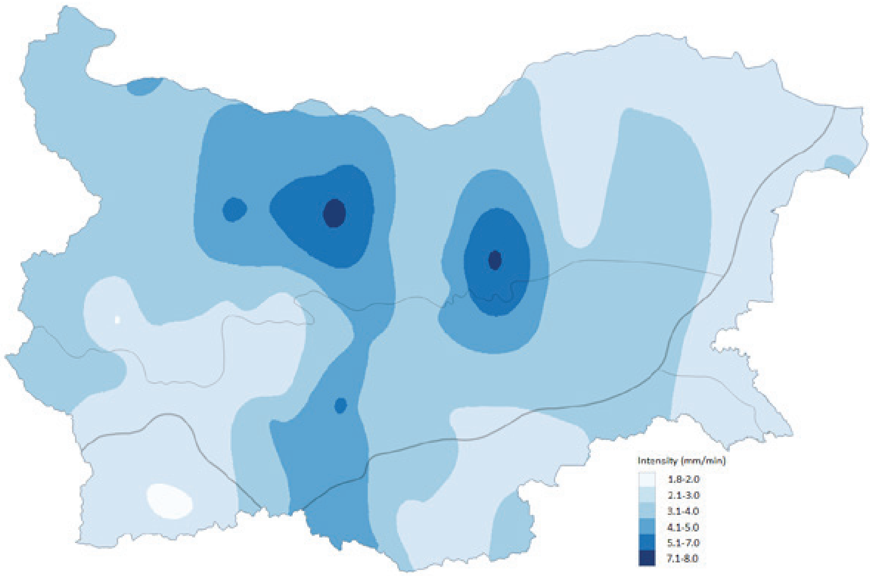

Fig. 12. Maximum five-minute intensity in the period 1976-2015

Absolute maximum value of 5-minute intensity in the period 1976-2015 is 8.00 mm/min (Lovech), followed by 7.58 mm/min (Elena). The lowest maximum values are 1.88 mm/min (dam "Studena") and 1.94 mm/min (Gotse Delchev). Spatial distribution of the maximum five-minute intensity (Fig.12) discloses the vulnerability of the different regions to some damaging processes such as the soil erosion and flash floods.

The empirical relationship between maximum intensity *I* (mm/min) and duration *D* (min) can be represented by a power function of the form:

$$I = aD^b$$

where the calculated values (by stations) for the scaling factor *a* and the power coefficient *b* vary in the intervals [3.6, 71.6] and [-1.06, -0.25], respectively.

3. CONCLUDING REMARKS

In the present study, an attempt to summarize the spatial and intra-annual distribution of intense rainfall in the period 1976-2015, is made. Main characteristics of intense rainfall are evaluated on the basis of digitalized archive information. Data pre-processing discloses data gaps and inhomogeneity in time series before 1975, which makes pointless the complete comparison with the outcomes of studies for earlier periods (Kyuchukova et al., 1986).

The obtained results confirm the importance of comprehensive studies of this phenomenon and above all the need of saving and restoration, as far as possible, of archive information that remains the unique source for long-term time series. Incorporation of data from automated measuring instruments is another impending task for future climate studies.

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