

Journal of Geology, Geography and Geoecology

Journal home page: geology-dnu.dp.ua

ISSN 2617-2909 (print)
ISSN 2617-2119 (online)

Journ. Geol. Geograph.
Geology,
30(3), 571–580.

doi: [10.15421/112152](https://doi.org/10.15421/112152)

Svitlychnyi O. O., Chemerys N. G.

Geol. Geograph. Geoecology, 30(3), 571–580

Spatially distributed assessment and forecast of soil erosion losses as a basis for optimization the use of erosion-hazardous agricultural lands

Oleksandr O. Svitlychnyi, Nadiia G. Chemerys

Odessa I. I. Mechnikov National University, Odessa, Ukraine, e-mail svetlitchnyi.aa.od@gmail.com

Received: 26.10.2020

Received in revised form: 11.04.2021

Accepted: 14.07.2021

Abstract. The article is devoted to the problem of sustainable use of agricultural lands in conditions of active manifestation of water soil erosion, which is typical for all natural zones of Ukraine, but to the greatest extent – for the Forest-Steppe and Steppe zone. The aim of the article is a spatially distributed quantitative assessment and forecast of soil erosion losses and

the development on this basis of recommendations to optimize the use of agricultural land on the example of the Pidhayetskyi district of the Ternopil region. The area is located within the Western region of Ukraine with a fairly high intensity of water erosion, where in accordance with the long-term climate forecast a further increase in erosion hazard of land is expected. A quantitative assessment of soil erosion losses for the basic period (1961–1990) and forecast periods (2031–2050 and 2081–2100) was carried out using a spatially distributed physical-statistical GIS-model of soil erosion-sedimentation developed at the Department of Physical Geography, Nature Management and Geoinformation Technologies of Odessa I. I. Mechnikov National University. Spatial realization of the model performed using the analytical capabilities of the Software for Environmental Modeling PCRaster (University of Utrecht, Netherlands). The forecast of the changes in the hydrometeorological conditions of water soil erosion was made using the forecast of monthly average air temperatures and monthly average precipitation, developed at the Ukrainian Hydrometeorological Institute. It established that most of the arable land (about 52 %) of Pidhayetskyi district is erosively dangerous. Due to the projected increase in summer rainfall in the middle and at the end of this century, further intensification of soil erosion is expected, especially in 2031–2050, when soil losses on arable land will increase to 16.9 t/ha/year, and only due to rainstorm erosion. Soil losses by meltwater will be insignificant. Based on the calculations, it was concluded that it is impossible to protect the agricultural lands of the region from erosional degradation without withdrawal from the arable land about 8.15 thousand hectares (28) of the most erosion-hazardous lands (with annual soil losses exceeding 20 tons per a hectare), changing the structure of sown areas and introduction a soil-protective adaptive-landscape farming system over a significant area.

Ключові слова: soil erosion, spatially distributed assessment and forecast, optimization of land use, Pidhayetskyi district, Ternopil region.

Просторово-розподілена оцінка і прогноз ерозійних втрат ґрунту як основа оптимізації використання ерозійно-небезпечних земель

О. О. Світличний, Н. Г. Чемерис

Одеський національний університет імені І. І. Мечникова, e-mail svetlitchnyi.aa.od@gmail.com

Анотація. Стаття присвячено проблемі раціонального використання сільськогосподарських земель в умовах активного прояву водної ерозії ґрунтів, характерного для всіх природних зон України, але найбільшою мірою – для Лісостепу і Степу. Метою статті є просторово-розподілена кількісна оцінка і прогноз ерозійних втрат ґрунту і розробка на цій основі рекомендацій щодо оптимізації використання сільськогосподарських земель на прикладі Підгаєцького району Тернопільської області. Район розташований в межах Західного регіону України з досить високою інтенсивністю водно-ерозійної діяльності, де відповідно до довгострокового кліматичного прогнозу очікується подальше збільшення ерозійної небезпеки земель. Виконана кількісна оцінка ерозійних втрат ґрунту для базового періоду (1961–1990 рр.) і періодів прогнозу (2031–2050 і 2081–2100 рр.) з використанням просторово розподіленої ГІС-реалізованої фізико-статистичної моделі змиву-аккумуляції ґрунту, розробленої на кафедрі фізичної географії, природокористування і геоінформаційних технологій Одеського національного університету імені І. І. Мечникова. Прогноз зміни гідрометеорологічних умов водної ерозії ґрунту виконано з використанням прогнозу середньомісячних температур повітря і середньомісячних сум атмосферних опадів, розробленого в Українському гідрометеорологічному інституті. Встановлено, що більша частина орних земель Підгаєцького (близько 52 %) району є ерозійно небезпечною. У зв'язку з прогнозованим збільшенням кількості літніх опадів в середині і в кінці поточного сторіччя, очікується подальша інтенсифікація ерозії ґрунтів, особливо в 2031–2050 роках, коли середньорічні втрати ґрунту на орних землях району збільшаться до 16,9 т/га/рік, причому тільки за рахунок зливної ерозії. Втрати ґрунту талими водами будуть практично не значущими. На основі виконаних розрахунків зроблено висновок про неможливість захисту орних земель району від ерозійної деградації без виведення зі складу ріллі близько

8.15 тис. га (28 %) найбільш ерозійно небезпечних земель, зміни структури посівних площ і впровадження на значній площі ґрунтозахисної адаптивно-ландшафтної системи землеробства.

Ключові слова: водна ерозія, просторово-розподілена оцінка і прогноз, оптимізація землекористування, Підгасцький район Тернопільської області.

Introduction.

Comprehensive protection of agricultural land from water soil erosion common in all natural zones of Ukraine can be ensured only on the basis of the use of adaptive-landscape farming systems, such as contour-reclamation, landscape-ecological, precise (Shelyakin et al., 1990; Tarariko, 1990; Kashtanov et al., 1994; Magleby et al., 1995; Bulygin and Nearing 1999; Tarariko, 2005; Vergunov, 2006; Montgomery, 2007; Hobbs et al., 2008; Rykhliivskyi et al., 2014, etc.). The design of adaptive-landscape farming systems requires the use of spatially distributed mathematical models of soil erosion, which make it possible to estimate soil erosion losses on a given slope surface element, taking into account the spatial differentiation of all the main natural and economic factors of slope erosion-accumulative process.

The existing spatially distributed mathematical models of water soil erosion are primarily represented by physically sound dynamic models. The system of differential equations in partial derivatives of the balance of matter (water and sediments) and energy is a basis of these models. However, their high requirements for information support and excessive sensitivity to the accuracy of the input data limit possibility of their usage predominantly by research projects. The practice of conservation farming in different countries is still mainly based on the use of empirical mathematical models of soil erosion, such as the Universal Soil Loss Equation (USLE/RUSLE) (Wischmeier and Smith, 1978; Renard et al., 1997, etc.).

In Ukraine, for design of soil protection from erosion the mathematical models of soil losses developed by Shvebs (1974, 1981), Lavrovsky et al. (Lavrovsky et al., 1987), and Sribny (Sribny, 1977; Sribny, Vergunov, 1993), also belonging to the category of empirical mathematical models, are used or are recommended for use. All these models, including the Universal Soil Loss Equation, were originally developed to calculate the average annual soil loss on average for the slope, that is, they were models with lumped parameters that did not take into account the spatial variability of factors of modeled process. At a certain stage, the developers of the Universal Soil Loss Equation proposed a method for approximate accounting for changes in the factors of the erosion process along the length of the slope, but only within its convex part (Foster, Wishmeier, 1974). However, even this model is not properly calibrated and is not tested in the natural and economic conditions of Ukraine.

In recent decades, a spatially distributed physical-statistical model of soil erosion-sedimentation has

developed in the Odessa National I. I. Mechnikov University (Svetlitchnyi, 1995, 1999; Svetlitchnyi et al., 2004; Pyatkova, 2011, 2013; Svetlitchnyi and Piatkova, 2019). Currently, this mathematical model is software implemented using the operators of the Software for Environmental Modeling (GIS-package) PCRaster (PCRaster ..., 2018) and the programming language Basic. The model was successfully verified using observational data at runoff plots and experimental catchments of the Moldavian and Veliko-Anadol Water Balance Stations and the Boguslav Field Research Hydrological Base of the Ukrainian Hydrometeorological Institute (UkrHMI) (Svetlitchnyi, 1995, Piatkova, 2011; Svetlitchnyi and Piatkova, 2019), as well as of the results of field studies of water erosion using the radio-cesium method and the method of magnetic tracers (Zhidkin et al., 2015). The adequacy of modeling the spatial distribution of erosion-sedimentation by this model was also confirmed by comparison with the simulation results using the spatially distributed physically based dynamic model LISEM (Svetlitchnyi, Pyatkova, 2017). Recent studies on long-term forecasting of climate change (Krakovska et al., 2006; Krasovska et al., 2017), surface runoff (Gopchenko et al., 2012; Ovcharuk, 2017) and hydrometeorological conditions of soil erosion (Svetlitchnyi, 2018) make it possible to use this model not only for a spatially distributed assessment, but also for a forecast of soil erosion within the plain part of Ukraine until 2100.

The purpose of this study is the spatially distributed quantitative assessment and forecast of erosion losses of soil and the development on this basis of recommendations to optimize the use of agricultural land on the example of the Pidhayetskyi district of the Ternopil region. The area is located within the Western region of Ukraine with a fairly high intensity of soil erosion where, in accordance with the long-term climate forecast, a further increase in erosion hazard is expected, at least during the warm season (Svetlitchnyi, 2018).

Water erosion losses of soils on the agricultural lands of the Pidhayetskyi region is the object of the study. Spatially distributed retrospective assessment of erosion losses of soil for the baseline period (1961–1990), their forecast until 2100 and the development of recommendations for optimization the use of erosion-hazardous lands of the region is a subject of the study.

Material and methods of research.

Pidhayetskyi district is located in the western part of the Ternopil region on the border of the Western Podillya and the Eastern Opilia on the Volyn-Podilsk

Upland. The territory of the district is 49638 ha (496.38 km²) (Pidgajec'ka..., 2018).

The relief of the territory is wavy, crossed by river valleys of mainly meridian strike and beams, in the western part of it is hilly. The absolute heights of the divides are 380–410 m, and of the bottoms of river

valleys (the Zolotaya Lipa, Koropets, Strypa rivers) are 240–330 m. The maximal height of the earth's surface within the district is 414 m. The distribution of the Pidhayetskyi district agricultural land in the range of slope gradients is shown in the Table 1.

Table 1. Distribution of the Pidhayetskyi district agricultural land in the range of slope gradients

Slope gradients, degrees	Area	
	ha	%
<1	7356.5	20.7
1–3	11724.5	33.0
3–5	7741.3	21.8
5–7	4157.0	11.7
>7	4538.5	12.8
Total	35517.8	100.0

The climate of the district is temperate continental and is characterized by mild winters, warm summers, and a significant amount of rainfall. The area is located at the boundary of two climatic zones: of the Western European zone in the west with a humid and moderately warm climate and East-Continental zone in the East with a continental climate (Geografija ..., 2017). The average annual air temperature according to Berezhany meteorological station, which is located 25 km northwest from the administrative center of the district, is 7.2 °C, the average annual rainfall amount according to Berezhany meteorological station is 690 mm, according to the precipitation measuring post Pidhaitsi – 704 mm. (Klimatychnyj..., 2006). Most precipitation falls in the warm part of the year (April–October). The maximal rainfall in a single rain at Berezhany weather station was observed in August and reached 90 mm. The period 1961–1990 was characterized by a persistent winter with average monthly temperatures of –2.1 ... –4.9 °C, with an average duration of snow cover of 84 days and an average maximal height of 37 cm in the end of winter (Klimatychnyj..., 2006).

The soil cover in the eastern part of the district (in the Podillya) is represented by podzolized chernozems and dark gray podzolized coarse-dusty medium loamy soils and in the western part (at Opilia) by gray and light gray podzolized loamy soils.

Podzolized chernozems in comparison with dark gray podzolized soils are deeper, more humus-rich (2.5–3.5 %). Gray and light gray podzolized soils of Opilia in the upper horizons have a humus content of 1.8–2.2 %. The natural fertility of these soils is much less than that of the chernozems (Geography..., 2017).

Among 49638.00 hectares of land under the control of Pidhayetskyi district, agricultural land occupies 35517.79 or 71.6 % of the total area, including arable land – 29047.53 hectares (81.8 %), pastures – 4702.49 ha (13.2 %), hayfields – 1376.47 ha (3.9 %), perennial plantings – 391.29 ha (1.1 %). In addition, 451.49 hectares (1.3 %) are under farm buildings and yards, forests cover 9365 hectares (18.9 % of the area), reservoirs – 592 hectares (1.2 %), swamps – 212 hectares (0.4 %) (Pidgajec'ka..., 2019).

The structure of sown areas of the district is presented in the Table. 2. The largest share in the structure of sown areas is occupied by cereal crops, which account for 50.8 % of the arable land, including 23.6 % of spring crops and 27.2 % of winter crops. The group of high-stem tilled crops (corn, sorghum, sunflower), whose soil-protective efficiency is very low, occupies 29.7 % of the arable land area. Perennial grasses with high soil-protective efficiency occupy only 3.5 % of the sown area.

Table 2. Structure of sown areas of the Pidhayetskyi district (Pidgajec'ka..., 2019)

No	Crops	Area, ha	Share in the structure of sown areas, %
1	High-stem tilled crops (corn, sorghum, sunflower)	8640.6	29.7
2	Low-stem tilled crops (soybeans, buckwheat, peas, potatoes, vegetables, watermelons and melons)	4264.1	14.7
3	Spring cereals	6841.0	23.6
4	Winter cereals	7887.1	27.2
5	Annual grasses	388.1	1.3
6	Perennial grasses	1026.6	3.5
	Total	29047.5	100.0

A quantitative assessment of soil erosion losses on agricultural lands of the Pidhayetskyi district of the Ternopil region was performed using a spatially distributed version of the physical-statistical model of soil erosion-sedimentation (Svetlitchnyi, 1995, 1999; Piatkova, 2008, 2011; Svetlitchnyi & Piatkova, 2019). The years 1961–1990 were chosen as the baseline period due to the availability for this period of a complete set of information necessary for the model. The forecast was made for the middle of the current century (2031–2050) and its end (2081–2100) in accordance with the periods of the long-term climate forecast developed at UkrHMI (Krasovska et al., 2016; Krasovska et al., 2017).

The digital geodatabase for the territory of Pidhayetskyi district has been created using a topographic map of 1:100 000 scale, a soil map of 1:200 000 scale (Karta gruntiv..., 1967) and high-resolution satellite image from the GoogleEarth Internet service. Statistical materials from the website of the Pidhayetska State Administration, monographic literature and publications in the periodical scientific editions were used as a source of attributive information characterizing the use of land in the region. The values of climatic indicators for the baseline period were taken from the Climatic Cadaster of Ukraine (Klimatychnyj..., 2000), for forecast periods – taken in accordance with the climate forecast made in the Ukrainian Hydrometeorological Institute (Krakovska et al., 2016; Krakowska et al., 2017).

Comparative-geographical, cartographic, statistical and geoinformation modeling methods were used to achieve the purpose. The PCRaster environmental modeling package developed in the Department of Physical Geography of the University of Utrecht, the Netherlands (PCRaster ..., 2018) was used as the basic GIS software.

Results and Discussion.

Creating the digital geodatabase. The digital database of spatially distributed data (geodatabase) includes sets of basic and derived digital maps of the district area. Digital raster maps created on the basis of digitizing of paper maps or a satellite image we will consider as basic maps. Digital raster maps created on the basis of basic digital maps using GIS software tools we will consider as derived maps.

The hydrologically correct digital elevation model, digital maps of soils and land use are the basic digital data layers that provide a mid-scale assessment of erosion soil losses within an administrative district based on the physical-statistical model of ONU. Screen copies of these three basic digital maps for the territory of the Pidhayetskyi district of the Ternopil region are presented in the Figures 1–3.

All basic maps are built in the WGS-84 UTM coordinate system with the same spatial resolution. The raster cell size is 50 m for all maps. When constructing a digital elevation model on a topographic map of 1:100 000 scale all the main and additional relief contour lines were digitized, as well as the structural elevation lines (divides and talwegs). Spatial interpolation of point data was performed using methods of ordinary point kriging and radial basis functions, which gave similar results.

The set of derived maps includes a large number of digital raster maps, most of which are created in batch mode using capabilities of the Basic and PCRaster packages. Digital raster maps of slope gradients, expositions, streamlines, relative erodibility and partial characteristic of relative erodibility of soils, horizontal gradients of soil cover characteristics, in particular, are derivative maps are creating the process of implementation of the erosion-sedimentation model.

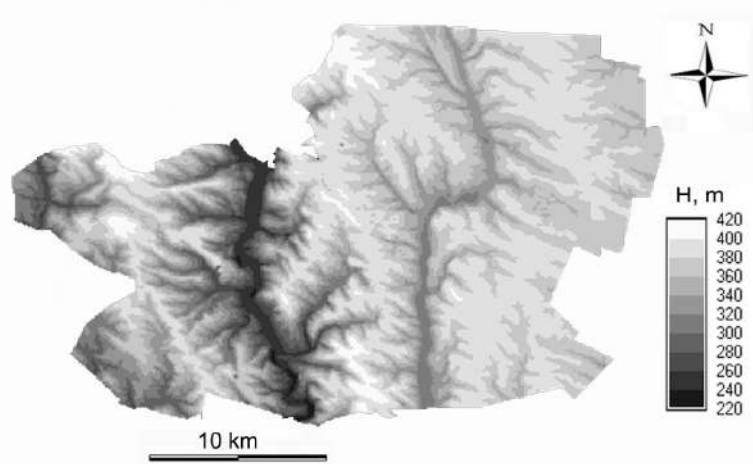


Fig. 1. Screen copy of digital elevation map of the Pidhayetskyi district

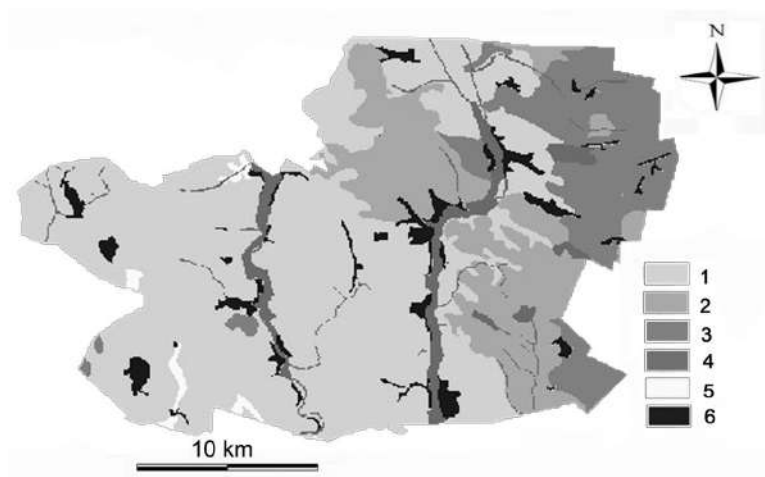


Fig. 2. Screen copy of soil map of the Pidgayetskyi district: 1 – light-gray and gray podzolized soils; 2 – dark-gray podzolized soils; 3 – podzolized chernozems; 4 – meadow-chernozem, chernozem-meadow, meadow, meadow-bog and other alluvial soils; 5 – exits of rocks; 6 – settlements

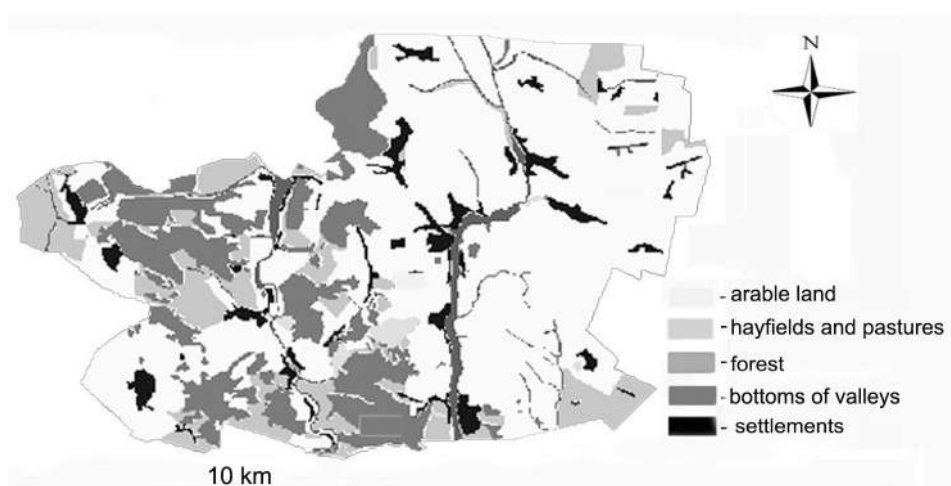


Fig. 3. Screen copy of land use map of the Pidhayetskyi district

Parameterization of the model. The hydrometeorological factor of rainstorm soil losses (K_{HM}) and the hydrometeorological factor of soil losses by the meltwater (K_{HMS}) are the main parameters of the used model of soil erosion, requiring geographical reference. The long-term average the K_{HM} values for the baseline climate period and for the forecast periods are determined by the previously established dependence of the K_{HM} on the long-term average sum of precipitation for May–September (Svetlitchnyi, 2018). The long-term average value of the hydrometeorological factor of rainstorm losses of soil for the baseline period, obtained using this dependence and the data from the precipitation

measuring station Pidhaitsi (Klimatychnyj..., 2006), is 0.0052. The long-term average values of the K_{HM} for 2031–2050 and 2081–2100 in accordance with the forecast of monthly precipitation (Krakowska et al., 2017) (Table 3) are 0.0071 and 0.0063, respectively. Due to the fact that the forecast of changes in the average monthly precipitation for 2031–2050 and 2081–2100 is given in relation to 1991–2010, it became necessary to assess the change in the average monthly precipitation of 1991–2010 in relation to the baseline period (1961–1990). This assessment was performed using observational data from the reference weather stations of the region.

Table 3. Long-term average precipitation for May–September for the Pidhaisi precipitation measuring post for the baseline period in accordance with the Climatic Cadaster of Ukraine (Klimatychnyj..., 2000) and for forecast periods for Western Region of Ukraine in accordance with (Krakowska et al., 2017)

	May	June	July	August	September	Sum
Average long-term precipitation for 1961–1990, mm	71	98	98	72	62	406
Change in precipitation 1991–2010 in relation to 1961–1990, %	-7	-12	4	10	35	
Average long-term precipitation for 1991–2010 years, mm	66	86	102	79	84	420
2031–2050						
Projected precipitation changes relative to 1991–2010 years, %	16	12	13	4	18	
Average long-term precipitation for 2031–2050 years, mm	77	96	115	82	99	469 411
2081–2100						
Projected precipitation changes relative to 1991–2010 years, %	7	4	13	-3	10	
Average long-term precipitation for 2081–2100, mm	71	89	115	77	92	444

The long-term average value of the hydrometeorological factor of spring snowmelt erosion (K_{HMS}) for the baseline period in accordance with (Svetlitchnyi et al., 2004) equals to 0.0010. The K_{HMS} values for the forecast periods (2031–2050 and 2081–2100) in accordance with the forecast of spring surface runoff values (Gopchenko et al., 2012; Ovcharuk, 2017) are either close to zero (in the middle of the century) or equal to zero (in end of the century). That is, the erosion hazard of the district's agricultural lands in the prospect under consideration will be determined only by rainstorm erosion during a warm season.

The values of other parameters of the model are taken in accordance with the existing recommendations (Shvebs, 1981; Svetlitchnyi et al., 2004; Lisetsky et al., 2012).

Results of calculation and forecast of soil erosion losses. The result of the calculation of soil erosion losses within the Podhayetskyi district for hydrometeorological and land use conditions of the baseline period (1961–1990) are presented in the Fig. 4. The result of the

calculation of soil erosion losses within the most erosion-prone arable land are presented in the Table 4.

The analysis in the Fig. 4 and the Table 4 allows us to state a generally high rate of erosion degradation of soils of arable lands of the district. Within hayfields and pastures, which make up the second main component of the farmland of the district, soil erosion losses are usually insignificant. This circumstance allows us to focus on the analysis of soil erosion losses precisely on arable land, occupying 81.8 % of the farmland and 58.5 % of the total district's area. The calculated average module of erosion losses of soils within the arable land of the district for the baseline period is 16.0 t/ha per year (Table 4). Most of the soil erosion losses, namely 13.6 t/ha/year or 85 %, are formed by rainfall in warm season, 2.5 t/ha/year (15 %) – by melt water in spring. The area of arable land with annual soil losses not exceeding 5 t/ha/year is 14056 ha or 48.4 %. The area of arable land with erosion losses exceeding 20 t/ha/year is about 6720 ha or 23.1 % of its area. Within 2407 ha (8.3 %) of arable land, the estimated soil loss exceeds 50 t/ha/year.

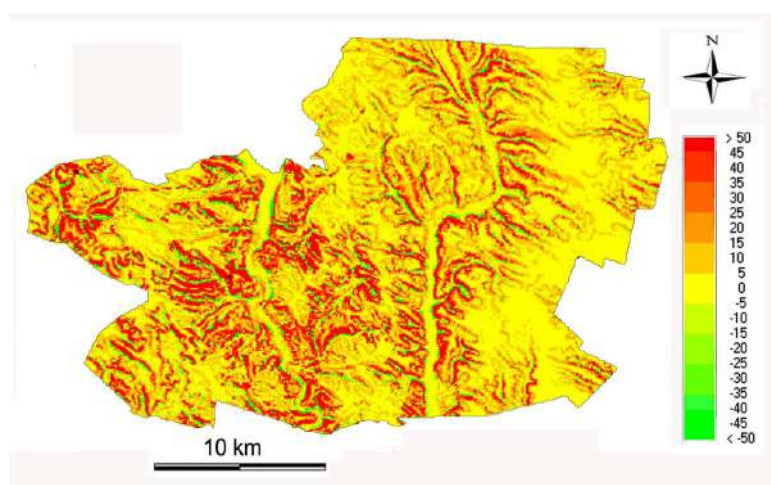


Fig. 4. The estimated average annual soil losses (t/ha/year) within the Pidhayetskyi district for the baseline period

Table 4. Average annual soil losses (t/ha/year) and distribution of the area of arable land of the district by gradations of erosion losses for the baseline period

Period, years	Season, year	<2		2–5		5–10		10–20		20–50		>50		Average annual soil losses, t/ha/year
		Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	
1961–1990	Summer autumn	9960	34.3	4412	15.2	3935	13.6	4088	14.1	4246	14.6	2407	8.3	13.6
	Spring	17012	58.6	7555	23.0	3317	11.4	1019	3.5	145	0.5	0	0	2.5
	Year	8546	29.4	5510	19.0	3917	13.5	4356	15.0	4314	14.8	2407	8.3	16.0

In the middle of current century (2031–2050), in accordance with the predicted climate change (Table 3) while maintaining the structure of sown areas, the soil cultivation system, and the absence of special anti-erosion measures the erosion hazard of arable land in the district will increase, despite a decrease to insignificant values of erosion losses of soil in spring. The area of arable land with an average annual soil losses exceeding 20 t/ha will amount to 8153 ha (28.1 %), that is, it will

increase by 1434 ha or 4.9 % compared to the baseline period. Accordingly, an area of land with erosion soil losses of less than 5 t/ha/year will decrease by 954 ha (up to 13102 ha or up to 45.1 %). At the end of the century (2081–2100), due to the projected decrease compared to 2031–2050 the amount of precipitation in the warm season, soil erosion losses on the arable lands of the district will slightly decrease (Table 5).

Table 5. Forecast of the average annual soil losses and distribution of the arable land area of the Pidhayetskyi district according to gradations of erosion soil losses (t/ha/year)

Period, years	Season, year	<2		2–5		5–10		10–20		20–50		>50		Average annual soil losses, t/ha/year
		Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%	
2031–2050	Summer-autumn	8423	29.0	4679	16.1	3656	12.6	4137	14.2	4869	16.8	3284	11.3	16.9
2081–2100	Summer-autumn	9392	32.3	4326	14.9	3771	13.0	4133	14.2	4646	16.0	2780	9.6	15.0

Discussion.

Based on the permissible erosion standards recommended by the National Standard of Ukraine (DSTU..., 2010), the arable land of the district with erosion losses of soil not exceeding 2 t/ha/year can be considered as erosion-safe. The estimated area of such lands in the district in 1961–1990 was about 8550 ha or 29.4 % of the arable land area. Another 5510 ha or 19.0 % of arable land with erosion losses of soil from 2 to 5 t/ha/year were characterized by low erosion risk. In total, these two categories of land occupied about 48 % of the arable land. They either do not require special anti-erosion measures, or allow to be limited by the simple soil-protective techniques, such as plowing transversely the slope, periodic deep plowing or plowing with soil deepening, as well as phyto-reclamation techniques (Svetlichnyi et al., 2004; Naukovi ..., 2010; Zonalni..., 2010). However, almost 52 % of arable land is characterized by significant erosion risk. Within 8153 ha (28.1 %), the estimated soil loss exceeds 20 t/ha/year, and therefore the erosion hazard of these lands is characterized as very high or catastrophic (with soil losses of more than 50 t/ha/year) (Svitlychnyi and Chornyy, 2007; Tarariko et al., 2017, etc.). These lands require a set of special anti-erosion measures. Moreover, given the projected further increase in the erosion risk

of arable land in the district, this requirement becomes even more urgent.

The calculations show that arable lands, on which the average annual soil loss exceeds 20 t/ha/year, cannot be protected from the progressive erosion degradation with their continued intensive use. They should be removed from the composition of the arable land. On lands with an average annual soil loss of 5–20 t/ha and moderate or high erosion hazard, it is necessary to implement the system of soil protection measures, the intensity of which is proportional to the degree of soil erosion hazard. Landscape-adaptive soil-protective farming system is by far the best option of such system. At the same time, it is necessary to emphasize the need to change the structure of sown areas here with a decrease of the share of row crops and an increase of the share of grasses, especially perennial ones. In accordance with the recommendations of agrarian science for the Western Forest-Steppe of Ukraine, even for the first (least erosion-hazardous) ecological-technological group of lands, the optimal permissible limits for saturation of crop rotation with perennial grasses are 10–30 % (Tarariko, 1990). Currently, perennial grasses occupy only 3.5 % of the sown area of the district (Table 2).

Provided that 8150 hectares of the most erosion-hazardous lands will be removed from the arable land and the share of perennial grasses in the crop rotation will be increased to 15 % due to a corresponding decrease in the share of row crops, it is predicted that for 2031–2050 the average soil losses on arable land of the district will decrease to 3.4 t/ha/year. At the same time, lands with no or weak erosion hazard, that is, with soil losses not exceeding 5 t/ha per a year, will occupy about 65 % of the arable land.

When 8150 ha will be removed from the arable land, the share of arable land in the composition of agricultural land of the district will decrease from 81.8 % to 58.8 %. Based on a generalization of the results of studies conducted in Ukraine, Makhortov (1999) recommends the optimal share of arable land in the composition of agricultural land from the range of 45–55 % for the Forest-Steppe zone. According to the research of Carik (2010) in an optimal model of the land use structure as a whole for Podillja, arable land as part of agricultural land should occupy 60 % of their area, and directly for Pidhayetskyi district – 58.7 %. Thus, withdrawal from intensive agricultural use of lands for which the erosion losses of soil projected for 2031–2050 exceed 20 t/ha/year (Table 4), will make it possible to bring the structure of arable land to the optimum.

The erosion-hazardous lands removed from the arable land are recommended for use under hayfields, pastures or permanent afforestation with the mandatory implementation of a range of anti-erosion measures, including, if necessary, hydro reclamation measures.

Conclusions.

1. Most of the arable land of the Pidhayetskyi district of the Ternopil region is erosion hazardous. Under the existing structure of crop area, the estimated average annual soil losses for hydrometeorological conditions of 1961–1990 is 16.0 t/ha per a year, and land with a very high erosion hazard with annual soil losses exceeding 20 t/ha per a year occupy 23 % of the arable land.

2. Due to the projected increase in precipitation during the warm season in the middle and the end of the current century, further intensification of soil erosion is expected, especially expressed in 2031–2050, when the average annual soil losses within arable land in the district will increase to 16.9 t/ha/year, and the area of land with a very high erosion hazard will increased up to 28 %.

3. Ensuring the protection of arable land of the district from erosion destruction is impossible without withdraw from the arable land about 8.15 thousand hectares of the most erosion-hazardous land. This will reduce the share of arable land to 58.8 % of the agricultural land, which will bring it as close as possible to the optimum and will allow to reduce soil losses due to erosion to permissible values using soil-protective landscape-adaptive farming systems.

4. In solving the problem of protecting the arable lands of the district from erosion degradation, the increase in the area of perennial grasses from 3.5 % to 15 % plays an important role.

References

- Bulygin, S. Yu., Naring, M. A., 1999. Formirovanie jekologicheskij sbalansirovanyh agrolandshaftov: problema jerozii [Formation of ecologically balanced agrolandscapes: the problem of erosion]. Eney Ltd, Kharkiv (in Russian).
- Carik, L. P., 2010. Do problem optymizacii' zemle- ta pryrodokorystuvannja regionu [To the Problem of Optimization of Land and Natural Use of a Region]. Nature of Western Polesie and surrounding territories: Coll. Sc. Papers. Volyn. Lesya Ukrainka Nat. University, resp. ed. F. V. Zuzuk and others. Lutsk, № 7, 35–46 (in Ukrainian).
- DSTU 7081:2009. Eroziya g'runtu. Dopustymy normy, 2010 [DSTU 7081: 2009. Soil erosion. Admissible standards]. State standard of Ukraine, Kyiv (in Ukrainian).
- Foster, G. R., Wishmeier, W. H., 1974. Evaluating irregular slopes for soil loss prediction. Trans. Am. Soc. Agric. Engrs., 17(2), 305–309. doi: 10.13031/2013.36846.
- Geografija Ternopil's'koi' oblasti. T. 1. Pryrodni umovy ta resursy, 2017 [Geography of Ternopil region. Vol.1. Natural Conditions and Resources] / Scientific editor M. Ya. Sivi. Vector, Ternopil (in Ukrainian).
- Gopchenko, Ye. D., Ovcharuk, V. A., Semenova, I. G., 2012. Naukovo-metodychni pidhody do vrahuvannja global'nyh zmin klimatu pry rozrahunkah maksimal'nogo stoku richok [Scientific and methodical approaches to taking into account global climate changes in calculations of maximum runoff of rivers]. Bulletin of Odesa State Ecological University 14, 141–150 (in Ukrainian).
- Hobbs, P. R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. Lond. B. Biol. Sci.; 363(1491): 543–555. Published online 2007 Jul 24. doi: 10.1098/rstb.2007.2169
- Karta gruntiv Ukrai'ns'koi' RSR, masshtab: 1:200000, 1967 [Map of soils of the Ukrainian SSR, scale: 1: 200000] ed. Krupsky M. K. Ukrzemproject, Kyiv (in Ukrainian).
- Kashtanov, A. N., Lisetskiy, F. N., Schwebs, G. I., 1994. Osnovy landshaftnogo zemledelija [Fundamentals of landscape agriculture]. Kolos, Moscow (in Russian).
- Klimatychnyj kadastr Ukrai'ny: standartni klimatychni normy za period 1961–1990 pp. 2006 [Climatic Cadastre of Ukraine: standard climate norms for the period 1961–

- 1990]. Electronic resource. Central Geophysical Laboratory, Kyiv (in Ukrainian).
- Krakovska, S. V., Gnatyuk, N. V., Shpital, T. M., Palamarchuk, L. V., 2016. Proekcii' zmin temperatury povitrya za danymy ansamblju regional'nyh klimatychnyh modelej v regionah Ukrai'ny v XXI stolitti [Projections of changes in air temperature according to the ensemble of regional climate models in the regions of Ukraine in the 21st century]. UkrNDGMI Scientific Papers, Issue. 268. 33–44 (in Ukrainian).
- Krakovska, S. V., Palamarchuk, L. V., Hnatyuk, N. V., Shpital, T. M., Shedenko, I. P., 2017. Zminy polja opadiv v Ukrai'ni u HHI st. za danymy ansamblju regional'nyh klimatychnyh modelej [Changes in the rainfall field in Ukraine in the 21st century. according to the ensemble of regional climate models]. GEOINFORMATIKA. № 4(64), 62–74 (in Ukrainian).
- Lavrovsky, A. B., Igumentsev, A. F., Anisimov, S. V., Schegoleva, L. G., 1987. K voprosu postroenija modeli stoka i smyva pochvy pri livnevoj jerozii [On the issue of constructing a model of runoff and soil erosion during storm erosion]. Patterns of erosion and channel processes in various environmental conditions. Moscow, 89–90 (in Russian).
- Lisetskiy, F. N., Svetlitchnyi, A. A., Chornyy, S. G., 2012. Sovremennye problemy jeroziovedenija [Modern problems of erosion science]. Sc. ed. A. A. Svetlitchnyi. Constanta, Belgorod (in Russian).
- Magleby, R., Sandretto, C., Crosswhite, W., Osborn, C. T., 1995. Soil Erosion and Conservation in the United States: An Overview. Natural Resources and Environment Division, Economic Research Service, U. S. Department of Agriculture. Agriculture Information Bulletin No. 718.
- Makhortov, Yu. A., 1999. Jekologo-jekonomicheskie problemy ispol'zovaniya zemel'nyh ugodij [Ecological and economic problems of land use]. Lugansk (in Russian).
- Montgomery, D. R., 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. U SA; 104(33): 13268–13272. Published online 2007 Aug 8. doi: 10.1073/pnas.0611508104.
- Natsionalna dopovid pro stan rodiuchosti gruntiv Ukrainy [National report on soil fertility in Ukraine], 2010. Baliuk, S. A., Medvedev, V. V., Tarariko, O. G., Grekov O. V., Balaev, A. D. (eds). VIK PRINT, Kyiv (in Ukrainian).
- Naukovi ta prykladni osnovy zahystu gruntiv vid erozii' v Ukrai'ni, 2010 [Scientific and applied bases of soil protection against erosion in Ukraine]. Bolyuk, S.A. and Tovazhnyansky, L.L. (eds). NTU "KPI", Kharkiv (in Ukrainian).
- Ovcharuk, V. A., 2018. Maksymal'nyj stik vesnjanogo vodopillja richok Ukrai'ny: rozrahunkovi modeli ta i'h realizacija [Maximum runoff of spring flood waters of Ukraine: estimated models and their implementation]. Dr. (Geogr.) Sc. Theses, Odesa, Odesa State Environmental University. Retrieved from http://eprints.library.odetu.edu.ua/1015/7/Ovcharuk_Maksimalnii%20stik_DIS_D_2018.pdf (in Ukrainian).
- PCRaster: Software for Environmental Modeling, 2018. Retrieved from <http://pcraster.geo.uu.nl/>.
- Pidgajec'ka rajonna derzhavna administracija. Oficijnyj veb-sajt, 2018. [Pidhayetska District State Administration. The official website]. Retrieved from <http://www.oda.te.gov.ua/pidhaetska/ua.4873.htm> (in Ukrainian).
- Piatkova, A. V., 2011. Prostorove modeljuvannja vodnoi' erozii' g'runtu jak osnova naukovoogo obgruntuvannja racional'nogo vykorystannja erozijno-nebezpechnyh zemel' [Spatial modeling of water soil erosion as a basis for scientific substantiation of rational use of erosion-hazardous lands]. Abstract. diss. cand. geogr. Sciences, 11.00.11. Odesa St. Ecol. Univ., Odesa (in Ukrainian).
- Piatkova, A. V., 2013. Urahuvannja struktury shylovogo stikannja pry prostorovomu modeljuvanni zlyvovogo zmyvu g'runtu [Consideration of slope runoff structure in spatial modeling of storm drainage]. Odesa National University Herald, Series of Geogr. and Geol. Sc., 18, 2(18), 82–87 (in Ukrainian).
- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., Yoder, D. C., 1997. Predicting Soil Erosion By Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)—USDA Agricultural Handbook 703. U. S. Department of Agriculture, Washington DC. Retrieved from https://www.ars.usda.gov/ARUserFiles/64080530/RUSLE/AH_703.pdf
- Rykhliivskyi, I. P., Laser, P. N., Chapai V. A., 2014. Adaptivno-landshaftne zemlerobstvo: navchal'nyj posibnyk [Adaptive-landscape agriculture: a tutorial]. PP Zvoleyko D.G, Kamianets-Podilskyi (in Ukrainian).
- Shelyakin, N. M., Belolipsky, V. A., Golovchenko, I. N., 1990. Konturno-meliorativnoe zemledelie na sklonah [Contour-reclamation agriculture on the slopes]. Urozhay, Kiev (in Russian).
- Shvebs, H. I., 1974. Formirovanie vodnoj jerozii, stoka nanosov i ih ocenka [Formation water erosion, sediment runoff and evaluation]. Hydrometeoizdat, Leningrad (in Russian).
- Shvebs, H. I., 1981. Teoreticheskie osnovy jeroziovedenija [Theoretical basis of soil erosion science]. Publishing House "Vishcha Schkola", Kiev–Odesa (in Russian).
- Spravochnik po pochvozashhitnomu zemledeliju, 1990. [Handbook of Conservation Agriculture] / I. N. Bezruchko, L. Ya. Milchevsky eds. Urozhay, Kiev (in Russian).
- Sribnyi, I. K., 1977. Srednegodovoj stok vody i smyv pochvy so sklonov [The average annual runoff and flushing of soil from the slopes]. Water management on small rivers: collection. Budivelnik, Kiev, 145–147 (in Russian).
- Sribnyi, I. K., Vergunov, B. A., 1993. Vyznachennja zmyvu gruntu zi shylyv [Determination of soil flushing from slopes]. Bulletin of Agrarian Science, № 7, 42–46 (in Ukrainian).
- Svetlitchnyi, A. A., 1995. Prostranstvenno-vremennaja ocenka livnevoj jerozii pochv [Spatio-temporal assessment of storm erosion of soils]. Deposited in the State Scientific Technical Library of Ukraine, № 1911-Uk95 (in Russian).

- Svetlitchnyi, A. A., 1999. The principals of improving empirical models of soil erosion. *Euras. Soil Sci.*, 32(8), 917–923.
- Svetlitchnyi, A. A., Chornyy, S. G., Shvebs, H. I., 2004. Jeroziovedenie: teoreticheskie i prikladne aspekty [Soil erosion science: theoretical and applied aspects]. VTD «University Book, Sumy (in Russian).
- Svitlychnyi, O. O., Chornyy, S. G., 2007. Osnovy erozijeznastva [Basics of erosion science: a textbook]. VTD «University Book», Sumy (in Ukrainian).
- Svetlitchnyi, A. A., Piatkova, A. V., 2017. Ocenka adekvatnosti prostranstvennogo modelirovaniya intensivnosti smyva -akkumuljatsii pochvy na osnove fiziko-statisticheskoy modeli [The assessment of the adequacy of spatial modeling of the intensity of erosion-accumulation of the soil based on the physico-statistical model]. *Odesa National University Herald, Series of Geogr. and Geol. Sc.*, 22, 2(31), 48–60 (in Russian).
- Svetlitchnyi, A. A., 2018. Ocenka izmenenij gidrometeorologicheskikh uslovij livnevoj jerozii pochvy v Step i Lesostepi Ukrainy v svyazi s izmenenijami klimata [Assessment of changes in hydrometeorological conditions of storm soil erosion in the Steppe and Forest-Steppe of Ukraine in connection with climate change]. *Odesa National University Herald, Series of Geogr. and Geol. Sc.*, 23, 1(32), 53–71 (in Russian).
- Svitlychnyi, O. O., 2018. Zminy intensyvnosti vodnoi' erozii' g'runtiv u zv'jazku zi zminamy klimatu [Changes in the intensity of soil erosion due to climate change]. *Agrochemistry and Soil Science. Interagency thematic scientific collection. Special issue. Book 2. Reclamation, recultivation, soil protection, agrochemistry, humus condition, soil biology, organic farming. PE «Style-Issue»*, Kharkiv, 125–126 (in Ukrainian).
- Svetlitchnyi, A. A., Piatkova, A. V., 2019. Spatially distributed GIS-realized mathematical model of rainstorm erosion losses of soil. *Journal of Geology, Geography and Geoecology*, 28(3), 262–271.
- Tarariko, A. G., 1990. Agrojekologicheskie osnovy pochvozashhitnogo zemledelija [Agroecological fundamentals of soil conservation agriculture]. Urozhay, Kiev (in Russian).
- Tarariko, O. G., Kuchma, T. L., Ilyenko, T. V., Demianyuk, O. S., 2017. Eroziynna degradacija g'runtiv ukrai'ny za vplyvu zmin klimatu [Erosion degradation of soils of Ukraine due to climate change]. *Agro-ecological journal*, № 1, 7–15 (in Ukrainian).
- Tarariko, Yu. O., 2005. Formuvannja stal'nykh agroekosystem: teoriya i praktyka [Formation of sustainable agroecosystems: theory and practice]. *Agricultural Science*, Kyiv (in Ukrainian).
- Vergunov, V. A., 2006. Pryrodoohoronne adaptivno-landshaftne melioratyvne zemlerobstvo v basejnah mal'nykh richok Lisostepu Ukrai'ny [Environmental adaptive-landscape reclamation agriculture in the basins of small rivers of the Forest-Steppe of Ukraine]. *Agrarian Science*, Kiev (in Ukraine).
- Wischmeier, W. H., Smith, D. D., 1978. Predicting rainfall erosion losses. *Agric. Handbook № 537*, United States Department of Agriculture, Washington, D. C. Retrieved from <https://naldc.nal.usda.gov/download/CAT79706928/PDF>.
- Zhidkin, A. P., Golosov, V. N., Svetlitchnyi, A. A., Pyatkova, A. V., 2015. Kolichestvennaja ocenka pereraspredelenija nanosov na pahotnykh sklonakh na osnove ispol'zovanija polevykh metodov i matematicheskikh modelej [Quantitative evaluation redistribution of sediment on arable slopes through the use of field methods and mathematical models]. *Geomorphology*, 2, 41–53 (in Russian).
- Zonal'ni metodychni rekomendacii' iz zahystu gruntiv vid erozii', 2010. [Zonal methodological guidelines for soil protection against erosion]. National Scientific Center “O. N. Sokolovsky Institute of Soil Science and Agrochemistry”, Kharkiv (in Ukrainian).