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The impact of climate change on the risk of soil erosion by water in the flysch zone of Istria, Croatia

Utjecaj klimatskih promjena na rizik od erozije tla vodom u flišnoj zoni Istre u Hrvatskoj

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ABSTRACT

Soil erosion by water is the most significant and dangerous process of soil degradation and loss. The flysch area of Istria is one of the most vulnerable regions to soil erosion by water in Croatia. The CORINE model for the period 1995–2024 was used to assess the risk of soil erosion by water in the Pazin area, and climate data (mean annual rainfall and air temperature) were analysed for three subperiods: 1995–2004, 2005–2014, and 2015–2024. Climate change was particularly evident in the third subperiod compared to the first, with 138.6 mm more rainfall and a 0.8 °C increase in temperature. The rainfall erosivity index increased from 6 (1981-1995) to 8 (1995-2024). A high potential risk of soil erosion by water was identified on 87.2% of the flysch zone area, moderate on 11.3%, and low on 1.5%. The actual risk of erosion was decreased and was high on 13% of the area, moderate on 77.9%, and low on 9.1%. On cultivated land, the potential risk of soil erosion by water matches the actual risk. When the potential risk of erosion increases to moderate and high on cultivated land, the actual risk of soil erosion by water rises by one and two classes, respectively. If abandoned land were converted into arable land, the areas with the actual risk of erosion would increase to 47.2%. In addition to vegetation cover and land use, it is essential to combine other anti-erosion soil protection methods (conservation, agrotechnical, and recovery). The maps of the potential and actual risk of soil erosion by water provide an important basis for further planning and land management aimed at sustainable development, rational use, and soil protection against erosion damage.

Keywords: potential and actual risk, CORINE, Istria, rainfall regime, land use

SAŽETAK

Erozija tla vodom predstavlja najznačajniji i najopasniji proces oštećenja i gubitka tla. Flišna zona Istre jedno je od najugroženijih područja od erozije tla vodom u Hrvatskoj. Za procjenu rizika od erozije tla vodom na području Pazina korišten je model CORINE za razdoblje 1995.-2024, a klimatski podatci (srednje godišnje količine oborina i temperature zraka) analizirani su za 3 podrazdoblja: (1995.-2004; 2005.-2014. i 2015.-2024.) Evidentirane su klimatske promjene posebno u trećem podrazdoblju u odnosu na prvo (138,6 mm vlažnije i 0,8 °C toplije). Indeks erozivnosti oborina povećan je sa 6 (1981.-1995.) na 8 (1995.-2024.). Na 87,2% površine flišne zone utvrđen je visoki potencijalni rizik od erozije tla vodom, na 11,3% umjereni, a na 1,5% niski. Stvarni rizik od erozije se smanjio te je bio na 13% površina visoki, na 77,9% umjereni, a na 9,1% niski. Na korištenom zemljištu potencijalni rizik od erozije tla vodom jednak je stvarnom riziku. Povećanjem potencijalnog rizika od erozije na umjereni i visoki kod obrađivanog zemljišta povećava se i stvarni rizik od erozije tla vodom za 1, odnosno 2 klase. Ukoliko bi se površine zapuštenog zemljišta prenamijenile u obradivo

zemljište, površine sa stvarnim rizikom od erozije bi se povećale na 47,2%. Uz vegetacijski pokrov i način korištenja zemljišta, obvezno je kombinirati i druge protuerozijske metode zaštite tla (konzervacijske, agrotehničke, sanacijske). Izrađene karte potencijalnog i stvarnog rizika od erozije tla vodom predstavljaju važnu podlogu u daljnjem planiranju i gospodarenju zemljištem u svrhu održivog razvoja, racionalnog korištenja i zaštite tla od erozijskih oštećenja.

Ključne riječi: potencijalni i stvarni rizik, CORINE, Istra, oborinski režim, način korištenja zemljišta

INTRODUCTION

Soil formation is a long-term process, and soil is considered a conditionally renewable natural resource. Its protection is a focus of both European Union and United Nations programmes, which particularly emphasise the implementation of practices to protect soil from degradation, with great importance attached to reducing erosion processes. According to the United Nations Report to Combat Desertification, 33% of the world's soil is already damaged by erosion, and over 90% will be at risk by 2050 (IPBES, 2018). Panagos et al. (2024) also note that on 23% of surfaces in Europe, soil loss due to water erosion exceeds 2t/ha/y. Soil erosion by water is the most significant and dangerous soil degradation process, both globally and in Croatia (Ljubić et al., 2001; Husnjak et al., 2001; Gulam, 2012). The term soil erosion by water refers to the process that leads to the destruction of structural aggregates, the separation of individual particles from the soil mass, their transport by water, and their deposition as erosional deposits (Davari et al., 2024). Numerous natural and anthropogenic factors influence the erosion process, with the most important indicator being the intensity of rainfall erosivity, which depends on the amount and intensity of rainfall, often spatially and temporally uneven (Bezak, 2021). Among the main anthropogenic factors are intensive cultivation (Martínez-Casasnovas and Concepcion Ramos, 2009) and inadequate agrotechnical methods. The direct effects of erosion are numerous: loss of the most productive arable soil layer, reduced soil fertility, and disruption of the soil water regime. However, less noticeable indirect effects often occur, such as pollution of soil, surface water, and groundwater with residues of plant protection products, and leaching of nutrients into canals, rivers, lakes, and reservoirs (Blinkov, 2017). On the Istrian Peninsula, the geomorphological unit "Grey Istria" (Pazin Paleogene Flysch Basin) is particularly susceptible to water erosion. This area is characterised by the dominant presence of a highly erodible flysch parent material with a high proportion of marl, pronounced terrain slopes, and high rainfall erosivity. Soils formed on such materials are mostly of silty clay and clay texture, with low infiltration capacity and prone to intense physical weathering. According to Racz (1992), central parts of Istria are the worst affected by erosion, with 100-200 t/ha of soil eroded annually. For this reason, the flysch area of Istria is considered one of the most vulnerable regions to water erosion in the Republic of Croatia (Kisić, 2016). The most erosive countries in Europe are Albania and Montenegro, where the mean annual intensity of erosion is > 10 t/ha. Macedonia, together with Italy, Portugal, Slovenia and Romania, is in the second group of countries, where erosion intensity is 5–10 t/ha. As a consequence, in Balkan countries, 30% of agricultural land and 45% of total land are affected by soil erosion. In North Macedonia, as much as 90% of the area is affected by erosion (Bilinkov, 2017), as is the case in Montenegro, where furrow and inter-furrow erosion dominate. (Spalević, 2011; EU 4 Green, 2024) In addition, social and economic conditions are causing changes in the demographic structure of the population, specifically a 38% increase in the urban population. The land use change and conversion of natural grasslands, meadows and forests into agricultural land, along with changes in vegetation cover structure (scrubs, macchia) and the abandonment of terraces, have led to gully erosion (Riccaboni et al., 2020) and significant loss of organic carbon from the soil. The Mediterranean region of Europe, to which Croatia belongs, is regarded as a “hot spot”, neaning it is highly sensitive to climate change (Salvia et al, 2021) Climate projections indicate that by 2070, intensification of the hydrological cycle will increase global soil erosion by water by 30–60%, affect-

ing 80–85% of the world's land area (Borrelli et al., 2020; Panagos et al., 2021). It is also expected that the average air temperature will increase by 20% compared to the global level, and that rainfall will decrease by about 20 mm /1°C (Lionello and Scarascia, 2018). In recent decades, climate extremes such as annual rainfall deficits, as well as increased rainfall intensity and erosivity over short periods (torrential floods), have become more frequent, alongside increasingly prolonged drought periods. (Panagos et al., 2021) The rainfall erosivity is also very important for identifying the most effective anti-erosion methods and soil protection practices. To determine the degree of potential and actual risk of soil erosion by water with relative reliability, the CORINE model is most commonly used (CORINE, 1992). The advantage of this model is that, in addition to climatic parameters (rainfall, air temperature), it also includes other soil and land characteristics (physical, chemical and physiographic properties, vegetation cover, land use). This combination enables the assessment of the actual risk of soil erosion by water, as well as the potential risk. The maps obtained can greatly assist in analysing soil degradation and developing adequate anti-erosion methods for soil and land protection. In Southern Europe, soil protection against soil erosion by water mainly focuses on managing vegetation cover, reducing tillage and implementing practices (eg., terracing) specific to certain agroecological conditions. Recognising the importance of soil as a conditionally renewable resource and carbon sink, the European Union has adopted a new Soil Monitoring Law (European Commission, 2025). Accordingly, guidelines have been established for adapting agricultural production to climate change and for sustainable soil management within the framework of the Common Agricultural Policy (2023-2027) and for soil conservation under the EU Green Deal Programme (European Commission, 2019). Conservation practices in sustainable land management include no-tillage, reduced tillage, contour tillage, terracing, grassing the belts between cultivated areas, permanent soil cover with vegetation, humification and fertilization, and avoiding intensive trampling of the soil by agricultural machinery. (Firoozi and Firoozi, 2024). The importance of planning sustainable land use with soil adaptation to climate change in the Balkan region is also highlighted by Markoski et al. (2023). Similar research about the effects of land use on erosion processes in Serbia was conducted by Srejić et al. (2023). Integrating sustainable use strategies based on analysed soil erosion dynamics and land use change over 30 years in Turkey was conducted by Çaglar and Dengiz. (2025). Analysis of the soil erosion by water in the highly vulnerable Flysch area of Istria, together with multiyear climate parameters observation, could be significant for a better understanding of soil degradation and the possibilities for protecting soils. In this regard, the objectives of this paper are: i) to assess the degree of potential and actual risk of soil erosion by water under changing climate parameters from 1995 to 2024, and ii) to recommend appropriate anti-erosion methods for soil protection in the flysch zone of Istria.

MATERIALS AND METHODS

The flysch Istria area occupies the central part of the Istrian Peninsula, specifically the Pazin Palaeogene flysch basin, which extends from the Gulf of Trieste in the west to Mount Učka in the east of Istria (Figure 1).



Figure 1. Spatial distribution of the Flysch zone of Istria

The main meteorological station (MMS) covering this area is Pazin (45°14'27" N, 13°56'43" E, 291 m a.s.l.). Due to its geographical position, Pazin has a continental climate with hot summers and cold winters (CMHS). The dominant soil types in this area are Regosol, Rendzina, and Terrestrial anthropogenic soils (Deep-ploughed and Terraced soils), mainly formed on flysch with a high proportion of marly components. Regarding vegetation and land use, agriculture (olive and grape growing) is the main human activity in this flysch area.

Application of the CORINE model to assess the potential and actual risks of soil erosion by water

The assessment of the potential and actual risk of soil erosion by water in the flysch zone of Istria was conducted using the qualitative cartographic model CORINE (1992) for the period 1995–2024. This model is used in most European Union countries, at both national and regional levels, as a basis for spatial analysis and evaluation of soil and land erosion risk and vulnerability. CORINE also provides fairly accurate information on areas where this form of soil degradation occurs, with the aim of implementing appropriate soil and land prevention and protection practices. This method serves as a planning document – a basis of exceptional importance for decision-making related to spatial planning and the implementation of soil protection against erosion damage, especially on sensitive parent material such as flysch. This model uses a minimum polygon area of 25 ha for the base layer of vegetation cover, while the minimum width of linear elements is 100 m. The stated model characteristics and resolution are suitable for assessing erosion risk at regional and national levels (M = 1:300,000). For more precise soil erosion assessments, CORINE data should be combined with more detailed satellite imagery, such as Sentinel.

To obtain the input variables required for this model (Figure 2), the following base maps were used:

- The Suitability Map of the Republic of Croatia, scale 1:300.000 (Bogunović et al., 1996)
- Digital orthophoto map (State Geodetic Administration, 2023)
- Map of the Potential Risk of Soil Erosion by Water of the Republic of Croatia, scale 1:300.000 (Husnjak, 2000)
- Land use map for the flysch Istria area, scale 1:25.000 (Kušan and Žiža, 2023).

Digitisation and partial generalisation of all data, along with polygon creation, were carried out using the AutoCAD software package. For further data processing in the Geographic Information System (GIS), the ArcGIS (Esri) software package was used.

In addition, meteorological data on daily, monthly, and annual air temperature and rainfall for the period 1995–2024 from the MMS Pazin were used (CMHS). To better analyse the impact of these climatic parameters on soil erosion, this period was divided into three climatic subperiods: the first subperiod (1995–2004), the second (2005–2014), and the third (2015–2024) Table 1. These data were used to calculate two climatic indicators that are very important for soil erosion: the modified Fournier rainfall variability index (MFI) and the Bagnouls-Gaussen aridity index (BGI). The modified Fournier index (Arnoldus, 1980) was calculated using the formula:

$$\mathrm{MFI} = \sum_{i=1}^{12} Ri^2/R \quad (1)$$

where are:

- R_i – total monthly rainfall for month *i* (1-12)
- R – total annual rainfall.

The Bagnouls-Gaussen aridity index (Gaussen i Bagnouls, 1952) was calculated using the formula:

$$\mathrm{BGI} = \sum_{i=1}^{12}(2\mathrm{t_m} - 2R\mathrm{i_m}) \times ki \quad (2)$$

where are:

- t_m – average monthly air temperature for month i (1-12)
- R_{im} – total monthly rainfall for month *i* (1-12)
- k_i – the proportion of months where the condition $2t_i - P_i > 0$

Based on the calculated data for MFI and BGI over a 30-year period, rainfall variability classes and aridity index classes were determined, and the interpretative values for each class are shown in Figure 2.

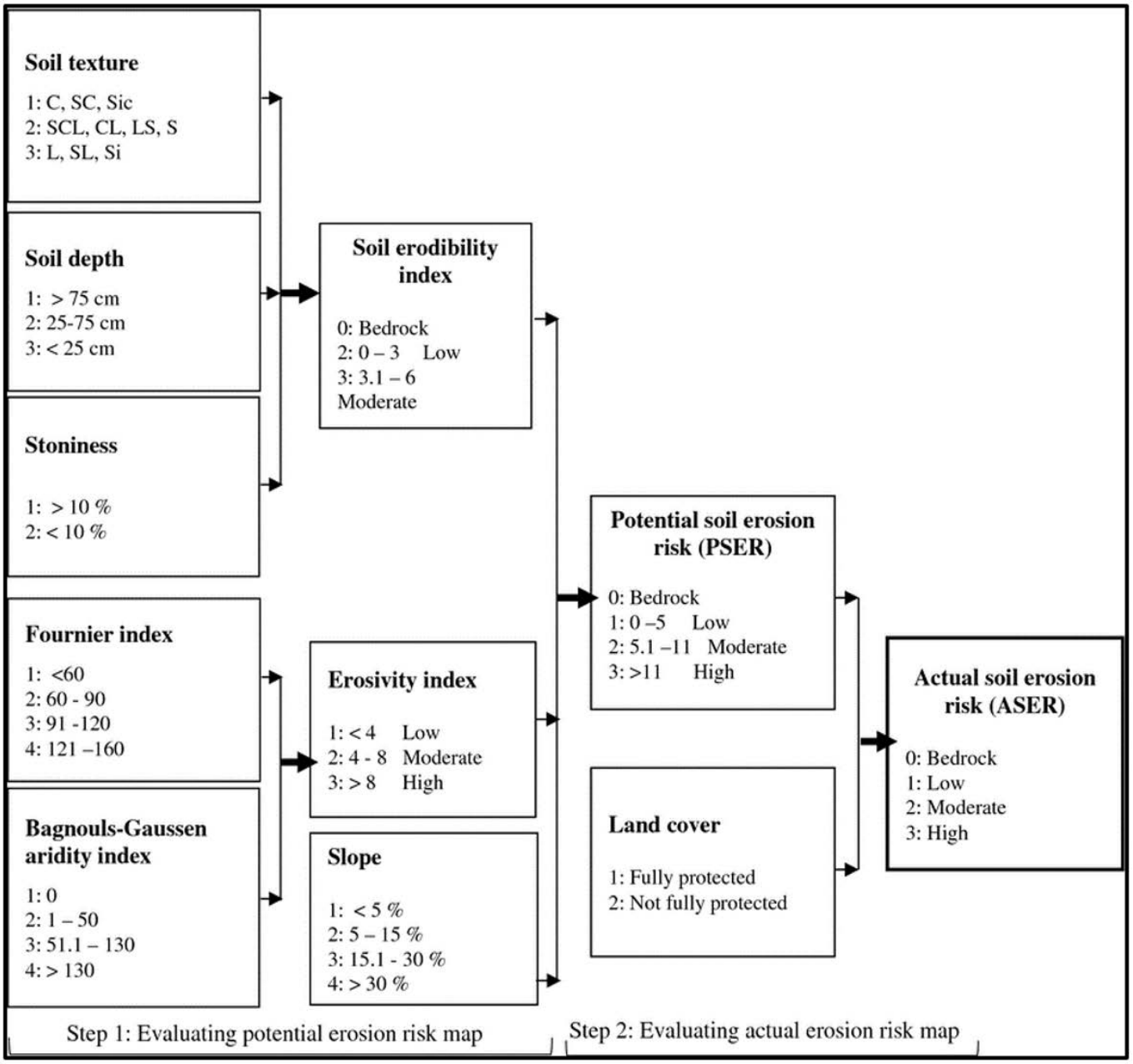


Figure 2. Methodology for determining the risk of soil erosion by water (CORINE, 1992)

The Rainfall erosivity index (REI) was calculated using the following formula:

$$REI = \text{Class MFI} \times \text{Class BGI} \quad (3)$$

Methodology for creating maps of potential and actual risk of soil erosion by water

For this study, the Suitability Map of the Republic of Croatia, scale 1:300,000 (Bogunović et al., 1996) was used, providing data on the distribution of systematic soil units developed on flysch. Based on their distribution in the Istrian region, the coverage of the flysch zone, or the geomorphological unit of Grey Istria, was selected (Figure 1). This coverage was then corrected using a digital orthophoto map, considering the morphological characteristics of the land. After corrections were made, the total area of the flysch zone was 60,127 ha. To display the potential risk of soil erosion by water, the Map of the Potential Risk of Soil Erosion by Water of the Republic of Croatia, scale 1:300,000 (Husnjak, 2000), created using the CORINE programme, was used. The assessment of

potential soil erosion risk (PSER) involved combining and overlaying multiple maps, such as soil erodibility, rainfall erosivity, and terrain slope. The classification thresholds for assessing potential and actual soil erosion risk by water (ASER) were defined according to the intensity of erosion processes and divided into three classes: low, moderate, and high risk (Figure 2).

RESULTS AND DISCUSSION

Basic characteristics of soil and climate

Based on the methodology for determining the potential risk of soil erosion by water from the key input variables for its assessment (soil, climate, relief), only the climate erodibility variable is subject to significant changes over time. The soil erodibility index was obtained by overlaying the soil texture, soil depth, and stoniness data. The dominant systematic soil units in the flysch zone of the Pazin area are mainly terrestrial anthropogenic soils (Deep ploughed and terraced soils from Rendzina on flysch) with a higher proportion of marly components. Therefore, these soils have a slightly higher proportion of silt particles and are mainly clay-loamy or silty-clay-loamy in texture. During the period 1981–1995, soil properties were determined, forming the basis for calculating the soil erodibility index (Husnjak, 2000). Given the above texture, these are moderately erodible soils (class 2). The increased content of silt particles in the soil leads to poorer water infiltration, which, combined with the pronounced slope of the terrain and the flysch properties, makes these soils extremely susceptible to water erosion (Škorić et al., 1987). The average depth of these soils ranges from 25 to 75 cm, so they are classified as soils with moderate erodibility (class 2). The stoniness of these soils is low (<10%), thus they are classified as incompletely protected (class 2). As part of developing a map of the risk of soil erosion by water for the period 1981–1995, a terrain slope base was created as a key factor influencing the dynamics and intensity of soil loss by erosion (Husnjak, 2000). According to this map, the central part of Istria has a hilly to mountainous relief, with altitudes ranging from 100 to 500 m and an average slope of 15 to 30%. The erosiveness of rainfall also depends on changes in climate parameters (rainfall and air temperature), thus during the period 1995–2024. The average annual rainfall was 1,136.4 mm, and the average annual air temperature was 12.1 °C (Table 1).

Table 1. Average annual amount of rainfall and average annual air temperature in the period 1995-2024 (MMS Pazin)

Climatic (sub)periods	Rainfall, mm	Air temperature, °C
1995-2004*	1047,5	11,8
2005-2014 *	1175,7	12,0
2015-2024 *	1186,1	12,6
1995-2024	1136,4	12,1

* climatic subperiods: 1995-2004 (1); 2005-2014 (2); 2005-2014 (3)

Analysis and comparison of mean annual rainfall values between individual climatic sub-periods revealed no statistically significant differences (Table 2). The largest increase in rainfall was observed between the first and third sub-periods (+138.59 mm), and the smallest between the second and third sub-periods (+10.36 mm).

Unlike rainfall, the increase in mean air temperature in the second and third periods was statistically significant ($P < 0.05$) compared to the first period (Table 3). The largest statistically significant increase in air temperature was recorded in the third sub-period compared to the first (+0.86 °C), and the smallest in the second compared to the first sub-period (+0.22 °C). The variability of rainfall in the last decade compared to the beginning of the 21st century is also evident among practitioners, including scientists at the Croatian Hydrometeorological Service, who recorded annual rainfall ranging from 738.8 mm to 1634.8 mm during 1949–2018 (Croatian Waters, 2020). One cause of this variability is the change in rainfall intensity and duration, with rainfall now mostly short-lived and of greater intensity. This increases surface runoff and soil loss, as confirmed by Morán-Ordóñez et al. (2020) and Mandal and Roy (2024). Analysis of rainfall intensity and duration in the Pazin area through the RAINMAN project (Faculty of Civil Engineering in Rijeka and CMHS, 2019) identified more pronounced extreme events of

Table 2. Statistics for the average annual amount of rainfall (MMS Pazin)

Climatic subperiods		Difference of average annual rainfall between subperiods, mm	DF	T-stat	*P*<0.05
1995-2004	2005-2014	-128.23	17	-1.26	0.230 ns
1995-2004	2015-2024	-138.59	18	-1.36	0.196 ns
2005-2014	2015-2024	-10,36	17	-0.08	0.935 ns

Legend: DF - degrees of freedom; T-stat - Student's t-distribution; ns - no statistically significant differences between mean values of rainfall.

annual maximum short-term rainfall lasting 2 hours (Croatian Waters, 2020). Between 1995 and 2024, a slight increasing trend in mean annual rainfall was observed in the Pazin area (R^2 = 0.0599) with high variability between the dry year 2015 (738.8 mm) and the extremely wet year 2010 (1642.0 mm), as shown in Figure 3.

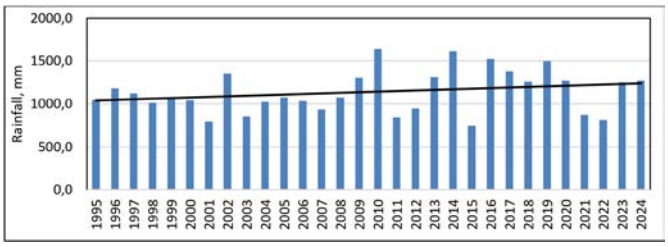


Figure 3. The annual rainfall trend

The alternation of extremely dry and wet years increases and decreases the cohesion of particles in flysch parent substrates, leading to greater instability and erodibility, and increasing the likelihood of gully erosion and landslides. In addition, the clay component in flysch swells rapidly when in contact with rainfall and disintegrates intensively, as confirmed by Aljinović et al. (2010). This indicates the need to adjust soil cultivation methods (reduced and no-tillage) to increase water infiltration in dry years and reduce leaching in wet years. Furthermore, excess rainfall should be drained by constructing appropriate channels and drainage systems, and soil material loss should be prevented by building terraces. In the last decade, the distribution of monthly rainfall was most pronounced in the autumn (September–December), with a maximum in October (125.8 mm) and a minimum in January (61.7 mm), as shown in Figure 4. For most of the year in the second and third sub-periods, average monthly rainfall exceeded the multi-year average. The increase in intensity and amount of rainfall during the autumn-winter, non-vegetation period enables surface washing and deep wetting of flysch and marl materials, which disrupts soil stability. Therefore, permanent soil coverage with vegetation should be ensured in this area, as specifically noted by Pernar et al. (2010). Permanent vegetation cover retains rainfall, stabilises soil structure, and enables humification and storage of organic carbon, which is extremely important in combating erosion.

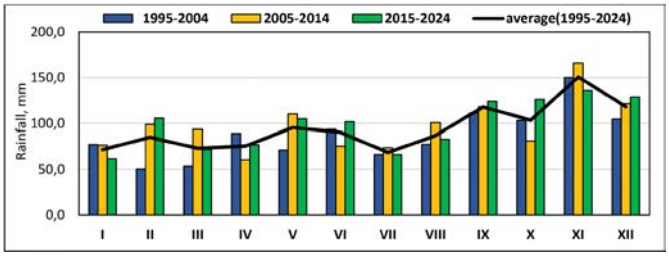


Figure 4. Monthly amount of rainfall changes (1995-2024)

The specific geographical position of the MMS Pazin (altitude), as well as the characteristics of the Pazin area itself (the basin), should also be noted for their influence on the redistribution of rainfall and on the air and soil temperature regime.

The increase in average air temperature during the second and third subperiods was statistically significant (P < 0.05) compared to the first one (Table 3).

The average annual air temperature values during the period 1995–2024 (MMS Pazin) ranged from 10.8 °C in 1996 to 13.6 °C in 2024. A significant upward trend in average annual air temperature (R^2 = 0.4809), especially in the third climate subperiod shown in Figure 5.

Table 3. Statistics for average annual air temperature (MMS Pazin)

Climatic subperiods		Difference in air temperature between subperiods, °C	DF	T-stat	*P*<0.05
1995-2004	2005-2014	-0.22	17	-0,85	0,410 ns
1995-2004	2015-2024	-0.86	18	-3,72	0.0016 *
2005-2014	2015-2024	-0.64	17	-2.48	0.0237*

Legend: DF - degrees of freedom; T-stat - Student's t-distribution; ns - no statistically significant differences; * - statistically significant differences found between average annual air temperatures.

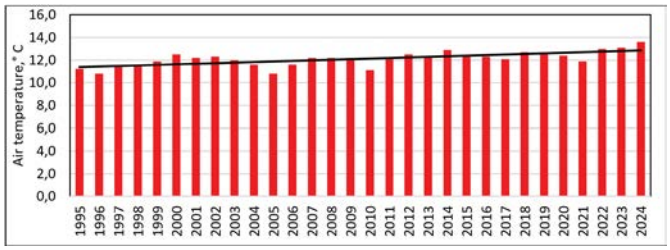


Figure 5. Air temperature trend

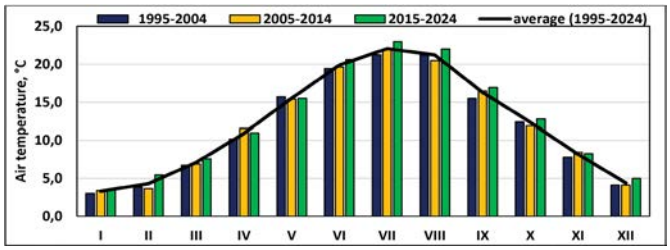


Figure 6. Monthly air temperature changes (1995-2024)

In the third subperiod, the average monthly air temperature is generally higher than in the previous ones, and from July to December, it is above the long-term average values (Figure 6). According to CMHS (2019), comparing data from the climate subperiod 1991–2018 with the reference period 1961–1990, a significant trend of increasing average air temperatures was recorded at the MMS Pazin of up to 1.9 °C per 100 years (CMHS, 2019). It should also be noted that there is a synergistic effect between air temperature and flysch, which, under conditions of high air temperature and increased evapotranspiration, dries out and cracks rapidly (due to its silty clay loam texture), thereby increasing the rainfall erosivity. During prolonged and frequent heat waves, in addition to inadequate tillage, lack of vegetation, and the occurrence of wildfires, there is a marked decrease in soil organic matter and soil moisture, as well as deterioration of soil structure, all of which intensify erosion processes, as confirmed by García-Palacios et al. (2021) and Patel et al. (2021). Given that the content of organic matter is negatively correlated with high air temperatures (Stolte et al., 2016), it is necessary to adapt human activity and agricultural techniques to these conditions. This requires the mandatory addition of humus, changes in crop rotation, the introduction of cover crops, and grassing of inter-row spaces in orchards, vineyards, and olive groves, which dominate in central Istria.

Rainfall erosivity (RE)

One of the most important parameters for determining the potential risk of soil erosion by water is the RE, which represents the ability of rainfall (kinetic energy) to mechanically break down soil particles and cause erosion through its intensity and duration (Weng et al., 2024). Nigam et al. (2017) established a direct connection between the amount and intensity of rainfall and soil erosion by water in their research. During the period 1995–2024, the MFI was 136.0, corresponding to the fourth class of RE (Table 4). Compared to the period 1981-1995, the RE value increased. Reis et al. (2016) obtained the same MFI value in the sub-Mediterranean part of Turkey.

The BGI value for the period from 1995 to 2024 was 14.3, which corresponds to the second aridity class, i.e., humid areas (Table 5).

Compared with previous research (Husnjak, 2000), there is a decrease in the BGI value from 15.7 (1981–1995) to 14.3 (1995–2024), which is related to the occurrence of more frequent and more intense rainfall in recent decades (Table 6). This index is important for a more reliable assessment of RE, as its calculation includes daily rainfall, allowing for an analysis of climate aridity. It also accounts for short-term storms during the dry season and moisture stress, which, along with decreased veg-

Table 4. Classes of the MFI in the period 1995-2024 (MMS Pazin)

Period	MFI *	Class	Evaluation
1995-2024	136,0	4	High
1981-1995	117,0	3	Moderate

* MFI- modified Fournier rainfall variability index

Table 5. Classes the BGI in the period 1995-2024 (MMS Pazin)

Period	BGI *	Class	Evaluation
1995-2024	14,3	2	Humid
1981-1995	15,7	2	Humid

*BGI- Bagnouls - Gaussen's aridity index

Table 6. Indicators of rainfall erosivity in the period 1981-2024, MMS Pazin

MMS	Period	Altitude	Longitude	Altitude m a s l	MFI	Class	BGI	Class	REI	Class
Pazin	1981-1995*	45°14'27"	13°56'43"	291	117,4*	3*	15,7*	*	6*	2*
	1995-2024				136,0	4	14,3	2	8	2

* Husnjak (2000)

etation cover, significantly contribute to increased soil erodibility. Akbari et al. (2022) found that in Iran, 97% of areas are exposed to high values of RE.

During the period 1995-2024, especially in the last sub-period, there was a slight decrease in BGI (R^2 = 0.0099), but also a more intense increase in MFI (R^2 = 0.0415) as a result of uneven rainfall both in terms of spatial and temporal distribution and intensity (Figure 7).

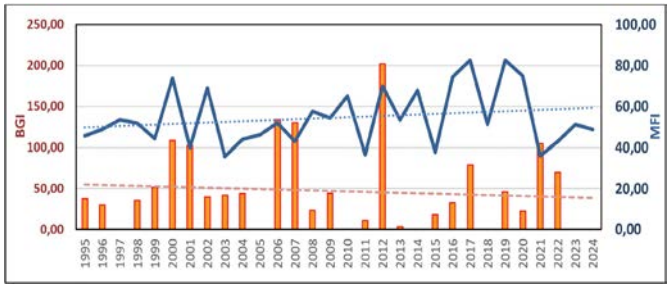


Figure 7. Trend for the modified Fournier rainfall variability index (MFI) and the Bagnouls-Gaussen aridity index (BGI)

The increase in the rainfall erosivity index is influenced more by the intensity, duration, and frequency of rainfall (Feyzi Koushki et al., 2019) than by the amount of rainfall itself (Luetzenburg et al., 2020).

Although the REI was increased by 33% during 1995–2024 compared to 1981–1995, it remained within the second class of RE. This is due to an increase in the MFI, which resulted from changes in the dynamics, distribution, and intensity of the rainfall regime, especially in the last decade (Figures 1 and 2). The data indicate an increased potential risk of soil erosion by water in the recent period as a consequence of changes in climatic parameters.

The potential risk of soil erosion by water (PSER)

The PSER is defined as the inherent sensitivity of the soil to water erosion, without considering vegetation cover or land use methods. The potential risk therefore, represents the worst-case scenario; that is, the assessment of PSER was based on the assumption that the entire research area is used as arable land. The flysch zone of Istria is quite heterogeneous in relief, with a pronounced terrain slope that mainly varies from 5 to 30% (Husnjak, 2000). This is one of the key factors that trigger erosion processes and influence their intensity. According to the map of PSER, it was determined that the largest part of the flysch zone, 87.2%, belongs to the third class, indicating high PSER values. The area with a moderate PSER (second class) covers 11.3% of the area, while a very small portion (1.5%) of flysch is classified as first class, with a low PSER (Table 7, Figure 8). Compared with, for example, the flysch area in Iran, where 43% of the area has a low and 30% a moderate PSER (Akbari et al., 2022), the flysch zone of Istria is significantly more potentially threatened by erosion.

Table 7. The potential risk of soil erosion by water

The potential risk of soil erosion		Area	
Class	Type of risk	ha	%
1	Low	870,0	1,5
2	Moderate	6.567,2	11,3
3	High	50.774,0	87,2
Total		58.211,2	100,0
Other		1.915,8	
Overall		60.127,0	

High potential erosion risk is associated with hilly and mountainous relief and steeper terrain slopes. In the Kahramanmaraş area in southeastern Turkey, where the average terrain slope is 38%, 45.48% of the area is affected by high potential erosion risk, while 54.52% of the area is identified as having moderate potential risk of soil erosion by water (Reis et al., 2016). High soil erodibility, and consequently PSER, is particularly pronounced in the Western Balkan countries, which exhibit significant vertical fragmentation of the relief.

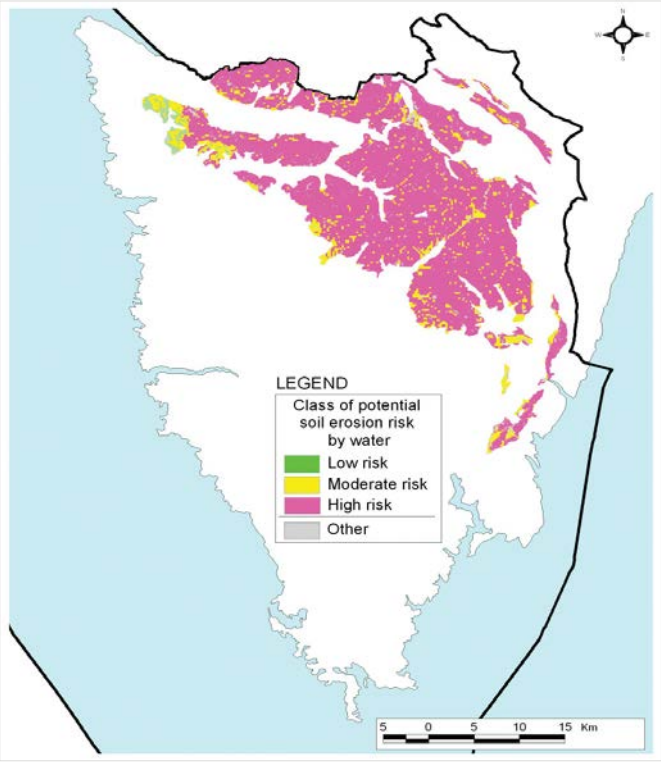


Figure 8. Map of the potential risk of soil erosion by water

In Kosovo, areas with medium (35.4%) and high erosion intensity (16.1%) predominate. In Albania, soil loss exceeding 10 t/ha/year has been recorded on 22% of the land, while in Bosnia and Herzegovina, as much as 80% of agricultural areas are affected. In Montenegro, 90% of the territory is subject to erosion, with half of these comprising areas with medium and high erosion intensity. More than 90% of North Macedonia is threatened by erosion, with 38% affected by medium, high, and very high intensity erosion (Zrduli et al., 2022).

The actual risk of soil erosion by water (ASER)

The ASER value refers to the actual, current risk of erosion, including the existing vegetation cover and land use. This risk is determined by overlaying the map of PSER with the map of vegetation cover or land use. The map of ASER was based on the principle that vegetation cover, such as forests or permanent grasslands (pastures and meadows), protects the soil from water erosion (Memarian and Akbari, 2021). Since traditional systems of livestock grazing and pasture use were abandoned for economic reasons, natural vegetation and forest gradually reclaimed this unproductive land. As a result, the structure and composition of the vegetation cover changed, which are characteristic of the Mediterranean area. As abandoned agricultural land is covered with dense shrubby vegetation and forest, it is considered that this vegetation cover also currently protects the soil from water erosion. Therefore, on land with a high or moderate PSER that is covered by forests, meadows, pastures, or shrubby vegetation, the ASER values were, according to the CORINE methodology, one class lower than the potential risk.

The land use map

The occurrence, intensity, and duration of erosion processes largely depend on the type of vegetation cover or land use. The positive effects of vegetation mainly involve soil protection through the stabilisation of soil structural aggregates, increased infiltration capacity of the soil, and interception of part of the rainfall by the above-ground plant mass, which significantly reduces

soil erodibility (Wei et al., 2009). In previous research for the period 1981–1995, according to the CORINE method (Husnjak, 2000), only two classes were distinguished within the vegetation cover: land completely protected by vegetation cover (forest) and land not fully protected (all other soils, such as arable soils, unvegetated or sparsely vegetated soils, and others). The problem of applying this model in flysch Istria is related to its low spatial resolution (the minimum mapping area is 25 ha and the object width is 100 m), which makes it impossible to observe smaller linear or point elements such as narrow forest belts, small vineyards, and small localised erosion phenomena. In addition, this model shows only the type of land use, without data on soil cultivation methods, soil composition and structure, or the amount and intensity of rainfall. There is also the problem of generalisation and inaccurate classification of several different mosaics of agricultural areas, as well as rocky areas and sinkholes, which leads to a loss of insight into the actual soil erosion. Another problem is the temporal variability in the use of this model (the average data update interval is about six years). This limits the ability to monitor rapid changes in land use and land conversion. For this paper, based on the situation in 2023, a map of land use classified into specific categories (Figure 9) and groups of used and abandoned land, forests, and other land was created (Table 8). The total cultivated agricultural land covers about 11,778.8 ha, or 19.6% of the total flysch area. The largest proportion is arable land, followed by vineyards, meadows, and olive groves. Abandoned agricultural land covers a very large area, amounting to 22,781.5 ha (37.9% of the flysch area). This land has not been used for a long period, and now it is completely overgrown, mainly with shrubs and forest vegetation. This abandoned land under intense warming and temperature extremes is also at high risk of wildfire and, consequently, erosion.

Table 8. Classes of the land use/vegetation cover (2023)

Land use	Vegetation cover	Area	
		ha	%
Cultivated agricultural land	Arable land	6.911,1	11,5
	Vineyard	1.494,8	2,5
	Orchard	496,5	0,8
	Greenhouse	1,5	0,0
	Olive orchard	1.203,6	2,0
	Meadow	1.261,3	2,1
	Pasture	410,0	0,7
Total of cultivated agricultural land		11.778,8	19,6
Abandoned agricultural land	Bushes and forests	22.781,5	37,9
Total of agricultural land		34.560,4	57,5
Forests	Forest	23.650,8	39,3
Total remaining land		1.915,8	3,2
Overall area of Flysch zone		60.127,0	100,0

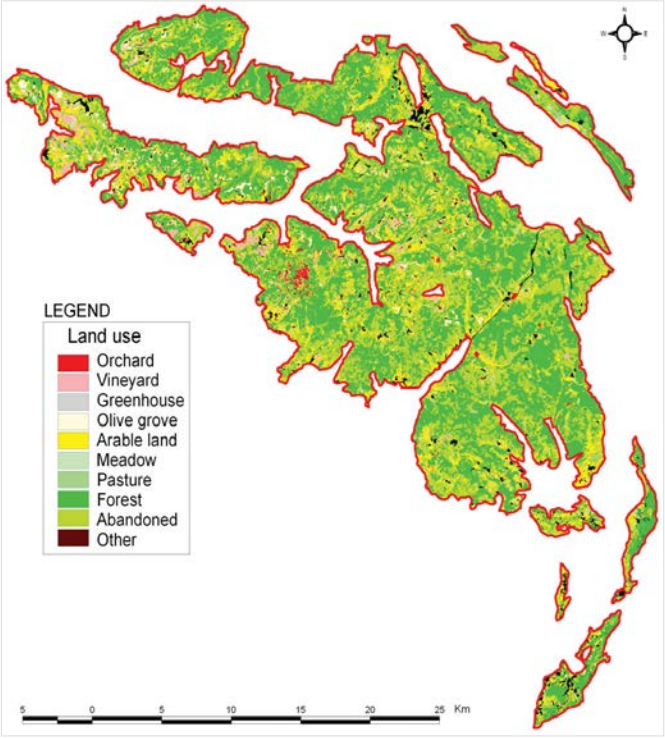


Figure 9. The land use map (2023)

The map of the actual risk of soil erosion by water

By overlapping and integrating the map of PSER with the land use map, a new map was produced containing data on the class of potential risk, land use class, and vegetation cover class in the attribute data. The assessment of ASER was then carried out according to the matrix shown in Table 9.

On cultivated land, that is, areas not covered by forest, permanent grassland, or shrub vegetation, the potential risk of soil erosion by water were equal to the actual risk of soil erosion by water. When the potential risk of erosion increases to moderate and high, the actual risk of soil erosion by water increased by one or two classes compared to the low potential risk. One of the main reasons for this is the anthropogenic impact in agriculture, which leads to changes in the erosion potential of agricultural land. This relationship was also confirmed by Khallouf et al. (2021).

Conversely, areas with permanent vegetation cover, such as forests and grasslands in conditions of low to moderate PSER values were less susceptible to ASER (class 1) due to the protective role of this vegetation. Abandoned or agricultural land with shrubby vegetation and forest exerts a similar effect, as its vegetation generally maintains the actual erosion risk at the same or a lower level (class 1) compared to the potential risk (classes 1 and 2). The role of interception in preventing surface water runoff should also be considered. The amount of rainfall that leaves and stems can retain, thereby reducing the erosive effect of rainfall on the soil, is significant (i.e. grassland vegetation has a larger interception surface than shrubby vegetation and forests). According to Cerdan et al. (2010), using EU-wide data, soil loss

Table 9. Matrix for determination of the actual soil erosion risk by water

Class the potential soil erosion risk	Class the vegetation cover	Actual soil erosion risk	
		Class	Evaluation
1	Forest and grassland	1	Low risk
Low risk	Cultivated land	1	Low risk
	Abandoned land	1	Low risk
2	Forest and grassland	1	Low risk
Moderate risk	Cultivated land	2	Moderate risk
	Abandoned land	1	Low risk
3	Forest and grassland	2	Moderate risk
High risk	Cultivated land	3	High risk
	Abandoned land	2	Moderate risk

through erosion is lowest under forest and grassland vegetation (0.2 to 0.4 t/ha/year) and highest under permanent crops such as orchards, olive groves, and vineyards (3.1–17.4 t/ha/year). As the flysch region of Istria is dominated by arable land, vineyards, and olive groves, the real risk of soil erosion by water is clear. Akbari et al. (2022) found that a 2.57% decrease in vegetation cover led to an increased actual risk of erosion. Zhao et al. (2019) reported a reduction in the amount of eroded Terra Rossa in China by 82.9–99.1% in areas with grass vegetation compared to soil without vegetation. In the flysch zone of Istria, a moderate ASER was identified on 45,371.1 ha, or 78.0% of the surface in the flysch zone (Table 10, Figure 10). A high ASER was found on 7,544.4 ha, which accounts for 13% of the flysch area, leading to intensive erosion processes in that region. The intensity of soil erosion by water is particularly high on land under vineyards and olive groves, due to their location (steep slopes, terrace edges, erodible parent material and low organic matter and nutrient content). In addition, the use of inadequate agrotechnical practices (conventional cultivation, fertilisation, removal of natural mulch) has been noted, as also determined by Peñuela et al. (2026) in their research. Based on climatic, topographic, and pedological characteristics, the same authors concluded that soil coverage by vegetation should be at least 30–40% to keep the amount of eroded material below the tolerable value. In most Mediterranean countries, poor management of natural vegetation persists (removal of undesirable weed species, intensive mowing, and denudation of the soil surface between trees and vines). In Spain, despite conservation cultivation, 50% of areas under olive groves have no vegetation cover (Ministerio de Agricultura, Pesca y Alimentación, 2024). Table 10 shows that the area with an ASER would be as much as 27,496.9 ha, or 47.2% of the flysch area of Istria, if abandoned agricultural land were cultivated. Notably, if abandoned agricultural land were cultivated, the area with a high ASER would increase to 27,496.9 ha, or 47.2% of the flysch area of Istria. A low ASER was present on 5,295.7 ha, or 9.0% of the flysch area. Similar results were reported by Akbari et al. (2022) in Iran, where 78% of the area was classified as having a moderate to high ASER.

Table 10. Classes of the actual risk of soil erosion by water

Potential risk		Vegetation cover	Actual risk		Area	
Class	Type of risk		Class	Type of risk	ha	%
1	Low	Forests and grassland	1	Low	190,1	0,3
		Cultivated land	1	Low	420,9	0,7
		Abandoned land	1	Low	258,7	0,4
2	Moderate	Forests and grassland	1	Low	1.854,0	3,2
		Cultivated land	2	Moderate	2.145,5	3,7
		Abandoned land	1	Low	2.572,0	4,4
3	High	Forests and grassland	2	Moderate	23.273,0	40,0
		Cultivated land	3	High	7.544,4	13,0
		Abandoned land	2	Moderate	19.952,5	34,3
Total					58.211,2	100,0
Other					1.915,8	
Overall					60.127,0	

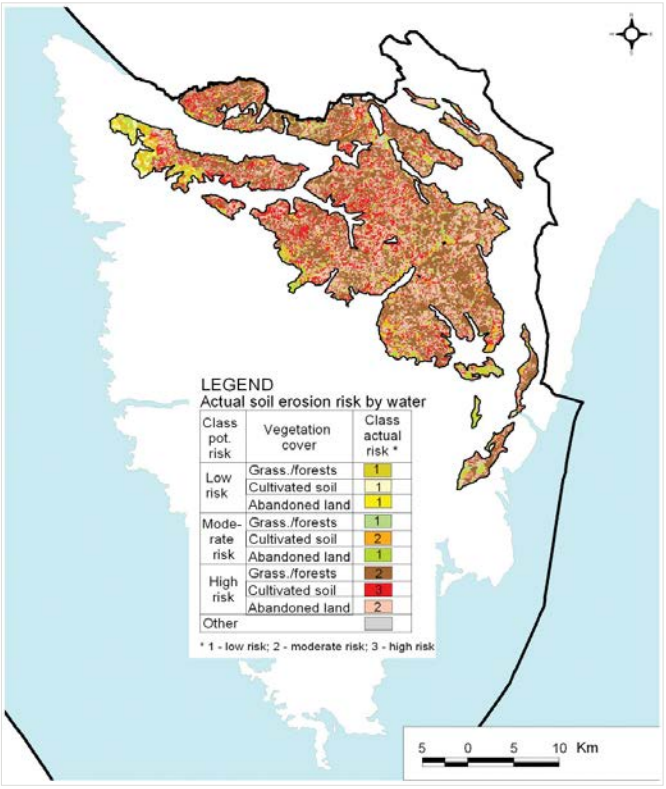


Figure 10. Map of the actual risk of soil erosion by water

Importance of the maps of PSER and ASER and recommendations for soil and land protection

Soil erosion by water is one of the greatest challenges for soil protection, particularly given the increasingly pronounced changes in climate conditions that have major negative consequences, especially for agricultural production. An indirect method of protecting soil and land from erosion is the creation of maps showing the PSER and ASER. These maps allow for a qualitative evaluation of the agro-ecological factors that cause erosion. They provide an important basis for further planning and implementation of soil protection practices against erosion damage, especially on sensitive parent materials such as flysch. For example, in areas with a high PSER or a moderate ASER, it is common for land management to involve changes in land use or purpose (e.g. when pasture areas are converted to cultivation or, after deforestation, the land is used for agricultural purposes). Such changes negatively affect soil carbon stocks, increase CO_2 emissions (Borrelli et al., 2020), and accelerate the mineralisation of organic matter, especially in flysch soils of Istria, which are naturally poor in organic matter. Additionally, on soils without vegetation or with sparse vegetation, under intense rainfall, soil bulk density decreases, compaction increases, and a crust forms on the surface, reducing cultivability and threatening agricultural production. Soil damage often occurs during intensive livestock farming and pasture exploitation, which disrupts the stability of soil structural aggregates and reduce infiltration capacity (Eddine et al., 2020). In such circumstances, combined with inadequate soil management, the erosive effect of rainfall increases, leading to the most severe forms of erosion, such as gully erosion and landslides, as highlighted by Paroissien et al. (2015) and Vanwallegherm et al. (2017). As a result, PSER becomes ASER. Increasingly pronounced climate change, human activity (inadequate cultivation systems, limited crop rotation, removal of nutrients and humus with yield, lack of soil mulching, improper implementation of hydromelioration practices), and socio-economic factors further increase soil degradation. Since the flysch area of Istria (arable and abandoned agricultural land) faces high and moderate ASER, it is necessary, in accordance with the Soil Monitoring Act (European Commission, 2025), to implement guidelines for sustainable soil and land management (conservation agriculture) in agronomic practice. These guidelines include various methods and practices to combat erosion and protect soil and land, based on continuous no-tillage or reduced soil cultivation, permanent vegetation cover (mulch) and changes in crop rotation. Conservation agriculture will, in the long term, increase organic matter content and soil fertility, improve infiltration capacity, reduce surface runoff, enhance water quality, and increase soil water capacity, as indicated by González-Sánchez et al. (2017). Petito et al. (2022) found that conservation agriculture in southern Italy reduced soil erosion by water by 7% compared to conventional agriculture, with reductions of 10% in mountainous areas and 14.1% in combined mountainous-lowland terrain. Interventions may include the use of cover crops, sowing undercrops and catch crops, strip sowing, minimising the period the soil surface is left bare, applying organic fertilisers, ploughing in plant residues,

reducing soil compaction, selecting appropriate mechanisation, adjusting the cultivation system to conservation practices, changing the crop production system, using soil conditioners, draining excess water, strip tillage, contour cultivation and terracing, and designing contour and grassed channels. One solution is afforestation with forest vegetation that is more resistant to drought and fires, as highlighted by Zorn and Komac (2009) in the case of Slovenia. Maps of potential and actual risk of soil erosion by water provide an important basis for further planning and land management aimed at sustainable development, rational use, and protection of soil as a conditionally renewable natural resource from erosion damage and/or conversion. Education and familiarisation of land users with sustainable management methods is also very important, given the continued tendency towards conventional or traditional agriculture in rural areas.

CONCLUSIONS

During the period 1995-2024 in the Pazin area, within the flysch zone of Istria, climate changes were identified. The third climate subperiod (2015–2024) was 138.6 mm wetter and 0.8 °C warmer than the first subperiod (1995–2004). Between 1995 and 2024, there was a trend of increasing MFI and decreasing BGI, as well as an increase in the REI compared to the period 1981–1995. Of the 60.127.00 ha of the flysch zone, 87.2% had a high PSER, 11.3% a moderate, and only 1.5% a low PSER. An assessment of the ASER indicates that areas under vegetation (forests, grasslands, and even shrubby vegetation on neglected and overgrown agricultural land) significantly reduce the risk of soil erosion by water. Thus, a high ASER was identified for only 13.0% of the areas, a moderate risk for 77.9%, and a low actual risk for 9.1% of the flysch zone of Istria. Although it has been established that abandoned land is less susceptible to erosion than cultivated land, care should be taken to ensure that land without vegetation or with sparse vegetation is not left in this state for extended periods. Particular emphasis should be placed on adjusting land use practices and addressing the issue of abandoned agricultural land. It is important to highlight the highly erodible nature and instability of flysch material, as well as its poor structure and tendency to crack in dry conditions, all of which contribute to the development of furrow and gully erosion. The prevalence of conventional agriculture, fragmentation of agricultural plots, and significant heterogeneity of terrain slopes make it essential to implement sustainable soil management practices in line with current climate changes. The observed increase in the erosivity index and the trend of rainfall variability indicate that soil damage caused by erosion will continue to worsen in the future. This underscores the need to incorporate various methods and techniques in agriculture to enhance soil resistance to extreme climate events. In addition to vegetation cover and land use in flysch Istria, it is necessary to combine other anti-erosion soil protection methods: adjusting soil cultivation systems (no tillage or reduced tillage, direct sowing, contour cultivation, terracing, reducing soil compaction); adapting crop production systems (crop rotation, intercropping, permanent cover crops/vegetation inter and between rows in orchard, vineyard and olive grove); adjusting types, doses, and methods of fertilisation (organic fertilisation, compost, crop residues); modifying plant protection methods (mechanical weed control, careful pesticide application); and ensuring rational water use through the application of appropriate irrigation systems (micro-sprinklers, sub-irrigation, drip irrigation) and drainage (drainage and canal systems). Analysis of the erosion status based on maps of potential and actual erosion risk, alongside monitoring multi-year climate parameters and changes in land use patterns, represents a step towards better understanding soil degradation and the possibilities for protecting soils from the destructive effects of erosion processes. In future research, the data obtained should be used to evaluate conservation management methods and planning processes, and to assist land users in preserving and improving soil health, quality, and productivity

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