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Rainfall Erosivity Factor within the Volyn Region

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ABSTRACT

The article presents results of the research and mathematical modelling of the rainfall erosivity factors. Erosion, whether water, wind or resulting from soil cultivation, includes three processes – soil descaling, movement and sedimentation. Spatial characteristics of precipitation during two researched periods are similar, having certain quantitative peculiar features. A common feature is maximum precipitation in the southwest and to a lesser extent in the eastern part of the region. Minimum precipitation is typical for the western part of the region. Peculiar feature of the second period of research is increase of contrasting effect of precipitation regime, when minimum values of precipitation decrease and maximum ones increase. Enhancement of contrasting effect of precipitation in space or time may cause increased intensity of erosion processes to the extent where the intensity of precipitation increases due to such contrasting effect. Thus, doubtless interest lies in the research of greater spatial or time contrasting effect of precipitation regime to activate water erosion. Thus, spatial peculiarities of distribution of precipitation within territory under study and time patterns correlate, but have their own special features. Clearly, total amount of precipitation as well as time distribution as a marker of correlation of intensification factor of erosion processes and defence mechanisms of vegetative cover are dominant for total losses of soil due to erosion. Coincidence of time of intense precipitation in summer and availability of vegetative cover reduces erosion. Nevertheless, continuance of intense precipitation when harvesting is started may cause intensification of water erosion of soil. Use of spatial variables and regression equations for spatial data calibration helped to estimate the spatial variation of precipitation on the territory under study. Comparison of two periods of research showed that in 2010–2016 significant reduction of rainfall erosivity factor has taken place in comparison with the previous period 9.6–65.4 MJ mm ha^{-1} h^{-1}per year. In Turiyskyi and Kovelskyi district changes in rainfall erosivity factor were minimal (9.6 and 16.7 MJ mm ha^{-1} h^{-1}per year respectively). Conversely, in Ivanytskyi and Gorokhivskyi districts changes were the most significant – 58.1 and 65.4 MJ mm ha^{-1} h^{-1}per year respectively.

Keywords: agriculturally used areas, relief, soil, erosion, climatic condition, pattern, cluster analysis.

INTRODUCTION

Excessive load on cultivated lands in the past, irrational and patternless use of lands in contemporary transformational conditions has initiated notable degradation processes. According to the information of the State Committee for Land Resources of Ukraine erosion has spread over approximately 10.5 mln. ha or 30% of croplands. Soil scientists estimate the modern state of the land fund of Ukraine as critical (Medvedev et al., 2001). The problem of soil degradation is one of the most pressing challenges of today (Matviichuk et al., 2021; Santra et al., 2017; Panagos et al., 2015; Orgiazzi et al., 2018).

The main types of soil degradation are water and wind erosions (Medvedev et al., 2001, Blocken et al., 2006); they lead to the loss of fertile soil layer (Daryanto et al., 2012); desertification (Scheffer et al., 2003), salinification (Alberts et al., 1983), solonetzization, acidification (De Boer et al., 2001), ad alkalinization. These destructive phenomena deteriorate the physical characteristics of soil (Bullard et al., 2002) and cause damage of its structure (Barthès et al., 2002), compaction (Celik et al., 2010), crust formation (Elliott, 1986); reduction of its filtering capacity (W Ding, 2017); loss of macro- and microelements, adverse changes in quantity, species composition and activity of microorganisms (Arnaez et al., 2002; García-Díaz et al., 2017), and decrease of surge capacity (Baldock et al., 1992). Danger of water erosion lies in reduction of fertility of the plough layer, silting of rivers, ponds, water bodies, and flooding of plain soils (Isabirye et al., 2007; Ruysschaert et al., 2006).

Erosion control – is a number of actions that are aimed at prevention of damaging effect of erosion, reduction of erosion intensity to acceptable level or lower (He et al., 2010). Erosion whether water or blowing or occurring as a result of soil cultivation includes three different processes – detachment of soil, transportation and deposition of soil (Wangpimool et al., 2013). Erosion constantly occurs under environment conditions (Gabet et al., 2003). Erosivity of any surface is predetermined by four main factors: soil characteristics, vegetative cover, relief and climate (Ranzi et al., 2012).

In the Forest-steppe zone soil, cover is mostly damaged by melt and storm water. Most precipitations fall during warm period and often have storm nature. Almost 4.9 million ha of land are affected by erosion, water – 4.6 and blowing – 0.3 million ha (Furman et al., 2016). In the Forest-steppe zone of Volyn region 136 k ha, which comprises 10% of total area of agriculturally used areas and 13% of tilled soil, are affected by water erosion (Molchak et al., 2010). The level of water erosion depends on the amount and intensity of precipitation and slope angle (Alewell et al., 2019).

The most important measure to protect soil from loss is erosion-preventing arrangement of the territory, which includes contour-reclamative planning of the territory (field and soil-protective rotation of crops, alkalization) (Furman et al., 2016; Molchak et al., 2010). Tillage across slope and implementation of subsurface cultivation is an important preventive measure against erosion (Meena et al., 2015). Systems without soil cultivation can reduce the negative influence of intensification of agriculture on soil characteristics. Nevertheless, knowing long-time influences of systems without soil cultivation on soil characteristics is not enough. It is important to know which quality parameters of soil are most sensitive to management practices in each specific environment (Sokolowski et al., 2020; Matviichuk et al., 2020). In order to reduce the soil loss on slopes during winter period, rowing snow bands with ring rollers across the slope is effective (Molchak et al., 2010).

Compaction of autumn ploughing is a cost-effective agrarian measure to reduce land loss. Under the conditions of the Volyn region, meadow-improving measures of protection from erosion are advantageous and effective on lands of hydrographic fund (Molchak et al., 2010). Hydrotechnical measures can fully regulate as well as rationally use snowmelt and storm water through construction of water regulating dam-trenches, drainage terraces, retaining water catches and benthal deposits, runoff water sprays, ponds and water bodies (Shi et al., 2020).

Reduction of erosion-deflation soil losses is possible when soil-protective technologies are constantly used and applied, erosion-preventive arrangement of agrarian landscape is assured, real-time monitoring of territories susceptible to erosion is done and, among other things, distance methods of testing soil cover are applied (Biddoccu et al., 2020; Pysarenko et al., 2020).

METHODS OF RESEARCH

Rainfall erosivity factor (R) reflects the influence of precipitation on erosion of soil and requires detailed, continuous precipitation statistics for its calculation (Zerihun et al., 2018; Wischmeier et al., 1978). R is an indicator of the two most important characteristics of storm that reflects its erosivity, in particular, amount of rainfall and peak amplitude that remain unchanged for a continuous period. Previous studies show that soil losses on fields in cultivation are associated with energy and intensity of precipitation. The value of rainfall erosivity factor used in RUSLE must quantitatively assess the influence of drop stroke and reflect amount and speed of wash that may be related to precipitation. Rainfall erosivity factor is often calculated by precipitation intensity, provided that such data is available. In this research, the monthly data about amount of precipitation for 30 years (1970–2000) were used to calculate R factor using the following equation (Wischmeier et al., 1978):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \qquad (1)$$

where: R – rainfall erosivity factor (MJ mm ha^{-1} h^{-1} per year);
P_i – monthly precipitation (mm);
P – annual amount of precipitation, mm.

WorldClim 2 based on a set of data about spatially interpolated monthly climatic data for global land plots with very high spatial separating capacity (approximately 1 km^2) was used as a spatial example of precipitation in the area under study (Cedrez et al., 2018). Raster models WorldClim 2 were built for 1970–2000. It was assumed that general pattern of spatial variability of precipitation is invariant. Calibration of spatial models was done based on meteorological observations at meteorological stations for the specific time period. There are 6 fixed meteorological stations on the territory under study. At the point of raster models WorldClim 2 that correspond to locations of meteorological stations data was extracted. They were used as independent variables of linear regression models to measure the data of meteorological stations. The obtained linear models were applied to estimate spatial patterns of precipitation variability in a certain period of time.

RESULTS OF RESEARCH

Relief influences the character of agricultural production. Relief specifically influences the location of croplands, use of agricultural machinery, etc. Local climatic data, radiation and temperature balance of the territory, lightning and moistening depend on the relief of a certain area as well (Matviichuk et. al., 2020). In the Volyn region, the climatic conditions are observed at six meteorological stations located in Polesie transition and Forest-steppe zones (Fig. 1).

According to the results of meteorological observations annual precipitation during researched period was 652±11 mm. The differences in the annual amount of precipitation in 2002–2009 and 2010–2016 are not statistically probable (F = 0.27, p = 0.60). Statistically probable differences between meteorological stations were ascertained by the amount of recorded annual precipitation (F = 2.79, p < 0.02). The minimal amount of precipitation was recorded by meteorological station Svitiaz (614±24 mm) and Lutsk (616±28 mm) and maximum – by the meteorological station Liubeshiv (669±30 mm) and Volodymyr-Volynskyi (660±23 mm). The general trend of annual dynamics of precipitation is increase of its amount in May-August (Fig. 2). During 2002–2009, maximum precipitation was observed in July (minor local maximum was observed in May) and during 2010–2016 maximum was observed in May. Meteorological stations Liubeshiv, Manevychi and Svitiaz are located in Polissya. Maximum precipitation in July was typical of the meteorological station Liubeshiv in 2002–2009 and amounted to 97 mm. It should also be noted that local precipitation maximum in May was 83 mm. Reduction of precipitation intensity in summer is typical for the period 2010–2016 to local maximum of 77 mm. In this context maximum is observed in May and equals to 78 mm. Significant reduction of amount of precipitation at the end of winter and beginning of spring in comparison with the previous period is also characteristic of this period. Similar dynamics of precipitation as described above were recorded at the meteorological station Manevychi. Maximum amount of precipitation was observed in 2002–2009 in July and amounted to 115 mm. In 2010–2016 maximum in May was 85 mm. According to the data obtained by Svitiaz meteorological station maximum precipitation in July-August is observed during whole researched period. Maximum precipitation in 2002–2009 was observed in August and was 103 mm. Maximum precipitation in 2010–2016 was observed in July and was 80 mm.

Local maximum precipitation in May is worth noting. Meteorological station Kovel is located in transition zone. Maximum precipitation was recorded in July and was 92 mm. In 2010–2016 maximum shifted to May-June and was 84 mm.

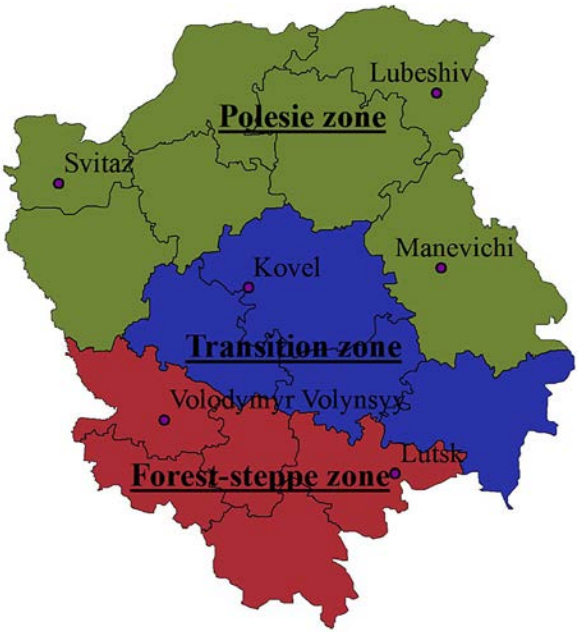

Figure 1. Distribution of physiographic zones and location of meteorological stations in the Volyn region

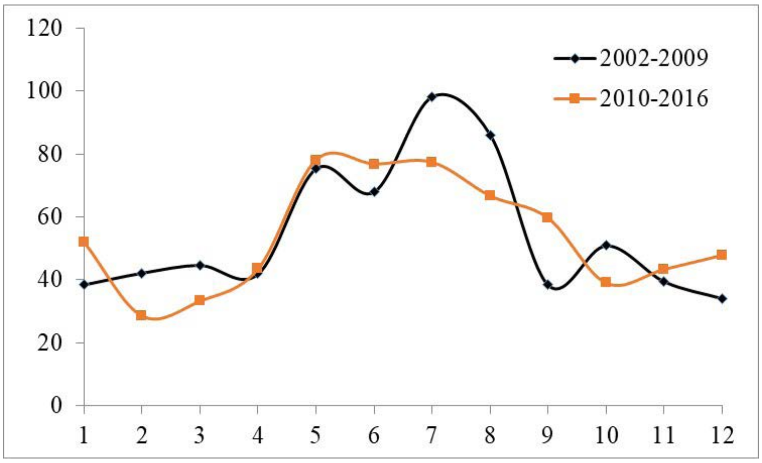

Figure 2. Monthly dynamics of precipitation in (a) 2002–2009 and (b) 2010–2016. Abscissa – order of months of the year, axis of ordinates – precipitations, mm

Local maximum was also observed in July. Volodymyr-Volynskyi and Lutsk meteorological stations are located in the Forest-steppe zone. According to the observations recorded at Volodymyr-Volynskyi station in 2002–2009 local maximum of precipitation was in May and equaled 105 mm. This shows that local maximum was observed in May. Maximum precipitation in 2010–2016 was observed in June and was 89 mm. Annual distribution of precipitation similar in both periods with maximum in July and local maximum in May was recorded at the meteorological station Lutsk. Maximum precipitation in 2002–2009 was in average 110 mm and in 2010–2016 – 97 mm. Thus, in general it is characteristic of this region precipitation maximum in annual dynamics observed at the end of spring or beginning or middle summer and during the second researched period (2010–2016) maximum, as a rule, is shifted to the earlier period. It also leads to conjunction of maximum and local maximum and as a result one state of extremum is observed and is longer-termed.

Use of space variables and regression equations for calibration of spatial data helped to estimate spatial variation of precipitation on the territory under study (Fig. 3).

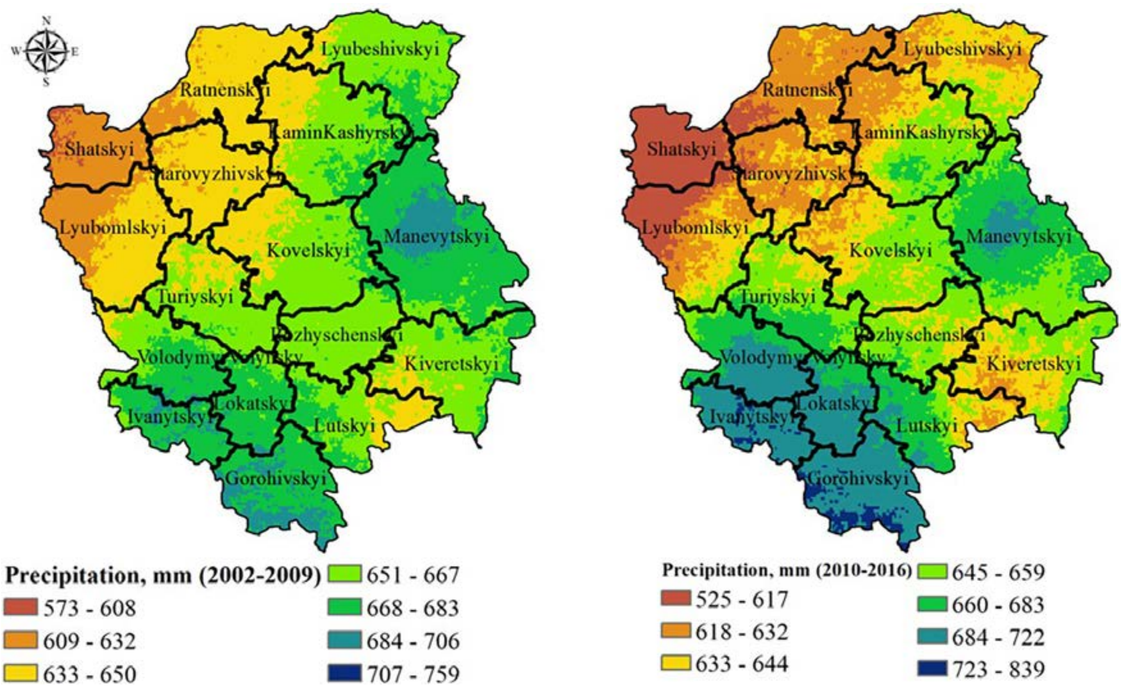

Figure 3. Spatial distribution of annual precipitation

Spatial characteristics of precipitation in two researched periods are similar with certain quantitative peculiar properties. Common feature is maximum precipitation on the south-west and to a lesser extent in the eastern part of the region. Minimum precipitation is typical for the western part of the region. A peculiar feature of the second period of research is increase of contrasting effect of precipitation regime, when minimum values of precipitation decrease and maximum ones increase.

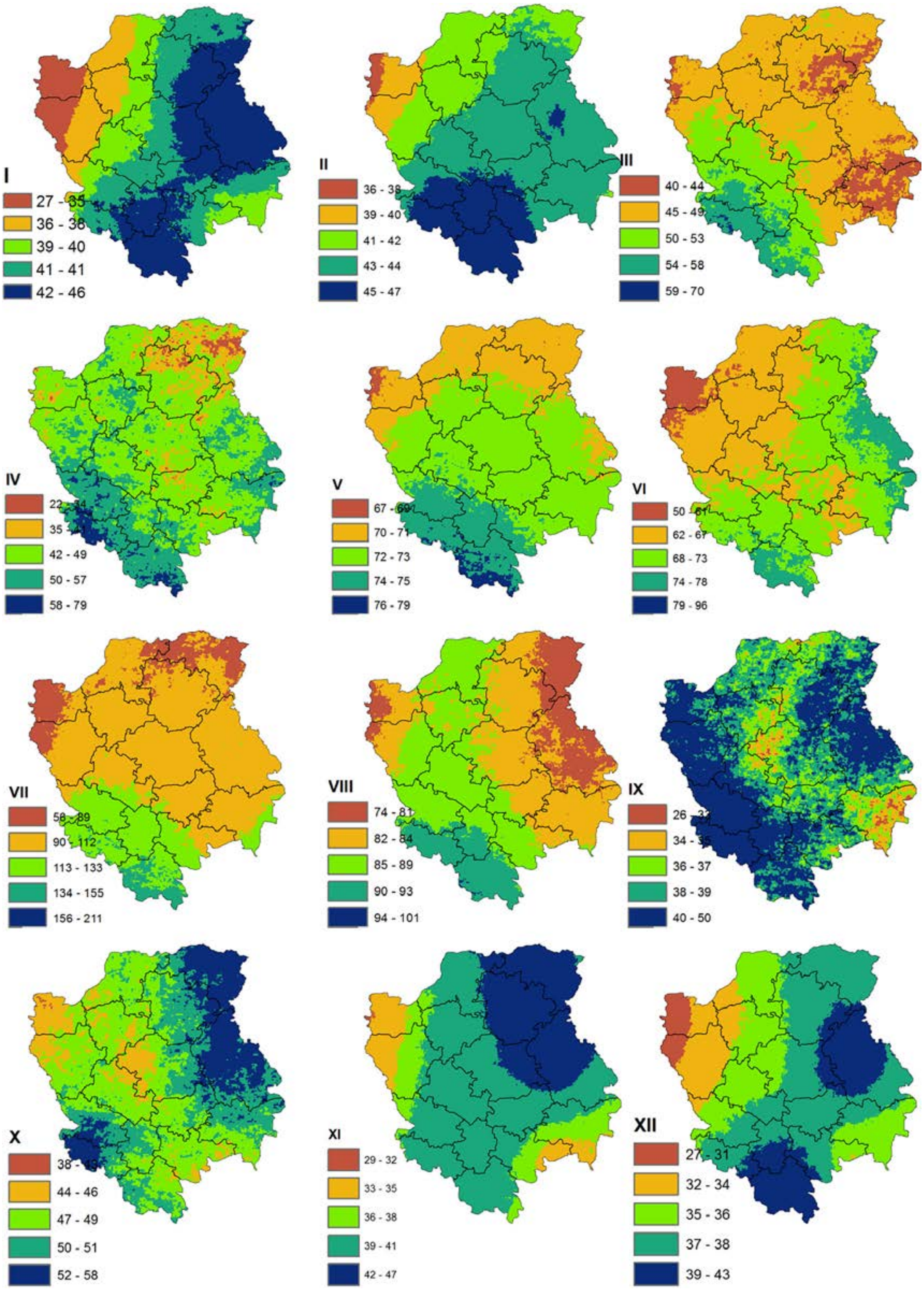

Figure 4. Spatial variation of monthly precipitation in 2002–2009 (I – January, II – February, III – March, IV – April, V – May, VI – June, VII – July, VIII – August, IX – September, X – October, XI – November, XII – December)

In 2002-2009 in January, maximum precipitation was observed in the east of the region (Fig. 4).

Minimum precipitation was observed in the west. In February, the zone of maximum shifts to the south and minimum remains in the west. In March, the zone of maximum shifts to the south-west and minimum of precipitation is typical for the south and northeast. In April, the zone of maximum was in the south and southwest, whereas the zone of minimum – in the north. In

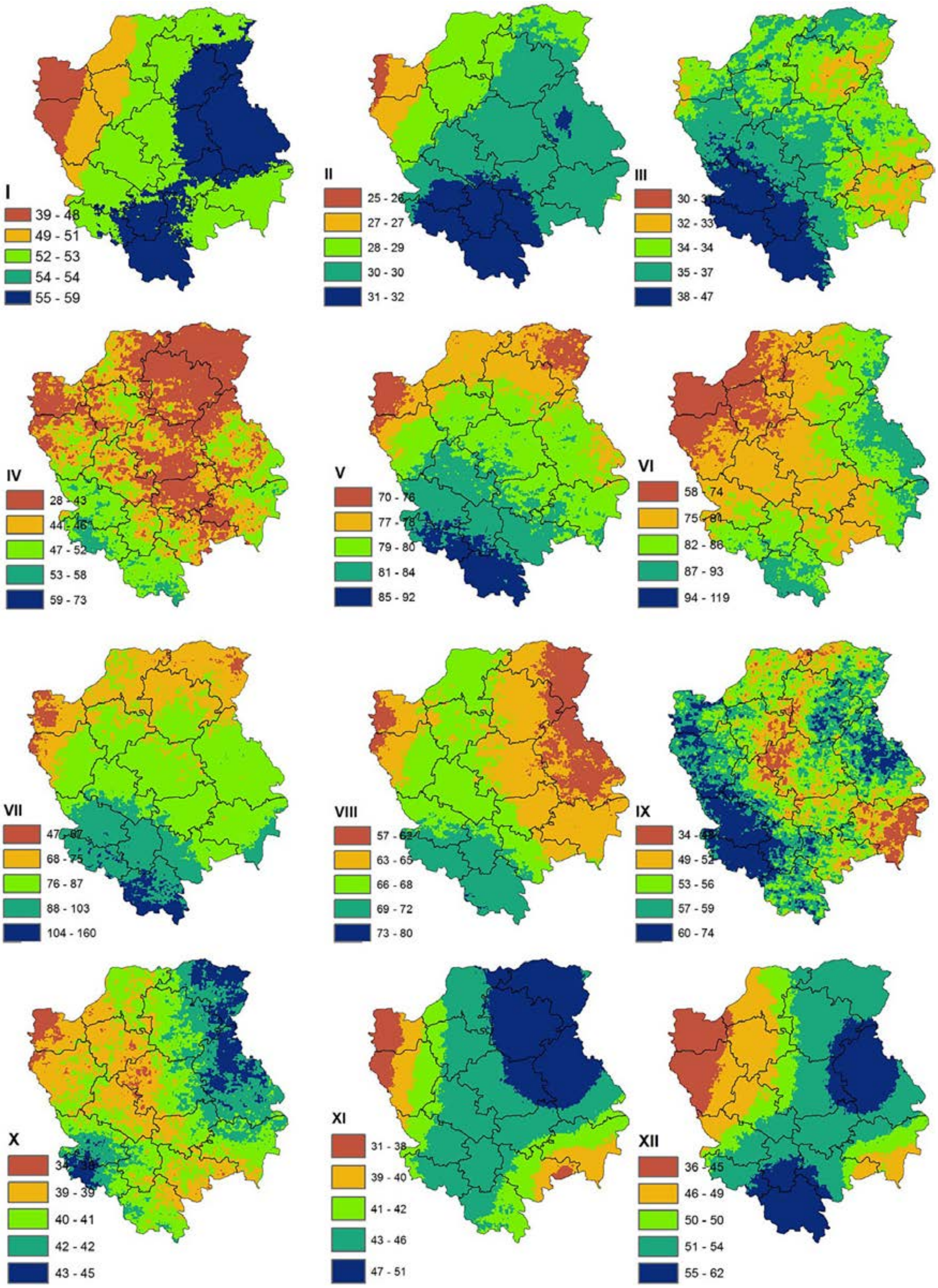

Figure 5. Spatial variation of monthly precipitation in 2010–2016 (I – January, II – February, III – March, IV – April, V – May, VI – June, VII – July, VIII – August, IX – September, X – October, XI – November, XII – December)

May, the pattern of precipitation distribution repeated the April configuration. In June, the zone of maximum remained in the south and the zone of minimum shifted to the west. Significant increase of the general level of precipitation in July takes place mostly in the southern part of the region.

In August, the spatial configuration of precipitation distribution is the same as that observed in July. In September, the maximum of precipitation is observed in the south-west and another local maximum is observed in the east. In October, the eastern zone of maximum prevails and the south-west no longer has advantage. In November, this tendency picks up and compact zone of precipitation maximum in the east of the region is formed as a result, whereas zone of minimum is formed in the western part of the region. In December, two zones of precipitation maximum are observed – in the east and south. Thus, the zones of maximum and minimum precipitation within the area build repeated the spatial patterns of precipitation distribution that are characterized by distribution of the zones of maximum and minimum precipitation in the south and to some extent in the east of the region and the zone of minimum is typical for the east and sometimes for the north of the region.

General picture of precipitation distribution in 2010–2016 repeats the patterns established for the previous period (Fig. 5). Specific features have quantitative character. The level of precipitation in January and February in 2010-2016 increased comparing to the previous period at the same time, spatial pattern of variation of precipitation has not changed significantly. In March in 2010-2016, the zone of maximum precipitation has significantly increased, whereas general variation of precipitation in the region has decreased and became more contrast.

Contrasting effect of precipitation distribution in April in general is somewhat lesser, than in the previous month. A peculiar feature of this month in 2010–2016 is considerable extension of the zone of minimum. The contrasting effect increases in May and the zone of maximum is built

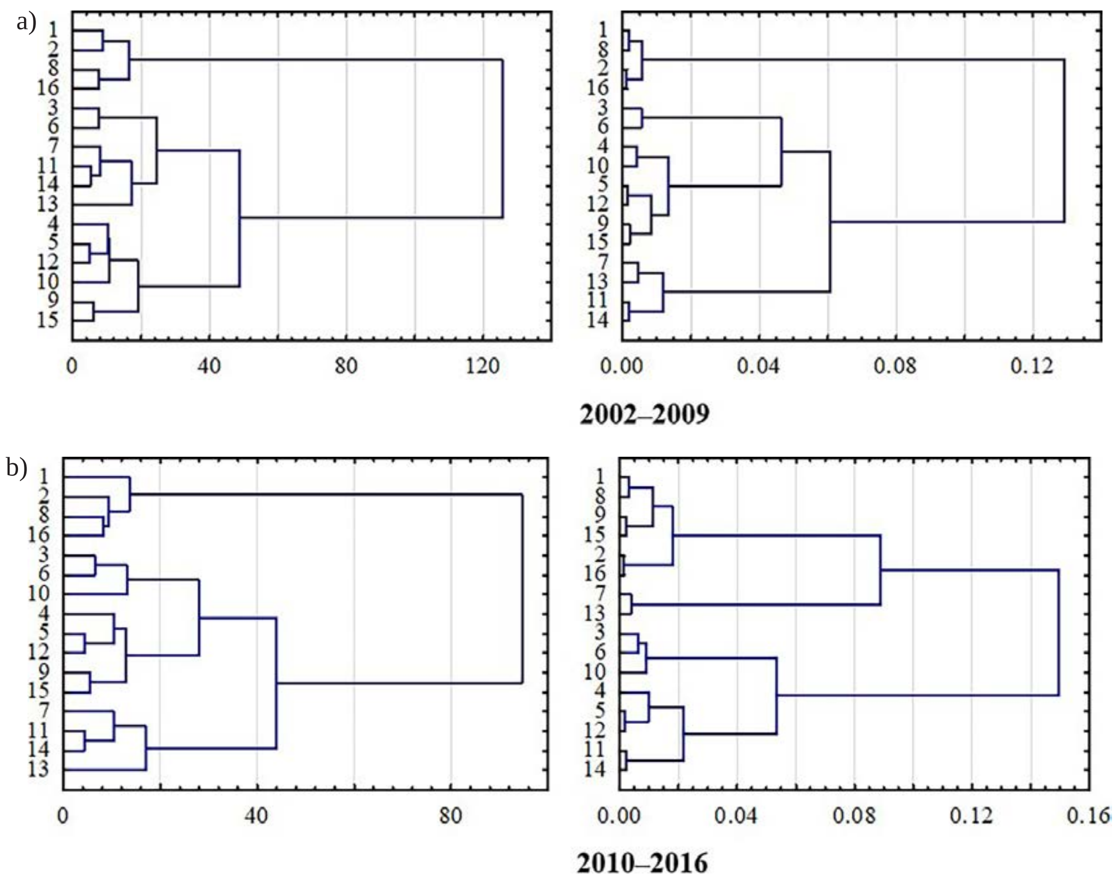

Figure 6. Cluster analysis of administrative districts of the Volyn region according to the Ward-method by annual dynamics of precipitation in 2002–2009 and 2010–2016 ((a) *Euclidean distance*, (b) *Pearson distance*) (1 – Gorohivskyi; 2 – Ivanytskyi; 3 – Kamin Kashyrskyi; 4 – Kiveretskyi; 5 – Kovelskyi; 6 – Lyubeshivskyi; 7 – Lyubomlskyi; 8 – Lokatskyi; 9 – Lutskyi; 10 – Manevytskyi; 11 – Ratnenskyi; 12 – Rozhyschenskyi; 13 – Shatskyi; 14 – Starovyzhivskyi; 15 – Turiyskyi; 16 – Volodymyr-Volynsky)

in the south of the region, whereas two zones of minimum in the northeast and northwest. It should be mentioned that such polarization has not been noted during the previous period of research. Considerable area of precipitation minimum in the northwest of the region is typical for the June pattern of precipitation distribution. The contrasting effect of territorial distribution of precipitation in July decreases in comparison with the previous month, as well as in July of the previous period. The spatial pattern of August in both periods is very much alike. It is characteristic of the September to extend zone of minimum by means of zone of maximum. Under the conditions of general increase of precipitation, it evidences an increase of contrasting effect of spatial distribution regime of precipitation fall. The patterns of precipitation falls in October-December within the region in both periods are very much alike.

Therefore, two investigated periods (2002–2009 and 2010–2016) are characterized by practically equal level of precipitation. The differences between these periods are related to the rhythmicity of precipitation during year and variation of precipitation fall in space. More contrasting regime of precipitation in time is typical of the first period resulting in occurrence of the less durational diapason of annual maximum precipitation in summer. During the second period, this diapason becomes longer and amplitude of this maximum decreases. On the other hand, more contrasting regime of precipitation in space is typical of the second period. The zones of maximum and minimum precipitation acquire distinct limits. The general spatial pattern of precipitation fall and its dynamics during year is an invariant peculiarity of the territory under study.

It is obvious that enhancement of contrasting effect of precipitation in space or time may cause increase of intensity of erosion processes to the extent when intensity of precipitation increases due to such contrasting effect. Consequently, doubtless interest lies in the research of the greater spatial or time contrasting effect of precipitation regime to activate water erosion.

Cluster analysis of precipitation fall by districts within a year has helped to determine three typical groups of administrative regions – clusters (Fig. 6).

Belonging of a certain district to cluster depends not only on quantitative dynamics of precipitation during a year typical of a certain area, but also on the aspect of similarity that was taken as basis for clustering. Euclidean distance and distance based on Pearson correlation coefficient were used for the clustering procedure.

Euclidean metrics is sensitive to absolute distance in many-dimensional space of features between researched objects. In this case, it is an absolute value of precipitation during a year by months. An object will most probably be classified as belonging to a certain cluster based on Euclidean metrics if amount of precipitation is similar to such value for other objects of a respective cluster. Pearson metrics are more sensitive to the form of distribution of values on which clustering is based. The rate of precipitation intensity change, which may be quantitatively estimated with the help of derivative, may be considered as form characteristics.

Cluster solutions for both researched periods according to both distance metrics are similar, but characterized by certain peculiar features. Profile distribution of precipitation within a year characteristic of each cluster may provide for its substantial interpretation (Fig. 7). Cluster 1 is characterized by a certain domination of amount of precipitation practically during whole year with the most increase of this advantage in July. Cluster 2 is characterized by the very low amount of precipitation with the exception of June and July, when precipitation within this cluster is the lowest within the area under study. Respectively, cluster 3 is found between clusters 1 and 2.

Clusters distinguished on the basis of Pearson's metrics are more sensitive to the derivative of flow consistency curve of intensity of precipitation fall, so derivatives were used to interpret relative clusters. Cluster 1 is characterized by the most intense increase of precipitation in July comparing to the previous month. Moreover, the quickest decrease of precipitation in August is typical of this cluster. Thus, cluster 1 represents the territories with the greatest contrasting regime of moisture in summer. The highest rate of precipitation in September is a characteristic of the cluster 2. An increase in the amount of summer precipitation in September is also a peculiar feature of cluster 3, peak of intensity of precipitation in summer stops for cluster 1 in August. Cluster 3 is characterized by the most levelled changes in intensity of precipitation during year.

Clusters make compact spatial formations generally corresponding to the physio-geographical zoning of the territory (Fig. 8). The clusters distinguished based on different metrics can be

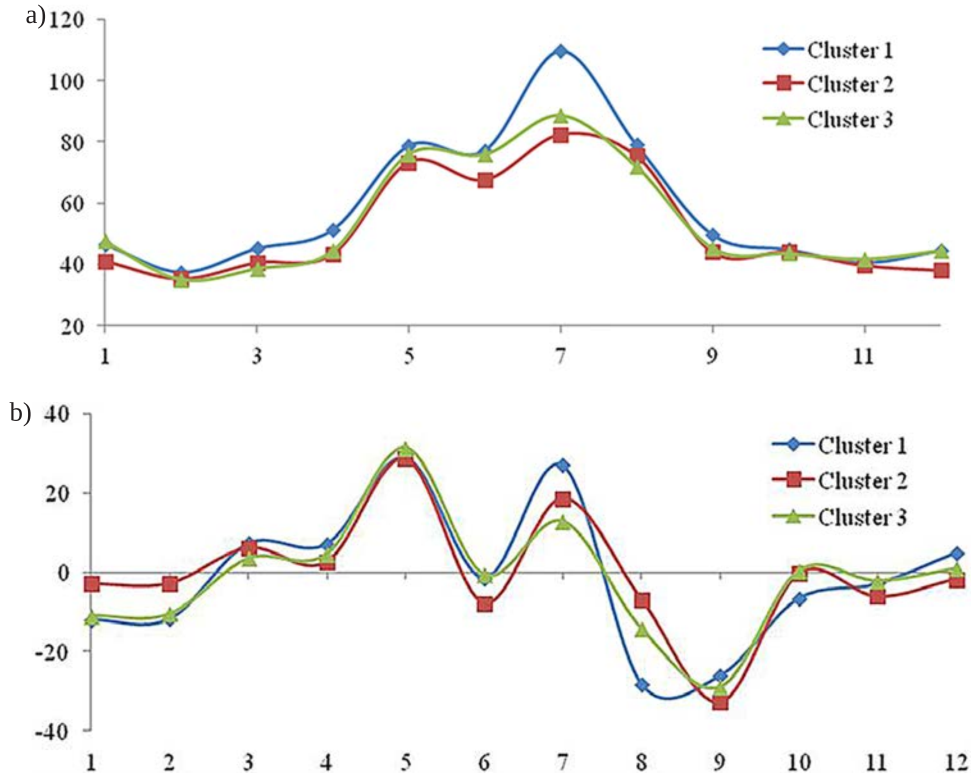

Figure 7. Annual precipitation trend by months within clusters (Abscissa – order of months in year; (a) clusters distinguished on the basis of Eucledean distance, axis of ordinate – precipitation, mm; (b) clusters distinguished on the basis of Pearson's distance; axis of ordinate – derivative of precipitation (growth in comparison with the previous month), mm/month)

compared as well. In this way, cluster 1 in general is related to the Forest-steppe landscapes, cluster 2 – to Polissia and cluster 3 – to transition zone. Nevertheless, such connection is rather broad and it is especially accented by variation of cluster configurations in different periods of research. Main characteristic feature of dynamics of spatial distribution of clusters distinguished based on Euclidean metrics is increase of the area of cluster 3 by means of cluster 2 in 2010–2016 in comparison with previous period. The area of the cluster 2 remained the same. It is obvious that this transformation in the transition zone was conditioned by the increase of precipitation in June and July and decrease of precipitation in August, proceeding from peculiar course of precipitation in time that are typical of clusters 2 and 3. This factor is very important for understanding the dynamics of erosion process, as synchronization of outbreaks of precipitation intensity and density of vegetative cover are, actually, the most important factors that influence water erosion.

Extension of the area of cluster 1 by means of cluster 3 and objects of cluster 3 expanding to the area of cluster 2 are typical of time dynamics of clusters distinguished based on Poisson's metrics. Because of such rotation, cluster 2 that comprised four districts in 2002–2009 was represented by two districts in 2010–2016. In other words, clusters rotated in an anti-clockwise direction. It should be emphasized that the clusters distinguished based on Euclidean and Poisson's metrics at the most coincide, but, this coincidence is not identical either in space, or in time. As it was previously mentioned, Euclidean metrics is more sensitive to the amount of precipitation and Poisson's metrics – to precipitation curve shape or its derivative.

Rainfall Erosivity Factor (R) in 2002–2009 varies 178–734 MJ mm ha $^{-1}$ h^{-1}per year (Fig. 9).

Zone of factor maximum is in the southwest of the region. Zone of minimum is in the eastern and partially northern part of the region. In 2010–2016, figures are slightly smaller. The factor varies from 160–461 MJ mm ha^{-1} h^{-1}per year. Spatial configuration of variation of erosivity factor remained unchanged characterized by more distinct borders of the zone of factor minimum and tendency to the increase in rainfall erosivity factor in the east of the region. In 2002–2009, the

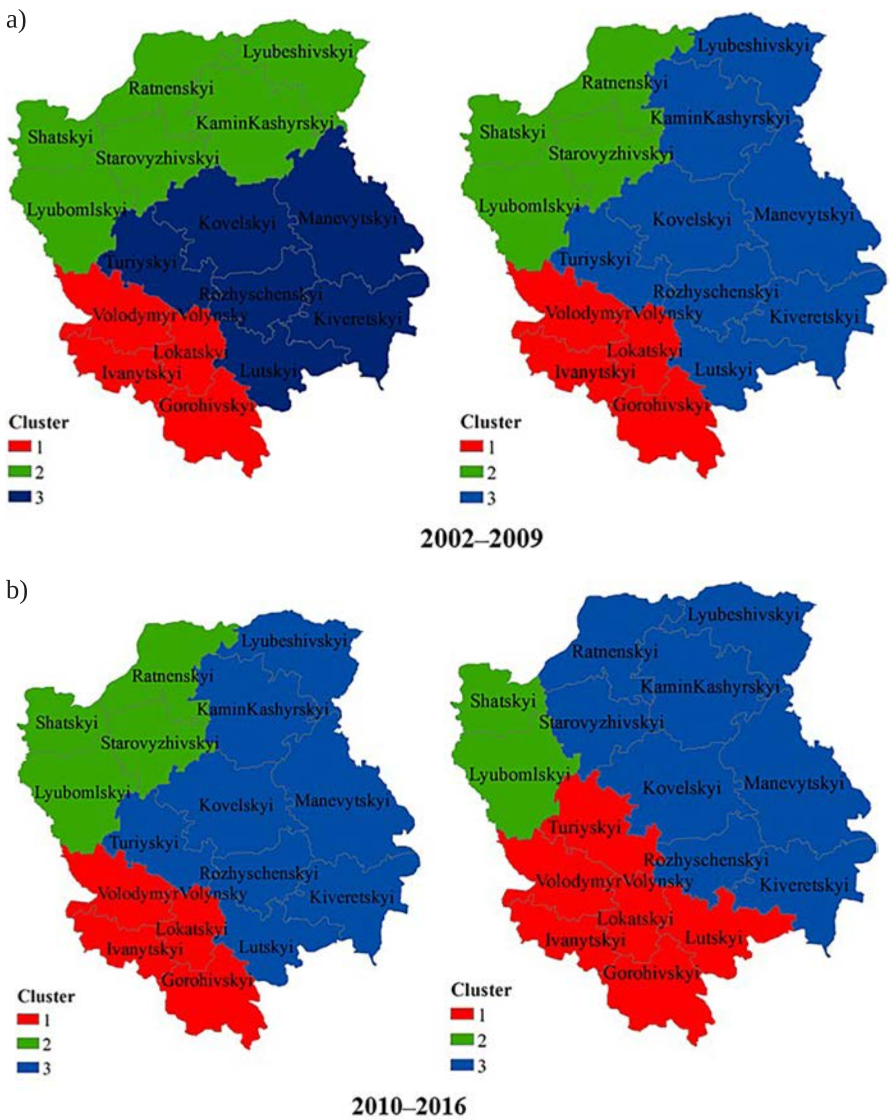

Figure 8. Cluster analysis of precipitation trend by districts within a year (a) Euclidean distance, (b) Pearson's distance

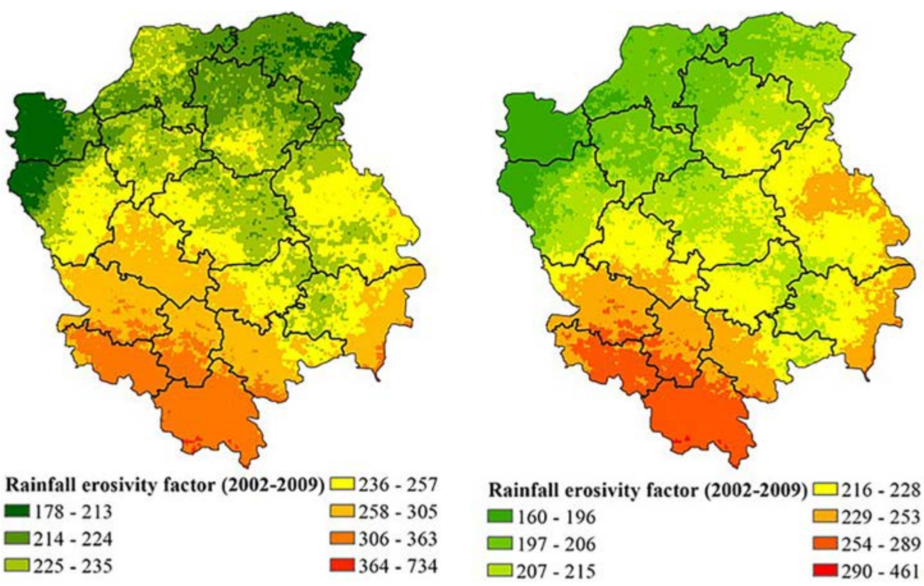

Figure 9. Spatial variation of rainfall erosivity factor (MJ mm ha $^{-1}$ h^{-1} per year)

maximum values of the rainfall erosivity factor were defined in Gorokhivskyi and Ivanytskyi districts (334.1 and 319.9 MJ mm $ha^{-1} h^{-1}$ per year respectively). Minimum values were defined in Turiyskyi and Kamin-Kashyrskyi districts (216.5 and 210.4 MJ mm $ha^{-1} h^{-1}$ per year respectively).

CONCLUSIONS

In 2010–2016, the maximum values of rainfall erosivity factor were defined in Gorokhivskyi and Ivanytskyi districts (268,7 and 257,8 MJ mm $ha^{-1} h^{-1}$ per year respectively). The minimum values were defined in Starovyzhivskyi and Kamin-Kashyrskyi districts (199,7 and 187,2 MJ mm $ha^{-1} h^{-1}$ per year respectively).

When comparing two period of research, the authors came to the conclusion that in 2010–2016 a considerable decrease of the rainfall erosivity factor has take place in comparison with previous period by 9,6–65,4 MJ mm $ha^{-1} h^{-1}$ per year. In the case of Turiyskyi and Kovelskyi districts, the changes in rainfall erosivity factor were minimal (9,6 and 16,7 MJ mm $ha^{-1} h^{-1}$ per year respectively). Conversely, in Gorokhivskyi and Ivanytskyi districts changes were the most powerful – 58,1 and 65,4 MJ mm $ha^{-1} h^{-1}$ per year respectively.

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