USING NORMALIZED DIFFERENCE INDEXES TO DETERMINE EROSION-PRONE AREAS: THE CASE OF THE BĂLȚATA RIVER BASIN (REPUBLIC OF MOLDOVA)

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Abstract

The analysis presented in the article determines erosion-prone areas, using remotely sensed data and ancillary information. Bălțata River Basin, selected as a case study, is exposed to quite a significant extension of erosion due to natural drivers and human pressure. Normalized Difference Vegetation Index and Normalized Difference Water Index are computed to assess the severity of dangerous surface processes and to determine erosion-prone areas. Ancillary information, such as gully and landslide layers, slope angles, soil types, and land-use types are used as factors of land degradation control. They are also used in the assessment of land degradation distribution within the basin. Our findings show that 1413 ha (8.4% of the basin's area) are exposed to dangerous exogenous processes. About 70% of eroded and highly exposed areas are located on croplands, while the other 26% are confined to forests because of land consolidation measures. For diminishing the land degradation risk, we recommend the lands highly exposed to erosion be converted to other land-use types less likely to degrade.

Keywords: *erosion, land use, slope angle, soil type, NDVI, NDWI, Republic of Moldova*

1. INTRODUCTION

Erosion is a complex process, which causes soil fertility losses, land degradation, and sedimentation in the lakes and ponds. Ultimately, it leads to the loss of agricultural resources and threatens built facilities. Water is by far the most important erosion agent being responsible for 85% of global land degradation [Oldeman et al., 1990], while inappropriate tilling techniques on the slopes can significantly increase the water's erosion impact in local contexts [Constantinov et al., 2011]. In recent decades, we are witnessing how land use, previously considered an environmental issue of local importance, has become a global driver with various adverse effects [Foley et al., 2005]. That is why estimating the severity of erosion is a necessary step in reducing its effects, for land consolidation measures and increasing agricultural production, etc.

In the regional context, land degradation is one of the major problems. Thus, research studies in neighbouring Romania [Prăvălie et al., 2020a, b] reveal a significant increase in degraded lands as well as lands susceptible to degradation. Among the causes of such an increase, besides natural drivers, the authors mention climate change effects, poor agricultural practices, post-socialist institutional changes etc. In a short perspective, institutional transition to the market economy gained more importance than global environmental change [Petrișor et al., 2020], however, in recent decades, the impact of climate change has become one of the most important drivers. Among the possible effects, the authors of the study name susceptibility to aridization or even desertification, in the southeastern part of Romania [Prăvălie et al., 2020a].

Several large-scale studies made in the Republic of Moldova have highlighted the unfavourable evolution of the great majority of natural and socio-economic parameters due to climate change effects [Oprunenco, Prohnițchi, 2009], in general, an increased risk for sustainable agriculture [Constantinov et al., 2011] and the significant vulnerability of the broader local communities to the expected climate change [Corobov et al., 2013], in particular. Under these circumstances, there is a strong need for a detailed assessment of various parameters to get prepared for the expected and projected changes.

Erosion, and especially surface erosion, is one of the factors that significantly reduce land stability, soil fertility and crop yields in the country. The Republic of Moldova is well known for the low strength of rocks and the lithological composition of the cover deposits, which are dominated by clays, sands, loams and loess. In this regard, on rather gentle slopes (starting from 5°), such widespread forms of erosion as ravines and landslides develop. However, this unique combination of natural factors is not limited to national borders, but is characteristic of a wider regional context, including neighbouring territories of Ukraine or Romania [Prefac et al., 2016].

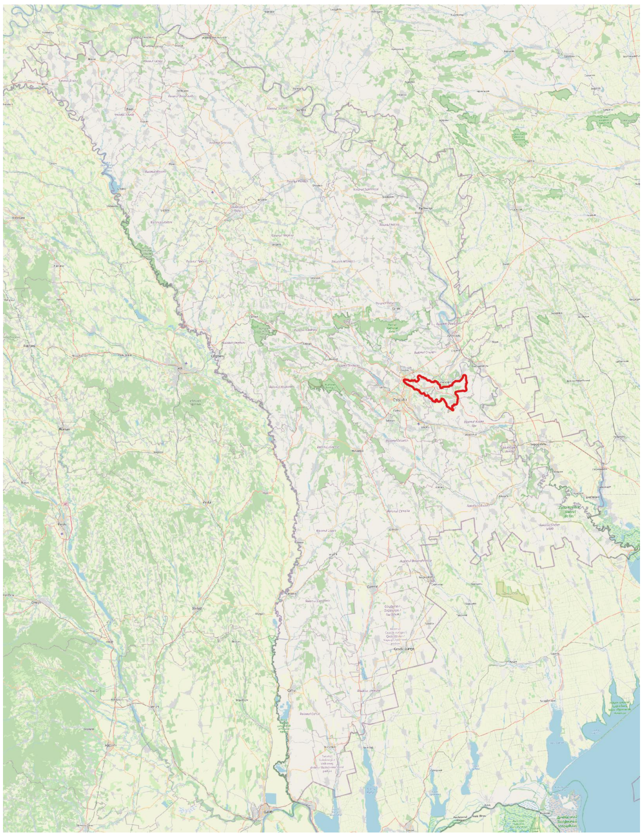

Fig. 1. Location of Bălțata River basin (red line) within the Republic of Moldova

Source: Google Maps (for geographical background)

Taking into consideration local specificity, detailed knowledge and accurate modelling of linear and surface erosion in Moldova, as well as mapping land susceptibility for development of such processes, represent an important premise for the projections of crop production and assessment of future likely impact on water resources [Sîrodoev et al., 2022]. In the past two decades, there were made several nationwide assessments of land degradation [Nour, 2004; Sîrodoev et al., 2009; Sîrodoev et al., 2019]. In recent years, attempts to model erosion processes have been made at national [Shaker et al., 2011], regional [Ercanoglu et al., 2009] and local scales [Boboc et al., 2009, 2010, 2011]. However, the great majority of these studies, while using classical or modern modelling tools, employ remotely sensed data to a very limited extent. Knowing the added value, that satellite remote sensing brings to mapping, analyzing, and modelling surface erosion [Vrieling, 2007; Sepuru, Dube, 2018], such a gap must be covered to obtain a more detailed and accurate assessment of surface erosion in Moldova.

The purpose of the study is to determine the erosion-prone areas in the Bălțata River basin (Republic of Moldova), using long term satellite monitoring of the Earth's surface and ancillary information and analyze how these areas are distributed among the structural drivers, such as land-use types, soils types, and slope angles ranges. The proposed methodology can be extrapolated at the larger scales, while the expected output will be incorporated in the models, which assess climate change on the large river-basin scale or nationwide.

2. MATERIALS AND METHODS

2.1. Study area

Bălțata is a small right tributary of the Dniester River, being entirely located on the territory of the Republic of Moldova, in its central-eastern part (Fig. 1). The basin is quite small, having an area of about 167 sq. km. Most of it is confined to a plain area, whose lowest altitude is below 20 m at the mouth. Close to the watersheds, the altitudes rise up to 220 m, while its average value is about 120 m above sea level. Nonetheless, the slope angles vary from sub-horizontal to steep ones (about 17 degrees). Slope angles from 2 to 5 degrees are the most common, while the true horizontal surfaces occupy less than 0.1% of the basin's area (Fig. 2a). The western slope aspect is dominant (30%), while eastern and southern ones are slightly rare (by 26% each); the even rarer are northern and northeastern slopes (18%).

Despite the dominance of the plain and low hilly landforms, surface erosion is quite developed. It is due to fragile lithological structure, in which loam, clay, and sand are the dominant rocks, as well as due to relatively high slopes, with the steepest close to watershed lines. Among all the dangerous geomorphological processes, ravines and landslides are dominant, while the latter has a greater spatial extent (Fig. 2b).

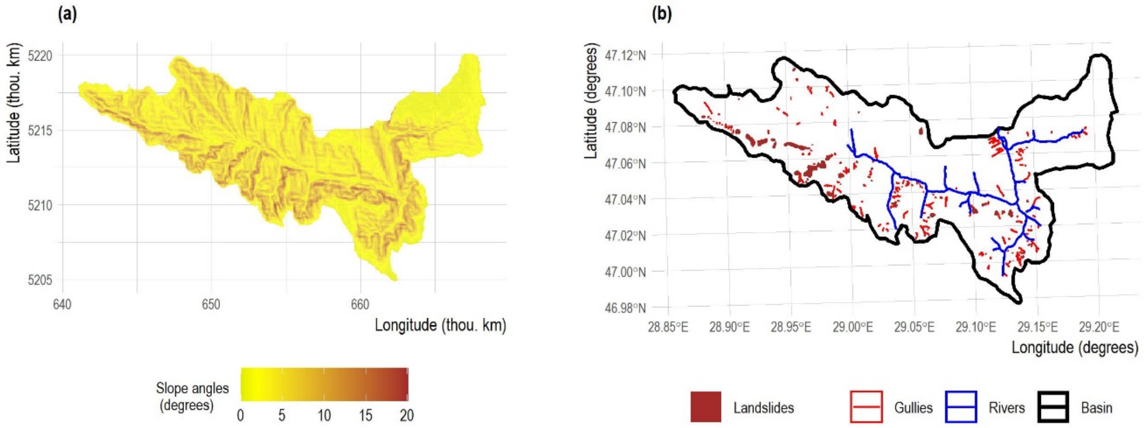

Fig. 2. Slopes angles (a) and distribution of gullies and landslides (b) within the Bălțata River basin

Source: elaborated by authors

Moldova, as a whole, and the study area, in particular, have a temperate continental climate, with mild little snow winters and warm, often dry, summers. As for the Bălțata River flow, due to an intensive anthropogenic load, it is completely transformed; its natural conditions have significantly changed. Almost all flow accumulates in four reservoirs. As a result, the river channel has turned into a shallow watercourse, and a water intake for serious practical needs can be carried out only from these reservoirs.

Most of the Bălțata River basin is located within the Eurasian steppe zone, while its small northwestern part lies in the forest-steppe zone. The scarce natural vegetation, typical for the forest-steppe and steppe zones, does not significantly contribute to slope stabilization. At the same time, due to such a combination of natural factors, The Bălțata River basin belongs to the soil region of leached chernozems, with clear features of their differentiation in altitude. However, in general, the soil cover is complex and heterogenous, being presented not only by different chernozem subtypes but by forest and alluvial soils as well. However, chernozems have become the dominant soil type, covering more than 90% of the basin's area (Fig. 3a).

The main types of land use are croplands, forests, pastures and meadows, orchards and built-up plots (Fig. 3b). About 46% of the land is used for crop production, which causes a large load on soil. Orchards and pastures occupy 13.8% and 11.4%, respectively. Only 17.4% of the basin's area is covered by forests. Among the natural vegetation, the forest-steppe and purely steppe elements are present. Due to intensive farming with poorly implemented land protection measures, which people have been practicing in the basin, more than 29% of local soils are degraded.

In addition to natural factors, man-made drivers significantly changed land-use patterns in the basin. However, we should not say that man's influence in the area was unidirectionally destructive, as one might expect. Bălțata River basin is a predominantly rural area, with 20 000 inhabitants. Despite this relatively low figure and the presence of rural landscapes only, population density is quite high: about 120 pers./sq.km, which is 1.4 times higher than the national average. That is why three major land-use types result from human activity: arable lands, orchards, and forests. These black locust forests are confined to landslides, being planted in the 1960s and 1970s as a part of the massive state-administrated program on improving and increasing the resilience of unstable lands. Under recent trends of land development, we should expect that in a medium- to long-term perspective there might be seen land rotation due to changes from arable to other agricultural types and vice-versa.

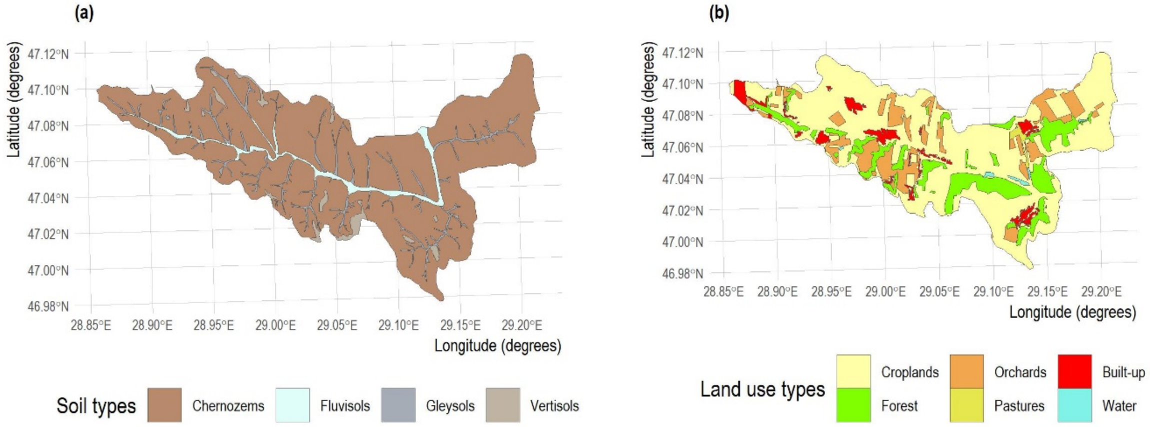

Fig. 3. Main soil (a) and land-use (b) types within the Bălțata River basin

Source: elaborated by authors

2.2. Data

Since the 1960s there has been developed a set of models to assess the soil erosion and land degradation risks: in 1965, USLE - Universal Soil Loss Equation [Wischmeier, Smith, 1978; Fox, Bryan, 1999]; in 1992, RUSLE – Revised USLE [Renard et al., 1991]; in 1995, WEPP – Water Erosion Prediction Project [Flanagan, Nearing, 1995]; in 1998, SWAT – Soil and Water Assessment Tool [Arnold et al., 1998; Gassman et al., 2007] and EUROSEM – Soil Erosion Model [Morgan et al., 1998], just to name the most widely used ones. However, mapping surface erosion on large, river-basin-wide areas is a difficult task. That is why after the medium-resolution satellite images became available to a large scientific community in the early 1980s, they started to be used in erosion assessment as well [Vrieling, 2007]. Initially, satellite images were used for visual interpretation and detection of eroded areas. Later, with the development of the digital indexes, various remotely sensed data were used for erosion assessment alone or as one of the entries in the classical soil erosion models as substitutes for one of the standard parameters (usually, vegetation cover) or newly elaborated ones, in which remotely sensed information is included as a separate factor [Vrieling, 2007; Aiello et al., 2015, Langat et al., 2019; Mhangara et al., 2012; Petropoulos et al., 2015; Sepuru, Dube, 2018; Žížala et al., 2019].

It also has been proved that a quick and rough assessment of surface erosion can be made solely on such remote sensing data as the Normalized Difference Vegetation Index (NDVI), which assess the fraction of a vegetation cover within a pixel [Rouse et al., 1974], or Normalized Difference Water Index (NDWI), which reflects water content in soil and vegetation [Gao et al., 1996].

Our approach is based on involving freely available data and analysis tools, with the contribution of some ancillary information (such as land use and soil types) obtained as a result of manual interpretation of satellite images and field research.

In the first phase of our analysis, we used the satellite images acquired using Thematic Mapper (TM) and MultiSpectral Instrument (MSI) sensors on the board of Landsat 5 and Sentinel-2 missions, accordingly. To detect erosion-prone areas, we used early spring and late autumn images, acquired at the close dates in the months, in which vegetation cover is less developed. Less than 5% of cloud cover was, among others, one of the important image quality criteria. The selected scenes were processed in the cloud (subsetting, radiometric and geometric correction) and downloaded using Google Earth Engine [Gorelick et al., 2017]. Thus, we got six scenes: three for spring and three for autumn. Each set of scenes covers the period between 1986 and 2020 while having one intermediate date in the middle, which differs for spring and autumn datasets due to scene availability: April and October for 1986 and 2020 as well as April 2000 and September 2003 for the intermediate date (Table 1). There were made corrections to the images to remove cross-platform differences [Flood, 2014, 2017; Roy et al., 2016 a, b; Claverie et al, 2018; Forkuor et al., 2018; Savage et al., 2018; Vogeler et al., 2018; Xi et al., 2019; Bonney et al., 2021; Cao et al., 2021]. Finally, we computed Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) [Gao, 1996] using the "RStoolbox" package [Leutner et al., 2019] developed for R statistical computing environment [R Core Team, 2020].

Scene ID		**Sensor**	**Scene acquiring date**	
Type of identifier	***No.***		*Spring*	*Autumn*
path/row	181/027	TM	22 Apr 1986	15 Oct 1986
			28 Apr 2000	28 Sep 2003
UTM grid tile	35TPN	MSI	2 Apr 2020	22 Oct 2020

Table 1. Characteristics of the satellite images

Source: elaborated by authors

For the determination of erosion-prone areas using vegetation and water indexes, threshold values should be established. According to the reviewed literature, the generally accepted NDVI value threshold for the bare ground is 0.2 [Rouse et al., 1974], while NDWI values below -0.1 point to water stress in plants [Gao et al., 1996]. That is, it is much more likely that pixels having NDVI <= 0.2 are covered with sparse vegetation or have no vegetation at all (Fig. 4a). Because we are rather interested in erosion than in plant stress, we adopted an NDWI threshold value less than −0.2 (Fig. 4b). In such a way, these areas become the most exposed to surface erosion processes.

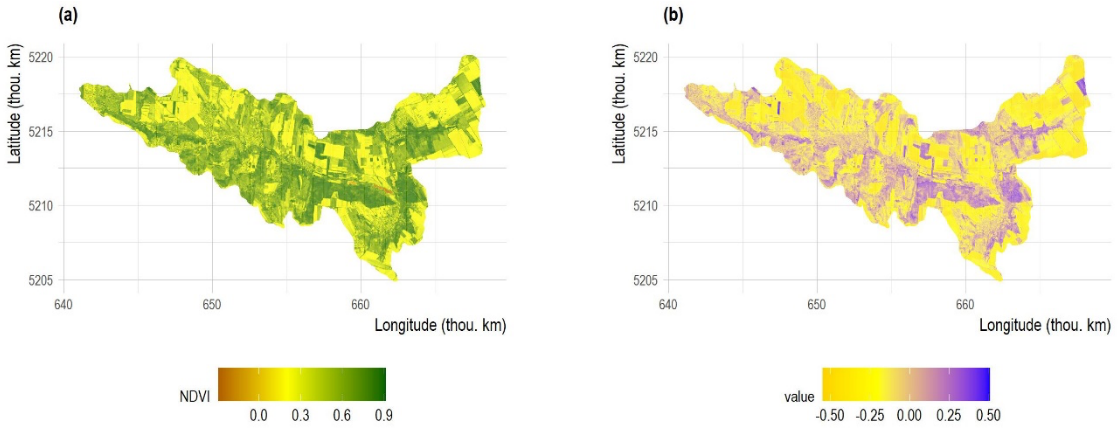

Fig. 4. Examples of NDVI and NDWI distributions within the Bălțata River basin:
(a) NDVI in April 2020 and (b) NDWI in October 2020

Source: elaborated by authors

Additionally, we used ancillary information (soil and land-use types, and slope angles) to determine whether we can find any confinement between these variables and lands exposed to degradation. Land use and soil types could be used as it is, while slope angle data should have been processed before usage. Thus, we grouped the continuous slope-angle modelling output into four discrete groups: flatlands (areas with slope angles less than 2°), gentle slopes (areas with slope angles between 2° and 5°), moderate slopes (areas with slope angles between 5° and 7°), and steep slopes (areas with slope angles more than 7°).

Finally, we prepared a 30x30 m square grid, whose spatial resolution is comparable to that of a Landsat-5 scene, involved in the assessment. We overlaid all our information (gullies, landslides, digital indexes, and ancillary data) on the grid and assigned appropriate values to each grid cell, in which the analyzed variables are located. Thus, a matrix with 187438 rows (grid cells) and 19 columns (17 variables + cell ID + cell area in sq. m) resulted, which was used in further analysis.

2.3. Methodology

Based on the distribution analysis of the digital indexes, for the determination of erosion-prone areas, we developed a multi-step approach using exclusively remotely sensed data and involving ancillary information for filtering out inappropriate areas. We are not interested in determining erosion within the urban fabric or water-covered areas, where no erosion is observed. Thus, after removing these two land-use types from the analysis, our area of interest represents about 94% of the Bălțata River basin's surface. We used the remaining four land-use types (croplands, forests, orchards, and pastures), four soil types (chernozems, fluvisols, gleysols, and vertisols), and four slope angle types (flatlands, gentle slopes, moderate slopes, steep slopes).

First, we selected the grid cells, in which gullies and landslides were observed and labelled them as "erosion". Second, we determined grid cells with critical values of NDVI and NDWI, below 0.2 and −0.2, accordingly, for each of the analyzed years for spring and autumn separately. Third, cells with critical values in both seasons and with any combination of the 2 out of 3 analyzed years were labelled "high probability" of erosion, while those having critical values just in one of the seasons were assigned "moderate probability". Thus, we obtained two parallel assessments of "erosion probability" within the grid cells by NDVI and NDWI.

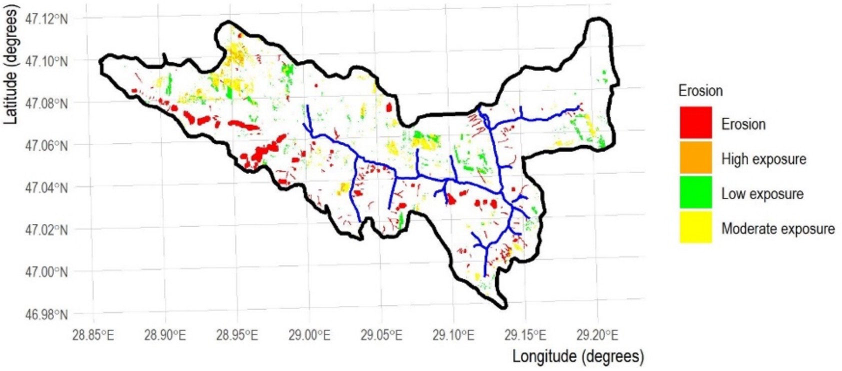

Fig. 5. Erosion-prone areas.

Source: elaborated by authors

Finally, we combined these two assessments according to the following schema: (a) cells with the "high probability" of erosion according to both indexes were labelled "high exposure" to erosion; (b) cells with the "high probability" of erosion according to either of the indexes were labelled as "moderate exposure", while (c) cells with "moderate probability" according to both indexes were labelled "low exposure" to erosion. In such a way, we obtained a map, in which the entire basin's area was divided into five categories: no exposure to erosion (transparent area, not shown in the legend), low exposure, moderate exposure, high exposure, and erosion (cells in which gullies and landslides are present) (Fig. 5).

3. RESULTS AND DISCUSSIONS

We will comment on the most important findings. Just 8.37% of the entire river basin's area is affected by erosion or exposed to it (Table 2). The dominant erosion forms are landslides, which cover 2 times larger areas than gullies. At the same time, these two forms occupy 40% of the entire area affected by erosion or exposed to it. Moderate exposure is the next category, with 32%, while low exposure accounts for 23%. High exposure is the least important category with the share slightly above 4%.

Type of erosion/exposure	**Area (ha)**	**Share (%) in:**	
		basin's area	*affected by erosion area*
Low exposure	322.83	1.91	22.84
Moderate exposure	453.33	2.69	32.08
High exposure	61.20	0.36	4.33
Erosion, including:	575.82	3.41	40.75
Gully	*184.05*	*1.09*	*13.02*
Landslides	*359.73*	*2.13*	*25.46*
Gully and landslides	*32.04*	*0.19*	*2.27*
Total affected by erosion	**1413.18**	**8.37**	**100.0**
Total basin's area	**16869.42**	**100.0**	—

Table 2. Types of erosion

Source: elaborated by authors

The distribution of slope angles is not quite equal: gentle slopes occupy more than 36% of the entire territory of the basin, while the other two slope categories and the flatlands oscillate between 18-23% each (Table 3). This dominance can explain why gentle slopes also have the highest share (44%) in the total areas affected by erosion, followed by steep slopes and moderate slopes accordingly. The share of slopes affected by erosion is more balanced: for each category, this figure falls within the interval of 10-13%. Obviously, no erosion was detected on flatlands, which means that these lands have not influenced the further analysis and final results.

Slope angle type	**Basin**		**Affected by erosion**		**Share of slopes affected by erosion (%)**
	area (ha)	*share (%)*	*area (ha)*	*share (%)*	
Steep slopes	3643.11	21.6	460.26	32.6	12.6
Moderate slopes	3078.54	18.2	329.94	23.3	10.7
Gentle slopes	6129.54	36.3	622.98	44.1	10.2
Flatlands	4018.23	23.8	—	—	—
Total	**16869.42**	**100.0**	**1413.18**	**100.0**	—

Table 3. Distribution of erosion by slope angles

Source: elaborated by authors

Soil types	**Basin**		**Affected by erosion**		**Share of soils affected by erosion (%)**
	area (ha)	*share (%)*	*area (ha)*	*share (%)*	
Chernozems	15028.47	89.1	1275.75	90.3	8.5
Fluvisols	600.03	3.6	12.15	0.9	2.0
Gleysols	832.95	4.9	75.60	5.3	9.1
Vertisols	407.97	2.4	49.68	3.5	12.2
Total	**16869.42**	**100.0**	**1413.18**	**100.0**	—

Table 4. Distribution of erosion by soil types

Source: elaborated by authors

The distribution of soil types is very unbalanced: chernozems occupy almost 90% of the basin's area, while their contribution to the areas affected by erosion even exceeds this figure (Table 4). Because of this extremely imbalanced situation, chernozems will dominate all erosion types; we will thus omit to highlight this finding each time. At the same time, vertisols are remarkable for their share of erosion-affected soils, more than 12%. Fluvisols are located at the other extreme, with just 2%. We should also emphasize that gleysols and vertisols have a higher share in eroded areas than their share in the total basin's area, by 2 and 5 times, accordingly. That makes them more vulnerable to erosion than the other two soil types.

Land use types	**Basin**		**Affected by erosion**		**Share of lands affected by erosion (%)**
	area (ha)	*share (%)*	*area (ha)*	*share (%)*	
Croplands	11369.7	67.4	983.07	69.6	8.6
Forests	2260.98	13.4	370.71	26.2	16.4
Orchards	2113.47	12.5	54.36	3.8	2.6
Pastures	91.89	0.5	5.04	0.4	5.5
Urban	980.73	5.8	—	—	—
Water	52.65	0.3	—	—	—
Total	**16869.42**	**100.0**	**1413.18**	**100.0**	**—**

Table 5. Distribution of erosion by land-use types

Source: elaborated by authors

Land-use type distribution is not as imbalanced as the soils' but croplands still dominate the basin on more than 2/3 of its area (Table 5). Forests and orchards follow them far behind, with 13.4% and 12.5%, accordingly. The importance of croplands in soil erosion is also proved by their share in the areas affected by erosion: almost 70% of erosion or exposure to erosion occurs on croplands. The next two categories are very interesting. Forests contribute to erosion twice more than their share in the basin's area (26.2% vs. 13.4%, accordingly). It might sound strange but this abnormal situation is explained by land protection measures taken in the second half of the XXth century: the majority of landslides were afforested for the sake of land stabilization. That is why many forest plots are located on landslides, being almost exclusively confined to the active erosion type. Unlike forests, orchards are much less exposed to erosion, they contribute. Pastures are poorly presented in the basin; they are confined exclusively to active erosion developed on chernozems and fluvisols. Due to this feature, they are overrepresented in the degraded areas: their share here is 11 times higher than the same figure in the entire river basin. The same situation happens with the forests; however, this ratio is much smaller, just 1.2 times.

The active erosion type is confined to steep slopes: 2/3 of its area is located on the slopes with angles greater than 7°. Moreover, about 65% of this erosion category is confined to afforested areas (50% on steep slopes), which represent stabilized landslides. Another 30% are located on croplands (including 14% on steep slopes, the highest figure).

The other three exposure types (high, moderate, and low) are exclusively confined to croplands, in a proportion that varies from 95% to 99%. About 16% of the steep slopes with erosion are affected by this type of exposure, while 2/3 of moderate slopes are affected by it. Gentle slopes are affected by it to even a greater extent (87%).

4. CONCLUSION

Quite a large area is exposed to dangerous surface processes: about 1413 ha (8.4% of the basin's area). The most critical areas (erosion and high exposure) represent 45% of the total erosion-prone areas, while the rest of 55% is moderate to low exposed. In the distribution by land use and soil types the relationship is usually simple: the larger the area occupied by a certain category the larger its share in erosion-prone areas. Thus, croplands having the highest share in land use have the highest share in the erosion-prone areas. The same situation occurs with chernozems, whose share in erosion-prone areas slightly exceeds 90%. We also must highlight that about 70% of eroded and highly exposed areas are located on croplands, while the other 26% of these two erosion types are confined to forests because of land consolidation measures implemented in the past. We should also emphasize that gleysols and vertisols have a higher share in eroded areas than their share in the total basin's area, by 2 and 5 times, accordingly. That makes them more vulnerable to erosion than the other two soil types. A similar situation happens to forests and pastures, however, here the relationship is inverse: these land-use types occupy already degraded areas, especially landslides, for land consolidation (forests) or because other uses are inappropriate (pastures). Only slope angle types do not have such abnormalities. However, gentle slopes (2°—5°) stand out for their extent and moderate exposure to erosion.

Diminishing the erosion risk in the future can be done by changing land-use types. Thus, the lands occupied by crops, which are highly exposed to surface erosion, can be converted into other types of land use that present a smaller risk of degradation, such as forests. Such a conversion will bring multiple benefits by not just protecting lands from degradation but also will help in growing the share of forests and will respond to the necessity of forested water protection belts.

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