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Erosion risk analysis in a changing climate

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Abstract: Soil is an irreplaceable natural resource, with irreplaceable ecosystem functions. One of the greatest risks of soil degradation in the Czech Republic is accelerated erosion, which causes numerous damages to soil properties with negative impacts on the environment. The climate development in recent decades and its forecasts may further intensify these processes. This article deals with the analysis of the impacts of changes in selected climatic factors on the development of erosion processes, which in the conditions of the Czech Republic are influenced mainly by the development of precipitation in the growing season and the development of the values of erosion potential of water released by snowmelt in the winter (non-growing) period. The analysis was carried out on a total area of 459.5 km^2, in different morphological and climatic conditions. The impact of climate change was assessed using historical and updated values of rain erosivity and snow erosion potential factors. The results show an increase in the risk of erosive loss in the growing season for all the analysed areas, while the values of erosive loss in the non-growing period differ from each other depending on the climatic and morphological conditions of the areas under study.

Keywords: climatic factors; erosion loss; snowmelt; vegetation period

One of the most significant problems currently affecting the world's population is the threat of the climate crisis. Global climate change has the potential to threaten all systems that have to cope with the consequences of a new climate state (Parry et al. 2007). Although climate change may affect all aspects of life on Earth, quantifying these impacts remains difficult (Tol 2018). In the Central European region, an increasing number of dry periods, longer duration, more severe drought and extreme rainfall events can be expected as a direct consequence of climate change (Trnka et al. 2016a). The continuing trend can have serious impacts on the quality of soil as an irreplaceable natural resource and source of food production (Pimentel et al. 1976; Hossain et al. 2020) and disrupt soil formation processes that are influenced by climatic conditions, soil substrate, soil organisms, landforms, water and humans (Vácha et al. 2019). Gradual impacts on soil organisms will have a greater degree of negative consequences (Jansson & Hofmockel 2020).

Over time, agro-climatic conditions have changed and agro-climatic factors have been transformed, expanding the areas potentially suitable for agricultural purposes. These changes may lead to efforts to increase the area of arable land as production space and reduce the extent of permanent grassland (Trnka et al. 2021). In the conditions of the Czech

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Republic, we can observe changes in the localization of traditional field crops of warm climatic regions, such as maize, rape, and wheat. Their sowing areas are shifting to higher altitudes. In the context of increased rainfall extremes, a higher risk of soil degradation due to the development of erosion processes can be expected in these areas (CzechGlobe 2016). The most fertile parts of the soil are carried away by erosion (Blaikie 1985; Verheijen et al. 2009; Šarapatka & Bednář 2015). Bennet and Chapline (1928), Wischmeir and Smith (1965, 1978), Jůva et al. (1977), Knisel (1980) defined erosion as a process that can be triggered by water, wind and snow. This process reduces the quality of soil (Butzer 1974; Norton et al. 1999; Šarapatka et al. 2018) and water (Issaka & Ashraf 2017). The climate change that has been taking place in recent decades has also influenced the development of factors entering into the assessment of erosion risks and also the design and sizing of erosion control measures (Garbrecht et al. 2015; Šarapatka & Bednář 2022). In the UK, they compared changes in erosion loss in three different catchments using temperature and precipitation characteristics for the period 1961–1990 and climate scenarios over the horizons 2010–39, 2040–69 and 2070–99. They identified a possible positive effect of increasing temperatures on biomass production and reduced erosive loss (Ciampalini et al. 2020). The study of rainfall erosivity trends for the 1987–2006 climate period and the 2046–2065 model in Iran shows an overall decrease in rainfall erosivity and soil erosion (Doulabian et al. 2021). The role of future land use change and its effect on erosion has been investigated in Belgium. The magnitude of erosion events in the model catchment will increase between 2021 and 2100 according to this research, with a significant increase from 2041 onwards under current land use; current mitigation measures will require significant adjustments to continue to control soil erosion and flooding in 2041–2100 (Brannigan et al. 2022). Apart from erosion processes caused by torrential rainfall, wind erosion and snowmelt erosion are also the focus of attention in the context of climate and climate variability (Edwards et al. 2019). The climate change studies show that a changing climate could increase the intensity and frequency of torrential rainfall, raising concerns about intensive soil erosion and sediment deposition. However, these models often do not take into account the impacts of freeze-thaw cycles (FTC) on soil erosion (Sun et al. 2021). FTCs play an important role in saturating the soil with water and affects the intensity of soil erosion. In cold regions, these processes can cause severe soil erosion due to changes in soil structure and texture (Wang et al. 2021). The changes in precipitation type (i.e., snow or rain), snow accumulation, and snowmelt rates will also have a significant effect on the net precipitation in the watershed (composed of direct precipitation plus snowmelt contribution), which can affect surface runoff, erosion, increased flows, sediment transport, and deposition (Cache et al. 2023). Further, Shen et al. (2020) state, that there are more studies on water erosion, wind erosion, or snowmelt erosion than studies on the effects of coupled soil erosion, such as coupled water and snowmelt erosion. The aim of this paper is to analyse these two erosion processes in a selected area using historical and current climatic factors and to evaluate their degree of connectivity and possible effects.

MATERIAL AND METHODS

The characteristics of the territory. This article uses data for the district of Nový Jičín, which is located in the eastern part of the Czech Republic (Figure 1). Nový Jičín (18°E; 49°42'N) is located in the Moravian-Silesian Region and has an area of 881.8 km^2. The territory of the Nový Jičín district belongs geomorphologically to two distinct geological formations – the Bohemian Highlands with the outcrops of the Nízký Jeseník with the Vítkovská vrchovina and the Carpathian Mountains with the Podbeskydská pahorkatina and the Moravian-Silesian Beskids. Most of the territory has a hilly character, the height difference between the highest and lowest point of the district is 896 m (233 m a.s.l. at Jistebnice Ponds and 1 129 m a.s.l. at the top of Radhošť' Hill). This area is located in the temperate climate zone. The central part of the district is the most favourable climatically; towards the west and east, the climatic conditions become more severe with increasing altitude. Although there are significant differences in climatic conditions across this region, the whole area is suitable for agricultural production, especially the centre of the district, where the demanding crops of the production area (sugar beet, wheat, barley) can be grown with the right agrotechnics. The marginal areas of the district are suitable for less demanding crops (rye, oats, potatoes and especially forage crops). The soils consist mainly of Stagnosols and Fluvisols along the Moravian Gate and Cambisols in the western part of the area. Total area of land parcel is 45 951.53 ha. Arable land is represented by 31 194.85 ha.

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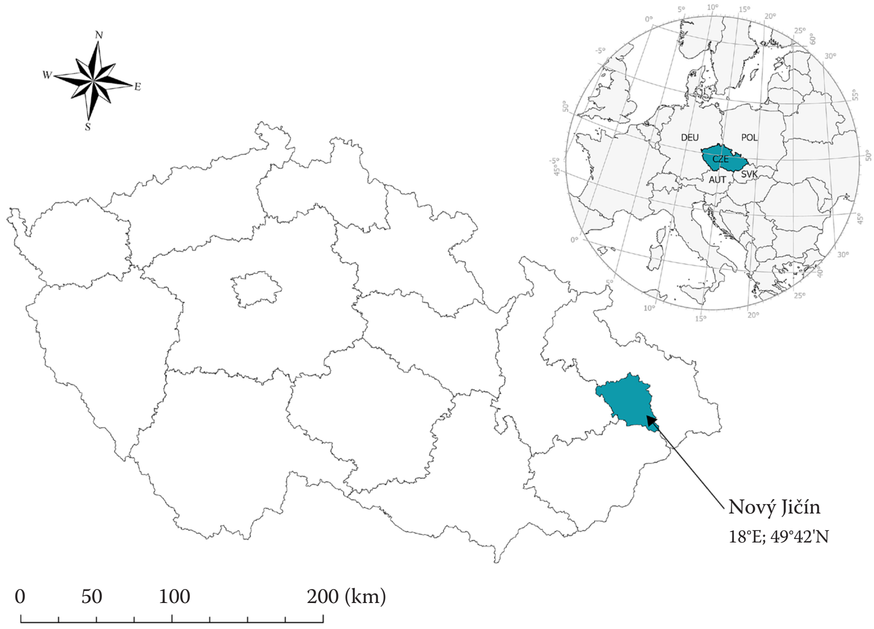

Figure 1. Location of the study area

Methods of determining water erosion risks. The determination of soil loss due to water erosion was used to identify the area of soil loss using GIS analyses in ArcGIS Pro (Ver. 3.0.3, 2023). The Wischmeir and Smith (1978) equation was used to calculate the soil loss, which is used in agricultural and design practice in the Czech Republic and also serves as a basis for determining the degree of erosion hazard in the land parcel identification system (LPIS) to meet the conditions of good agricultural and environmental condition (GAEC) for farmers farming under direct payments. For a detailed analysis of the influence of climatic conditions on erosion, the resulting equation was calculated.

$$E = R \times K \times LS \times C \times P$$

where:

E – intensity of erosion (t·ha^{-1}·year^{-1});
R – rainfall erosivity factor (MJ·ha^{-1}·cm·h^{-1}·year^{-1});
K – soil erodibility factor (t·h·MJ^{-1}·cm^{-1});
LS – topographic factors (–);
C – cropping management factor (–);
P – supporting practices factor (–).

At the present time, it is clear that the values of factors used in agricultural and planning practice to determine soil loss due to water erosion do not correspond to current conditions, which are affected by ongoing climate change. In particular, climate change is propagating into the development of rainfall characteristics. Therefore, the analyses focus on the comparison of erosion using current and updated rainfall erosivity R values.

The rainfall erosion factor R currently used in the methodological procedures (Janeček et al. 2012; SPÚ 2022) is set at a constant value for the Czech Republic, which is equal to 40 MJ·ha^{-1}·cm·h^{-1}·year^{-1} and is based on the evaluation of the normal climate period 1960–1990. The new value of the R factor was determined on the basis of current climatic data from the Czech Hydrometeorological Institute (CHMI) database for the period 1991–2020 using modern statistical approaches, which enabled the regionalisation of the R factor within the Czech Republic (VUMOP 2024). This value is variable within the area under consideration, taking values of 51–98 MJ·ha^{-1}·cm·h^{-1}·year^{-1}. This R factor is referred to as updated (Rch). The soil erodibility factor (K) or soil susceptibility to erosion, is defined in the USLE as the soil loss from a standard plot expressed in t·ha per unit rainfall erodibility factor R (MJ·ha^{-1}·cm·h^{-1}·year^{-1}). Data from the national Estimated Soil Ecological Unit (ESEU) database were used to determine the K factor. Based on the main soil unit, K factor value is assigned to each element of the ESEU vector layer (Janeček et al. 2012). In the area under consideration, the K factor takes values of 0.15–0.59 t·h·MJ^{-1}·cm^{-1}. The USLE2D program (Govers & Van Oost 2000) was used to determine the LS factor using the algorithm of McCool et al. (1987, 1989), which uses the method of calculating the LS factor presented in RUSLE. The procedure for calculating the LS factor is described

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in more detail in the handbook by Dumbrovsky et al. (2008). The digital elevation model of the Digital Terrain Model of the Czech Republic 4th generation and the actual land parcels registered in LPIS were used to calculate the intensity of erosion.

The cropping management factor C was determined for the cultivated crop according to § 3 of Government Regulation No. 307/2014 Coll., on determining the details of land use records according to user relationships, in which the types of agricultural crops are divided. Three groups of agricultural crops were used in the analysis: arable land, permanent grassland and permanent crops. The C factor for arable land was determined on the basis of the results found by Kadlec and Toman (2002), Janeček et al. (2012). Kadlec and Toman (2002) do not consider the C factor for permanent crops, therefore the C factor was set at 0.22 for permanent crops registered in LPIS – eg. orchards, vineyards, hops, where only partial grassing was used (Agroprojekt 1988). Permanent grassland was entered into the calculation with a factor value of C = 0.005 (full grassing). For the overall erosion calculation, the value of the supporting practices factor (P = 1) was set, which means the use of erosion control measures such as contour farming or crop rotation strips was not considered (Janeček et al. 2012). The individual factors of the equation are converted to raster surface layers or constants using appropriate ArcGIS Pro tools. A cell size of 10 × 10 m was used to create raster bases of these factors.

Methods of determining snowmelt erosion risks. The snowmelt erosion intensity of Zachar (1982) is based on the universal equation for calculating long-term soil loss from land as given by Wischmeier and Smith (1978), in which the factor R is replaced by the factors snowmelt rate and the amount of water produced by snowmelt over a 20-day period.

The empirical equation for calculating erosion from snowmelt:

$$Es = m \times h \times k \times LS \times C \times P \times K$$

where:
Es – intensity of erosion (t·ha^{-1}·year^{-1});
m – factor of snow melting rate (mm·day^{-1});
h – factor of amount of water derived from snow during the 20-day period (cm);
k – factor of runoff water multiplied by 1.5 to 3 (according to the state of soil freezing).

The values of m and h can be replaced by the value of the so-called erosion potential (EP) which is the amount of water accumulated in the snow cover. The erosion potential of water accumulated in the snow cover can be derived from the CHMI database on the water value of snow (SVH) and total snow cover (SCE) according to Janeček et al. (2012) and Smolíková (2010). The modified Zachar equation (Zachar 1982) is then related to:

$$Es = EP \times k \times LS \times C \times P \times K \text{ (t·ha}^{-1}\text{·year}^{-1}\text{)}$$

The erosion potential (EP) was used to determine a map of potential soil erosion from snowmelt. For the purpose of this study, the EP maps developed from the CHMI data for the normal period 1981–2010 (EP) and for the period 1991–2020 (the updated erosion potential – EPch) were used. The values of EP and EPch are variable within the study area and can range from 0–274 cm·mm·day^{-1} for EP and 0–228 cm·mm·day^{-1} for EPch. These values were derived from the Map of Erosion Potential for the Czech Republic (Janeček et al. 2012; Podhrázská at al. 2022) The value of the runoff coefficient during the snowmelt period when the soil is saturated with water is equal to 0.5. The value of k is multiplied by a number from the interval 1.5 to 3 according to the soil freezing with respect to the possibility of water infiltration into the soil and the soil susceptibility to erosion. In the case, where data on soil freezing is not available, the mean value of the coefficient for frozen soil can be used 2 (the value of the runoff water coefficient is then k = 1).

The process for determining soil erosivity factors, gradient, topographic factor and effectiveness of antierosion measures (K, LS, and P) is the same for snowmelt erosion as for calculating soil loss due to the erosive effect of torrential precipitation.

The analysis of factor C in the non-vegetation period has been dealt with in the past mainly by the Mendel University team and e.g. Malenová and Toman (2005); Pokladníková et al. (2008); Středová and Toman (2012). The determination of factor C values can be done according to the equation:

$$C_{NO} = 0.8656C_{VO} + 0.128$$

where:
C_{NO} – C factor for non-vegetation season;
C_{VO} – C factor for vegetation season.

The C factor value must be determined for the period of occurrence of erosionally dangerous snowmelt.

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The tackled area is in climate region 6, 7 and 8, so the factor C value for non-vegetation season C_{NO} = 0.315; 0.304; 0.294 (Janeček et al. 2012); for growing season was chosen that one by Kadlec and Toman (2002) C = 0.216; 0.204; 0.192. For the localities with a permanent grass cover (full grassing), there was selected the C factor = 0.005 for both equations.

Determination of the soil erosion limit. In order to determine the risk level of excessive erosion in the selected area, it was necessary to determine the limit of long-term soil erosion. The Regulation No. 240/2021 on soil erosion protection came into force in the Czech Republic in 2021. This regulation sets the permissible long-term soil loss from erosion at 9 $t \cdot ha^{-1} \cdot year^{-1}$ for medium and deep soils and 2 $t \cdot ha^{-1} \cdot year^{-1}$ for shallow soils. However, at the same time, in the process of land consolidation (SPÚ 2022), the value of erosion limit according to the methodology of Janeček et al. (2012) of 4 $t \cdot ha^{-1} \cdot year^{-1}$ for medium and deep soils and 1 $t \cdot ha^{-1} \cdot year^{-1}$ for shallow soils is used to assess the erosion rate.

This approach was followed in the land consolidation for reasons of ensuring methodological continuity until the new methodological regulations for land consolidation were issued. For the purpose of this study, both limits of erosion were taken into account and compared with the calculated long-term soil loss in the study area. The erosion limit was calculated as the area average of the shallow, medium and deep soil limits. The histogram method was used via ArcGIS Pro tools to determine what areal proportion of agricultural land has an erosion hazard lower than the calculated limit. The LPIS were used to determine the erosion rated areas.

RESULTS AND DISCUSION

The analysis of erosion loss during the growing period (E) was performed for two specified values of the rainfall erosivity factor – the concurrently used value (R) and the updated value (Rch). The simultaneously used (EP) and updated erosion potential (EPch) were used to calculate the erosion potential from snowmelt (Es). Figure 2 shows the erosion loss calculated for these four values in the form of a box plot – in the middle of the box is bounded above by the 3rd quartile (75th percentile), below by the 1st quartile (25th percentile) and between them is a line defining the median. The cross inside the box plot shows the average value.

Using the R value to calculate the erosion rate, the median was 9.05 $t \cdot ha^{-1} \cdot year^{-1}$. When Rch was used to calculate erosion loss, there was an increase in values, with the median value being 13.18 $t \cdot ha^{-1} \cdot year^{-1}$. When evaluating snowmelt erosion, the results did not differ significantly when using Ep and EPch. The median for EP is 0.59 $t \cdot ha^{-1} \cdot year^{-1}$, while the median using EPch has a value of 0.63 $t \cdot ha^{-1} \cdot year^{-1}$. It is clear from the above, that updating the R factor climate data can have a significant effect on the erosion loss values from torrential rainfall. In the case of the snowmelt erosion assessment in the Nový Jičín district, no significant changes in erosion loss values are observed using the current and updated values, but a slight increase is observed in the case of EPch. With the change in climatic conditions over the year, soils dry out and soil retention decreases, then the soil becomes susceptible which is mainly reflected by the Rch factor. Trnka et al. (2016b) point out the increased risk of drought and erosion which will change the level of vulnerability and negatively affect soil quality and crop production. Brázdil et al. (2022) confirm that temperatures are increasing in the Czech Republic but note that periodic lower temperatures were observed in the 1850s.

Further analyses were carried out to identify the effects of the different forms of erosion in the study area by cadastre. Figure 3 shows the cadastral areas where water erosion in growing period (green), snow thawing erosion in non-growing period (blue) and

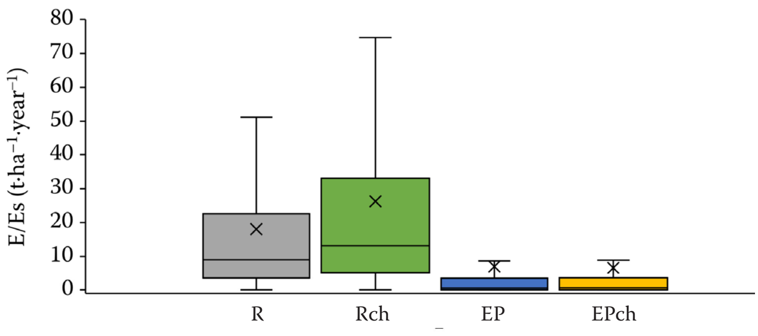

Figure 2. Erosion loss on arable land in the Nový Jičín district

E – intensity of erosion; Es – intensity of erosion from snowmelt; R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

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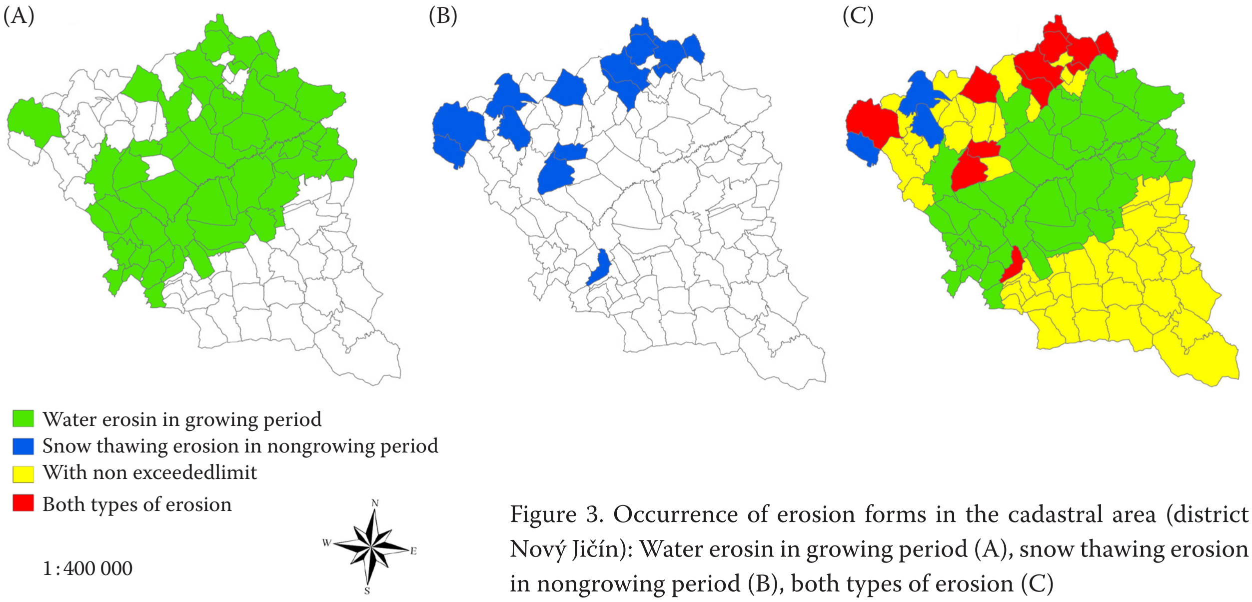

Figure 3. Occurrence of erosion forms in the cadastral area (district Nový Jičín): Water erosin in growing period (A), snow thawing erosion in nongrowing period (B), both types of erosion (C)

areas with non-exceeded limit (yellow) were identified. It also shows cadastral areas where both types of erosion processes are present (red). All these results are reported as the median values.

The cadastral areas were divided according to whether only one form of erosion (water erosion in growing period or snow thawing erosion in nongrowing period) or both types of erosion processes are present, and into areas where the erosion limit was not exceeded. Furthermore, an analysis was carried out of the areas where the permissible erosion loss was exceeded, both according to the current regulation (Regulation 240/2021), i.e. the limit of 9 t·ha^{-1}·year^{-1}, and according to the methodological guidelines (SPÚ 2022), i.e. 4 t·ha^{-1}·year^{-1}. The regulation is linked to the subsidy policy for farmers, which serves as an instrument for the protection of agricultural land. A limit of 4 t·ha^{-1}·year^{-1} is prepared for the change in climatic conditions and the tightening of soil protection, as laid down in the methodological guidelines for land development. Panagos et al. (2021) indicates that climate change will lead to an increase in erosion rates, with soil erosion expected to double by 2050. The future increase in erosion on a global scale is confirmed by Borelli et al. (2020). Furthermore, Panagos et al. (2021) describes, that agri-environmental policy is an appropriate tool. When the limit is exceeded, the creation of anti-erosion measures is an effective tool. These measures improve the soil condition, this statement is in line with Kadlec et al. (2014).

Table 1 shows the number of cadastral areas, according to the limits of permissible erosion loss for each form of erosion and coupled effects, and according to the current and updated values of climatic factors. The total number of cadastral areas is 113. In some cadastral areas both types of erosion occur. For this reason, the number of cadastres at risk may be greater than 113 when both erosions are combined.

The table shows that in the case of erosion from torrential rainfall, almost half of the area is affected by excessive erosion if the permissible limit according to the methodological guidelines (SPÚ 2022) is set at 4 t·ha^{-1}·year^{-1}. Using the currently valid R factor, 44 cadastral areas are affected by excessive erosion. if we use updated R factor (Rch) data, 49 cadastral areas are affected by excessive erosion. In the case of snowmelt erosion, the situation is different. The development of snowmelt erosion is clearly influenced by the ongoing climate changes in winter. There is a decrease in the number of catalogue areas with excessive erosion in winter. In cases where the two processes are combined in one cat. area, excessive erosion occurs in 12 and 14 areas respectively when the limit of 4 t·ha^{-1}·year^{-1} is applied, and in only 6 areas when the limit of 9 t·ha^{-1}·year^{-1} is applied. With a limit of 4 t·ha^{-1}·year^{-1}, a total of 15 areas are at risk of erosion from snowmelt, with a limit of 9 t·ha^{-1}·year^{-1}, a total of 7 areas are at risk. For the new data (Rch and EPch) there is an increase in erosion values from heavy precipitation.

Table 2 shows the percentage of areas affected by each form of erosion, the combination of both types of erosion and areas where the erosion loss limit has not been exceeded. The table includes

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Table 1. Number of cadastral areas (CA) according to the established limits of erosion loss for individual forms of erosion

Limit ($t{\cdot}ha^{-1}{\cdot}year^{-1}$)	No. of CA	Only water erosion in growing period, number of CA with exceeded limit	Only snowmelt erosion in non-growing period, number of CA with exceeded limit	Both types of erosion, number of CA with exceeded limit	Number of CA with non-exceeded limit
4 (R/EP)	113	44	3	12	54
4 (Rch/EPch)	113	49	1	14	49
9 (R/EP)	113	29	1	6	77
9 (Rch/EPch)	113	37	1	6	69

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

all agricultural land such as arable land, orchards, permanent grassland, etc.

If we evaluate the erosion loss using the currently valid R/EP values above the limit of 4 $t{\cdot}ha^{-1}{\cdot}year^{-1}$, 41.16% of the land parcels are threatened by excessive erosion in the growing season, 1.53% by erosion from snowmelt, and 14.17% of the land parcels are threatened by associated forms of erosion. When evaluating the erosion loss using the values of Rch/EPch (updated values of both factors) and with an erosion loss limit of 4 $t{\cdot}ha^{-1}{\cdot}year^{-1}$, the area threatened by above-limit erosion in the growing season increases to 45.26%, but also the area of land parcels threatened by associated forms of erosion increases to 15.87%. The change is also evident for the limit of 9 $t{\cdot}ha^{-1}{\cdot}year^{-1}$. This result shows that in the district of Nový Jičín the risk of erosion from snowmelt is decreasing, but the risk of erosion in the growing season is increasing.

Figure 4 shows the analysed land parcels in the area of interest (district Nový Jičín). The land parcels are divided according to the risk category: water erosion in growing period, snowmelt erosion in non-growing period, both types of erosion and with non-exceeded limit. The limit is set at 4 $t{\cdot}ha^{-1}{\cdot}year^{-1}$ and 9 $t{\cdot}ha^{-1}{\cdot}year^{-1}$. Without exceeding the limit, the south of the area and places in the north-west are particularly affected. The exceeded limit for water erosion alone occurs in a belt from north-east to south-west. Snowmelt erosion alone occurs sporadically in the northwestern part. The most at risk areas for both types of erosion are located mainly in the north of the area.

Table 3 shows the size of land parcels (LP) where the erosion loss limit was exceeded according to the given criteria.

The analysis shows that the largest percentage of the area at risk of excessive erosion (89.17% of the area) is when using the updated climate factor for erosion from heavy rainfall (Rch), and a limit of 4 $t{\cdot}ha^{-1}{\cdot}year^{-1}$. In the case of erosion from snowmelt, the highest percentage of areas at risk is found when using the EPch values for the limit of 4 $t{\cdot}ha^{-1}{\cdot}year^{-1}$, namely 23.56%. Comparing the percentages of areas affected by excessive erosion for both erosion loss limits, it can be concluded that when comparing the erosion loss values using the simultaneously valid and updated climate factor for erosion in the growing period (R respectively Rch), the percentage of areas affected by excessive erosion is 23.56%. Rch), there was a significant decrease in the area at excessive risk at the higher limit (9 $t{\cdot}ha^{-1}{\cdot}year^{-1}$) using both

Table 2. Percentage of land area in the district according to specified criteria

Limit ($t{\cdot}ha^{-1}{\cdot}year^{-1}$)	Total area of land parcels (ha)	Only water erosion in the growing period, area of land parcels with exceeded limit	Only snowmelt erosion in non-growing period, area of land parcels with exceeded limit	Both types of erosion, area of land parcels with exceeded limit	Area of land parcels with non-exceeded limit
4 (R/EP)	45 951.53	41.16	1.53	14.17	43.13
4 (Rch/EPch)	45 951.53	45.26	0.24	15.87	38.64
9 (R/EP)	45 951.53	33.30	2.05	8.34	56.31
9 (Rch/EPch)	45 951.53	38.57	0.73	9.49	51.21

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

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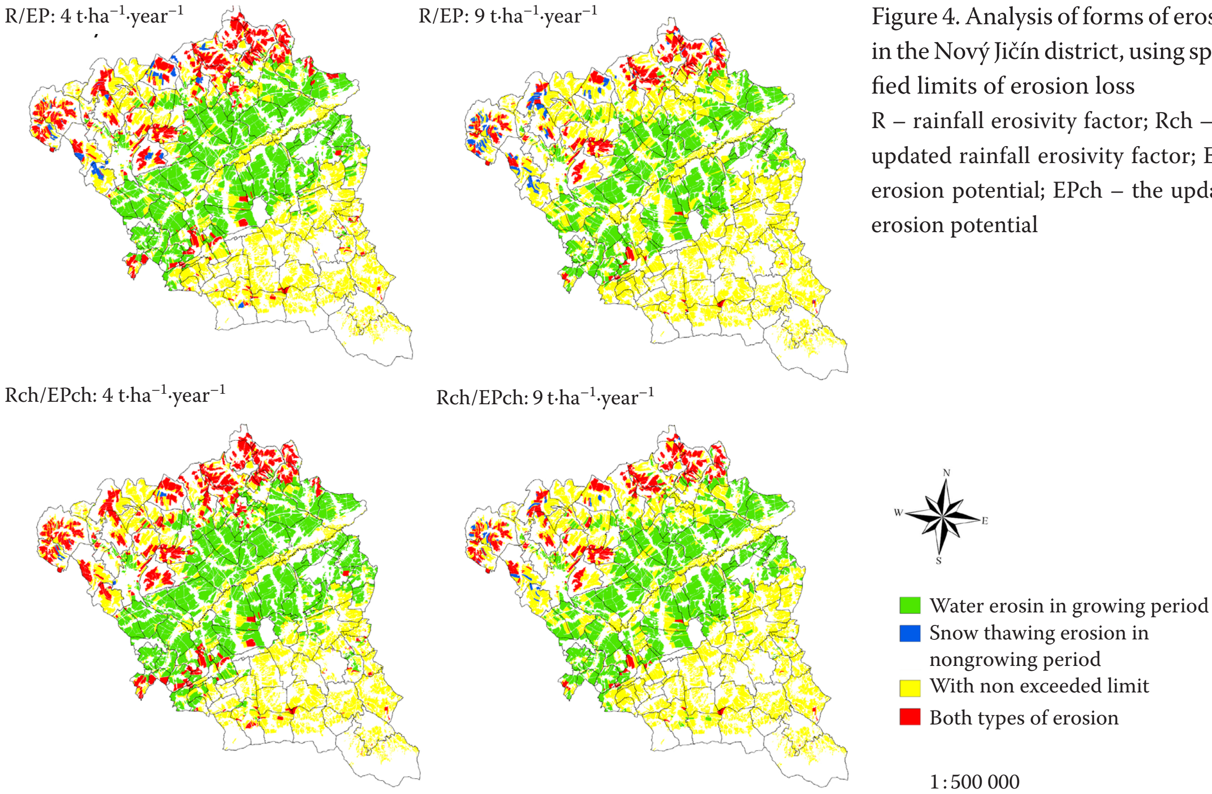

Figure 4. Analysis of forms of erosion in the Nový Jičín district, using specified limits of erosion loss

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

R and Rch, around 20%. If we evaluate the same percentage of areas, affected by excessive erosion from snowmelt, the situation is similar (reduction of about 8%), only the percentage of areas affected by this form of erosion is lower. When comparing the erosion loss using the current and updated R/Rch values, there is a clear increase in the area affected by excessive erosion of approximately 9% regardless of the erosion limit. If the erosion loss from snowmelt (EP, EPch) is evaluated similarly, the situation is different. When using a limit of 4 t·ha^{-1}·year^{-1} the proportion of areas with excessive erosion increases slightly (approx. 0.5%), when using a limit of 9 t·ha^{-1}·year^{-1} the proportion of areas with excessive erosion decreases slightly (approx. 0.2%).

Table 3. Total area of arable land parcels with exceeded limit

		4 (t·ha^{-1}·year^{-1})	9 (t·ha^{-1}·year^{-1})
Present values of climatic factors			
R: the size of the LP with exceeded limit	(ha)	25 180.33	18 964.63
	(%)	80.72	60.79
EP: the size of the LP with exceeded limit	(ha)	7 162.38	4 736.86
	(%)	22.96	15.18
Updated values of climatic factors			
Rch: the size of the LP with exceeded limit	(ha)	27 816.99	21 877.88
	(%)	89.17	70.13
EPch: the size of LP with exceeded limit	(ha)	7 348.28	4 661.66
	(%)	23.56	14.94
Total size of arable LP	(ha)	31 194.85	31 194.85

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential; LP – land parcels

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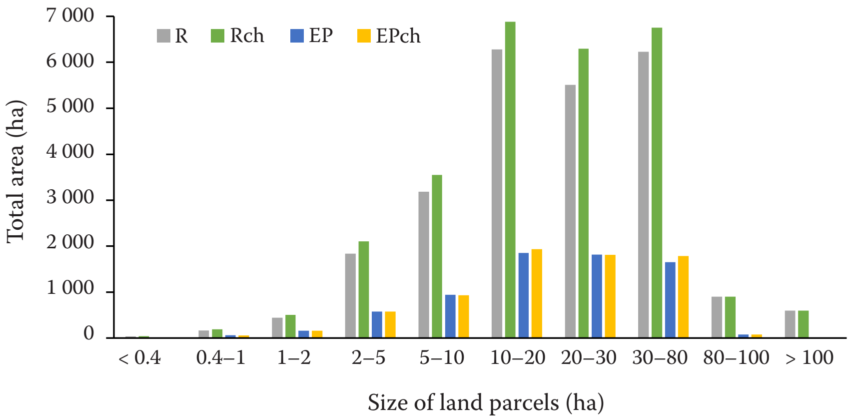

Figure 5. Distribution of the area of arable land affected by erosion of more than 4 t·ha^{-1}·year^{-1}

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

Figures 5 and 6 show the overall distribution of the area of arable land at risk with respect to land size. Large land parcels over 80 ha are less threatened because these land parcels are less represented in the area of interest (district Nový Jičín).

The most affected areas are in the category of 10 to 80 ha, with a significant share of erosion from torrential rainfall. When comparing simultaneously valid and updated data of climate factors R and Rch, an increase in arable land affected by excessive erosion can be detected, the biggest difference being in the 20–30 ha category, where the increase is 788 ha. In the case of erosion from snowmelt and a similar comparison of excessive erosion, the results differ slightly, but in the 30–80 ha category the increase in areas with excessive erosion using EPch is up to 131 ha.

Using a limit of 9 t·ha^{-1}·year^{-1}, arable land on land parcels of 30–80 ha is most at risk of excessive erosion at both values (R/Rch), with an increase in arable land area of 751 ha at Rch. Again, arable land blocks of 10–20, 20–30 and 30–80 ha are most at risk. Our results are in line with the final report of the farmland erosion monitoring (Kapička et al. 2021), which states that the most affected land parcels are 10–20 and 30–80 ha. It is further shown that all other categories take on similar values.

The slope of the land also has a significant effect on the magnitude of erosion loss. The Figures 7 and 8 present the results of the effect of the average slope of the land parcels on the magnitude of excessive erosion loss according to the limits used. Jáchymová et al. (2017) state that the danger is especially for large areas with high slope, which corresponds with the observed results. These results are also confirmed by (Wu & Wang 2011; Liu et al. 2014 and Mahmoodabadi & Sajjadi 2016).

The analyses show that arable land with a slope greater than 25° are the least at risk, due to the fact that arable land is rarely found on these land parcels. The largest percentage of arable land parcels at excessive risk of erosion from heavy rainfall (R and Rch) belongs to the slight slope (3–7°) and medium slope (7–12°) categories. In contrast, land with higher slopes is more at risk of excessive erosion from snowmelt. (EP and EPch) is the most at risk are land parcels with medium slope (7–12°) and significant slope (12–17°), which are mostly located at higher elevations. Our results are in line with the final report of the farmland erosion

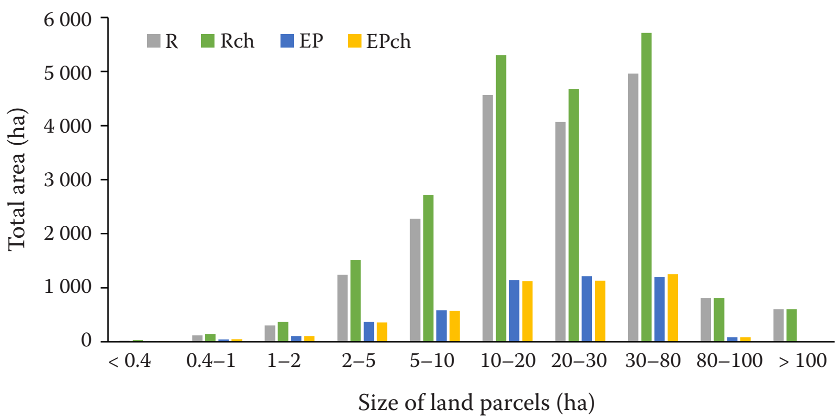

Figure 6. Distribution of the area of arable land affected by erosion of more than 9 t·ha^{-1}·year^{-1}

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

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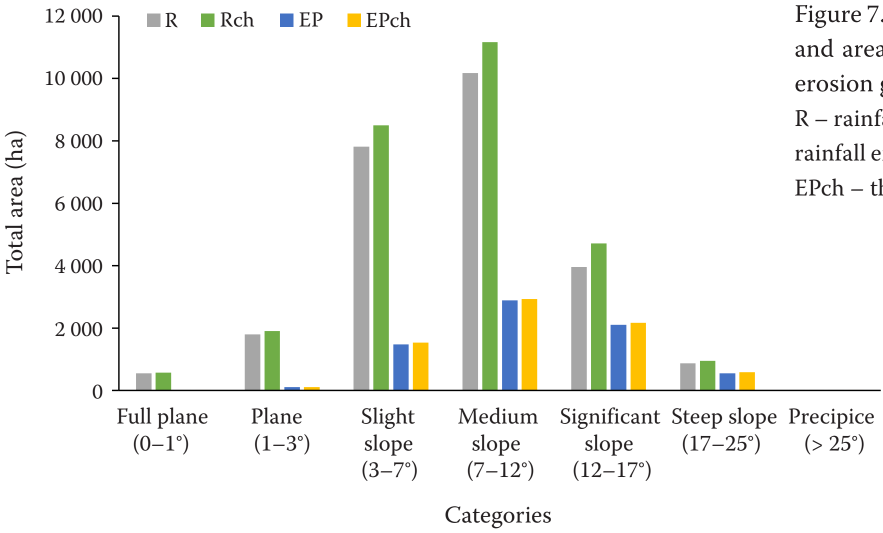

Figure 7. Slope categories (maximum slope) and areas of arable land affected by excess erosion greater than 4 t·ha^{-1}·year^{-1}

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

monitoring (Kapička et al. 2021). Erosion reduction can be achieved by following the Good Agricultural and Environmental Condition (GAEC) standards, which set out the principles for managing higher slope land. Van Oost et al. (2006) state that on higher gradient land, the land should be cultivated in a suitable way that eliminates erosion risks. Not only proper tillage, but also appropriate seeding practices have an impact on soil erosion (Hammerová et al. 2016; Chen et al. 2022; Preiti et al. 2022). According to Arnhold et al. (2014), conventional farming shows higher soil loss compared to organic farming.

CONCLUSION

Soil protection within the EU has become a key issue in recent decades and will remain a key issue in the future (Janků et al. 2022). Many studies address the future impact of climate change on soil erosion risks, soil management and changes in cropping patterns. Scenarios of future changes in climate factors and their impacts have been developed (Li & Fang 2016; Anderson et al. 2020; Edwards et al. 2019; Brannigan et al. 2022; Eekhout & de Vante 2022; and many others). In our paper, we focus on the impacts of real changes in climate factors affecting erosion processes. Methodologically, the values of climatic factors affecting erosion are back-calculated from 30 years of normal precipitation data. These factors are currently being re-evaluated using new normal periods. The use of existing and updated data of climatic factors for the assessment of erosion processes gives room for comparison of changes that will directly affect both the assessment of erosion risk for

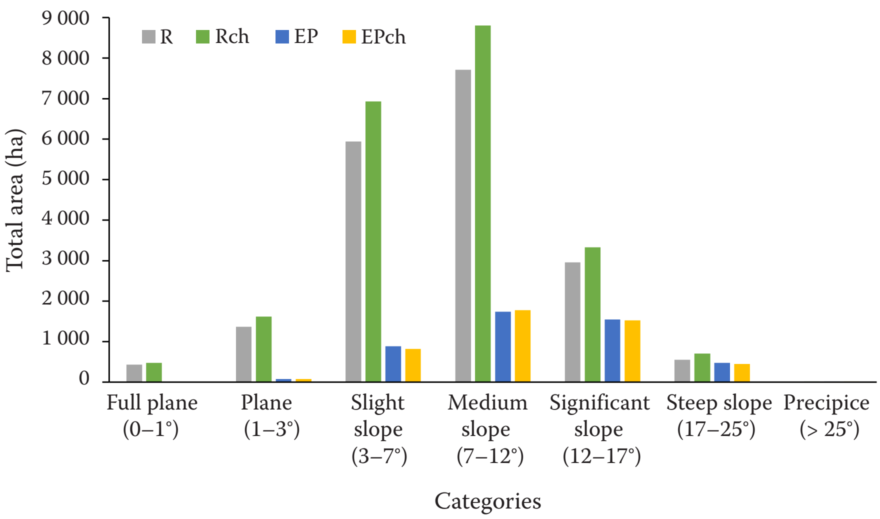

Figure 8. Slope categories (maximum slope) and areas of arable land affected by excess erosion greater than 9 t·ha^{-1}·year^{-1}

R – rainfall erosivity factor; Rch – the updated rainfall erosivity factor; EP – erosion potential; EPch – the updated erosion potential

the purpose of implementing the legislative measures in the form of a regulation (Regulation 240/2021) and the objectives of land consolidation, which set stricter rules for compliance with soil protection principles. The risk of soil erosion from snowmelt was also taken into account and the possible effects of changing erosion potential values on erosion loss in the non-growing period were analysed:

– Using updated rainfall erosivity data (Rch), the modelling identified an increase in the area of arable land (for the 4 t·ha^{-1}·year^{-1} limit by 8.45% and for the 9 t·ha^{-1}·year^{-1} limit by 9.34%) excessively vulnerable to water erosion. The increase for both limits is approximately 9%.
– The updated snowmelt erosion potential data provided different results for different limits of permissible erosion loss. On arable land, for the 4 t·ha^{-1}·year^{-1} limit, there was a 0.60% increase in erosion loss, and for the 9 t·ha^{-1}·year^{-1} limit, there was a 0.24% decrease in erosion loss. This statement can be applied to sites with similar characteristics. For lower elevations with higher temperatures, where the snow stays for only a short time, there will be more rapid erosive loss in the non-growing period.
– The risk of excessive erosion is also increased when erosion processes coexist, as these processes take place throughout the year. It has been identified 12 (R/EP) and 16 (Rch/EPch) cadastral areas at risk for the limit of 4 t·ha^{-1}·year^{-1}. There are three cadastral areas at risk for a limit of 9 t·ha^{-1}·year^{-1}. Figure 4 has been created to show the vulnerability of each land parcels for greater detail.
– When we compare the results of the erosion process assessment using the updated values of the climatic factors, we conclude that when the permissible erosion loss is set at 9 t·ha^{-1}·year^{-1} the area at risk of erosion is 10.4% ha more than the original area, when the permissible erosion loss is set at 4 t·ha^{-1}·year^{-1} the area at risk increases by 7.5%

The change in the R factor (Rch) is the most significant contributor to the increase in the area at excessive risk of erosion, while the change in the erosion potential (EPch) has a minimal effect. The results are valid for the area of interest Nový Jičín, which is located at the area of foothills. Despite the fact that the update of the erosion potential values revealed a decrease in its maximum values, the size of the area affected by excessive loss varied only minimally. The results of this study indicate that the size of areas excessively threatened by water erosion increases due to the update of the rainfall erosivity factor in the calculation of erosion intensity by the standard USLE method. This needs to be taken into account when selecting a system of erosion control measures, both in the area of arable land, where modern agrotechnical and organisational measures are to be applied and in the choice of technical measures. Only technical erosion control measures can permanently optimise the size and shape of land parcels to reduce erosion processes. In the conditions of the Czech Republic, the standard proposed measures against water erosion are usually sufficient to protect the soil in the non-growing period. In areas where snowmelt damage is frequent and where a higher erosion runoff from snowmelt than from heavy rainfall is detected, it is advisable to increase soil protection in the non-growing period and to design erosion protection measures in view of the higher erosion runoff value detected. For the protection of arable land in non-growing period it is very important to keep the soil surface covered by the winter crops, post-harvest residues or intercrops in combination with technical measures, that have also very important effect against water erosion.

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