Екологія та охорона навколишнього середовища

УДК 631:556.5:528.9

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SPATIAL PREDICTION OF SOIL EROSION RISK IN THE DNIEPER RIVER BASIN USING REVISED UNIVERSAL SOIL LOSS EQUATION AND GIS TECHNOLOGY

The paper presents the internal structure of the geomorphological system and performs geo-modeling of water-erosion processes in the basin of the Dnieper river. The aim of research – spatial prediction of soil erosion hazard within the boundaries of the Dnieper River catchment basin using the revised universal soil loss equation and GIS technologies. To simulate potential soil erosion loss caused by precipitation we used a modified empirical and statistical model RUSLE. Determined that land of erosion hazard makes up 20,4 % or 560 thousand ha of the total arable land area. The largest number of sub-basins with high erosive-accumulative potential are in the forest-steppe and steppe zones, in the middle and lower reaches of the Dnieper, respectively; the specific area of land at erosion risk in some sub-basins amounts to 47%. The results of the spatial prediction of water-erosion processes presented make it possible to identify discretely distributed priority needs for the implementation of adaptive-landscape anti-erosion design with elements of soil conservation agriculture on the whole territory of the transboundary Dnieper basin.

Key words: *water erosion, RUSLE, erosive potential of precipitation, soil erodibility, topography factor, erosion index of crops, river basins, river Dnieper, GIS technology, geo-modeling.*

Problem statement

The Dnieper runoff regulation has caused a natural and anthropogenic increase in accumulation processes in the river system that involve not only the products of erosive destruction of soils, but agrochemicals, myogena, heavy metals and radionuclides, which led to negative consequences – a significant deterioration in the quality characteristics of river water, eutrophication of water objects, siltation of reservoirs, partial and complete disappearance of many small rivers within the basin boundaries. Optimization of the erosion component of natural and economic territorial systems used for agricultural purposes in the major part of the transboundary Dnieper basin requires creating conditions for the formation and functioning of high-performance environmentally sustainable agricultural landscapes.

Review of recent researches and publications

The application of geostatistical and mathematical models with elements of remote sensing of Earth for space-time analysis of the joint effect of natural and economic factors on the nature and intensity of erosion processes should be the basis for their control and optimization within agricultural landscapes. These models are the basis for assessing the potential erosion hazard of the area, soil loss intensity, regulation of river ecosystems with the aim of substantiating the efficiency of land and water conservation measures to optimize the use of land resources based on basin position-dynamic and adaptive-landscape principles [1–5], which will allow preventing further erosion and degradation of soil and creating prerequisites for the rational use and rehabilitation of land and water resources of the transboundary Dnieper river basin. The implementation of effective ecological and economic anti-erosion and land and water protection optimization of using the land fund of the Dnieper basin is to be done based on the results of calculations of potential soil loss, primarily in arable land areas [6].

Purpose, objects and methods of research

Spatial prediction of soil erosion hazard within the boundaries of the Dnieper River catchment basin using the revised universal soil loss equation and GIS technologies.

To simulate potential soil erosion loss caused by precipitation we used a modified empirical and statistical model RUSLE (*Revised Universal Soil Loss Equation*) [7–9]:

$$A = R \cdot K \cdot LS \cdot C \cdot P\,,$$

where A – long-term mean value of rainwater runoff flush, t/ha per year; R – long-term mean value of erosion potential of precipitation (EPP), conventional units; K – washing away (erodibility) of soil, t/ha per unit of EPP; LS – factor of relief; C – erosion index of a crop or crop rotation as a whole; P – ratio of soil conservation efficiency of anti- erosion measures.

The author used the RUSLE model in the GIS environment of the licensed ArcGIS 10.1 software product, for that there were created raster models (cell size 90×90 m) of each integrated factor of the model of water erosion of soil in the entire transboundary basin of the Dnieper River. A spatial model of the average annual rainfall potential (*R*) was obtained based on the extrapolation of decomposition of data on cartograms of the rainfall erosion index [9]. In determining the factor of soil erosion or factor of compliance to soil erosion processes (*K*) we made vectorized soil maps of transborder countries (Ukraine, Belarus and the Russian Federation) within the boundaries of the Dnieper basin at 1:2,500,000 scale. For every kind of soil, taking into account its granulometric composition in accordance with the classification of factors of soil erosion (t/ha per year), parameter *K* was estimated and a constant spatial raster model was created.

Factors *L* and *S* in the *RUSLE* model reflect the effect of relief on erosion. The study shows [10] that an increase in the length and steepness of the slope creates a high-speed water flow and correspondingly aggravates the signs of soil erosion.

Specific effects of topography on soil erosion are estimated by dimensionless factor *LS* as a product of components of slope length (*L*) and steepness (*S*). The author evaluated the erosive potential of relief (*LS*) using spatial analysis of a hydrologically correct digital elevation model (DEM) with a cell size of 90 × 60 m. In ArcGIS 10.1 there were determined morphometric characteristics of the terrain and built raster cartograms of lengths (L) and slopes (S) of the surface using the Hydrology tools of Spatial Analyst Tools and Surface of Spatial Analyst Tools working module; then, using the Raster Calculator module, there were calculated LS values for each pixel by the formula [8]:

$$LS = L^{0,5} \cdot (0,0011 \cdot S^{2} + 0,0078 \cdot S + 0,0111).$$

The erosion index of a crop or vegetation coefficient (*C*) is an effect of growing crops and management practices in agriculture and the impact of areas of land covered with natural vegetation (trees, grass) on the reduction of soil loss in a non-farm situation. The vegetation cover coefficient (*C*) together with *LS* factor are the most sensitive to soil loss [11, 12]. For determining factor *C*, we used data on remote sensing (RS) of the correctly calibrated MODIS satellite image with geometric distinction (spatial resolution) of 230 × 230 m as of 26 June 2015. The generation of *C* factor values was performed based on dimensionless index NDVI (normalized difference vegetation index) using the formula [13]:

$$C = \exp(-\alpha((NDVI)/(\beta - NDVI)))$$

where α and β - dimensionless parameters that determine the shape of the curve referring to NDVI and *C* factor. Parameters α and β have values 2 and 1, respectively.

The coefficient of soil conservation measures (*P*) was 1, suggesting that additional measures were not carried out.

Research results

For the whole territory of the Dnieper basin (S = 511 thousand km^2), there were identified 776 basins of IV – IX orders ranging in size from 1.9 to 22,680,2 km^2.

Table 1. **Distribution of river basins within the area under study by orders**

Order	**Total, pcs**	**Total are, km^2**	**Relative value to the total area,%**	$\overline{S}$ **, km^2**
IV	607	298379,8	58,4	492,5
V	131	104036,7	20,4	795,6
VI	30	64555,0	12,6	2155,8
VII	5	15391,1	3,0	3083,8
VIII	2	5957,2	1,2	2984,1
IX	1	22680,2	4,4	22680,2
Total	**776**	511000	**100**	**–**

The length of the path and time spent on the movement of water and friable soil from the slopes into the bed are connected with the area of the river basin. Analysis of the structure of catchment areas of different orders of the Dnieper River basin showed that the area drained by thalwegs of orders 1–4 makes up 58,4 %, that of orders 5–6 – 33%, of orders 7–9 – 8,6 %; thus, the supply of the main riverbed with water and friable soil is made by the upper and middle parts of the river (91,4 %), while feeding with local upper soil layer components of the lower reaches of the Dnieper amounts to 1,8 %.

Geo-modeling of water-erosion processes in the Dnieper river basin was carried out based on four factors*: R, K, LS, and C.*

Factor R – long-term mean value of erosion potential of precipitation (EPP). Assessment of climate conditionality of potential soil loss is made using a factor of energy and intensity of rainfall reflected in erosion risk with the help of relative indices or erosion index of precipitation (EIO), which are determined by statistical analysis of pluviograms of all runoff forming rains with a layer of precipitation ≥ 10 mm (rains causing erosion) and their main parameters – total kinetic energy of rain and its maximum intensity within a 30-minute period of time. Erosion potential of precipitation (Fig. 1a) on the territory of the Dnieper basin uniformly increases from the southeast to the northwest and varies from 5,7 to 12,4. The highest values of *R* are observed in the upper (forest) and middle (steppe) areas of the Dnieper river.

Factor K – washing away (erodibility) of soil. The index of soil type and condition, i.e. the factor of soil compliance to erosion processes, is determined as a ratio of average annual washing away of soil off a $1m^2$ runoff area to *R* value depending on the steepness of the slope and content (percentage) of the size of soil fractions, organic matter in its structure and water permeability. The potential annual loss of fertile topsoil decreases on the territory of the Dnieper basin from north to south from 3,7 to 1,2 t/ha (Fig. 1*b*) depending on the erosive potential of rainfall. Agricultural lands located within the boundaries of the upper sub-basin (forest or mixed forest) area of the Dnieper river have maximum compliance to erosion processes.

Factor LS – factor of relief. Relief function *LS* reflects the cumulative effect of slope length and steepness on erosion hazard of the terrain. For the raster of *LS* values obtained by a method of zonal statistics, there were calculated mean values of relief function *LS* (State Standard 17.4.4.03-86) for each sub-basin of the transboundary Dnieper river basin River (Fig. 1*c*). *LS* values range from 0,2 to 4,7. Sub-basins of the eastern and south-western parts of the Dnieper river basin and the coastal part of the cascade of reservoirs (sub-basins of order IX) have the highest erosion potential of the relief, while the lowest LS values are registered in the sub-basins of the upper (forest zone) flow of the Dnieper river.

Factor C – erosion index of a crop or crop rotation as a whole. This index is mostly aimed at determining the impact of land use practice (crop rotation or vegetation) on erosion processes on agricultural land. The calculation of this factor is quite challenging because of a great diversity of crops and natural vegetation, but scientists [13] have shown high efficiency of using remote sensing data based on NDVI indicator for obtaining factor *C*. As a result of decoding a correctly calibrated MODIS satellite image we obtained a raster model of spatial distribution of the erosion index of a crop for the whole territory of the Dnieper basin (Fig. 1*d*). *C* values range from 0 to 1,4. The lower (steppe) zone of the

Dnieper river witnesses quite high *C* values, which is primarily due to the extensive method of farming (tillage percentage of separate sub-basin areas reaches 80 %) and lack of evidence-based soil conservation crop rotations.

According to the classification by A.A. Svitlychnyi [14, 15], areas with washing away of soil up to 2 t/ha a year are considered relatively safe against erosion. When potential washing away is more than 2 t/ha per year, the land is under erosion hazard and needs erosion control measures according to the category of danger.

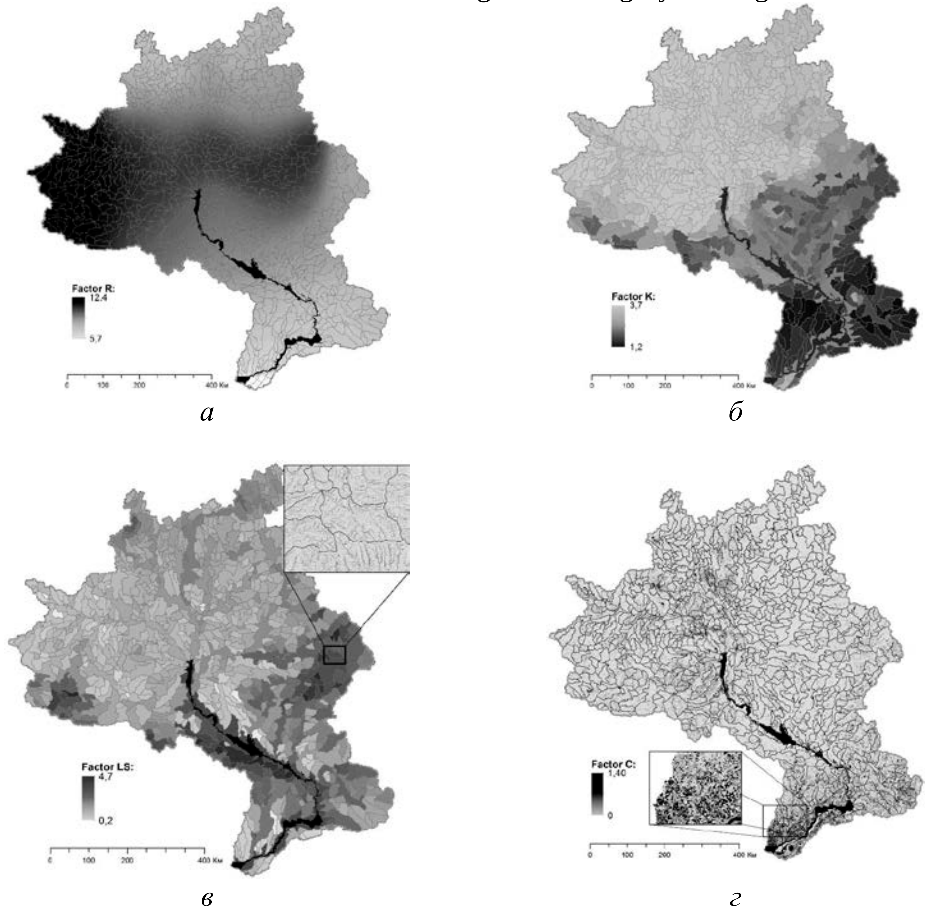
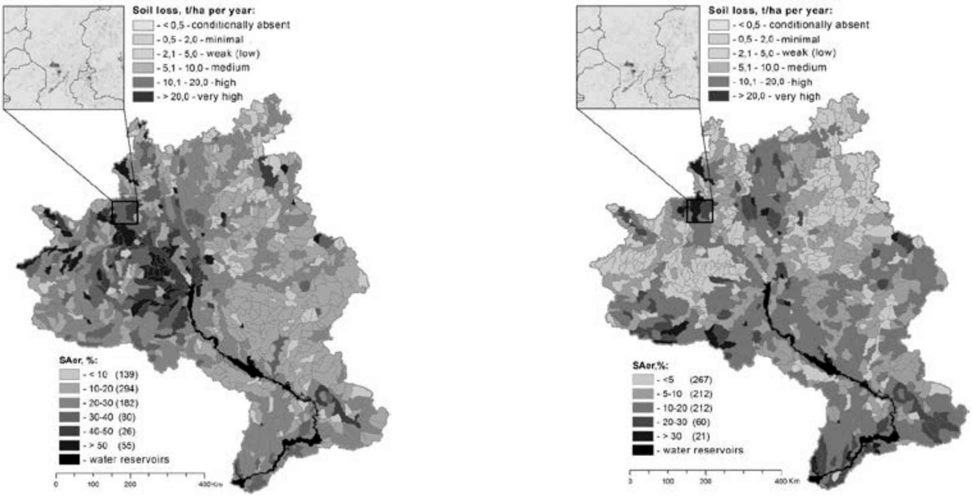


Figure 1. **Distribution of values of factors affecting the potential hazard of soil erosion under the influence of rainfall in the basin of the Dnieper*: a – rainfall erosivity index (R); b – compliance of soil to erosion (erodibility) t/ha (K); c – relief factor (LS); d – erosion index of a crop or crop rotation as a whole (C)***

As a result of GIS modeling with the application of the *RUSLE* modified model, we assessed erosion hazard, calculated the potential of annual soil loss on arable land (Fig. 2*a*) and performed spatial gradation of the potential of erosion damage to sub-basins of different orders on the territory of the Dnieper river basin (Fig. 2*b*). The spatial model (Fig. 2*b*) also reflects the prerequisites of intensity of erosive and accumulative processes and degradation of water bodies of different hierarchical levels because of natural and human activities. The distribution of the territory of the Dnieper basin by erosion hazard gradation is presented in Table 2.



а *б*

Figure 2. **The share of arable land (SAer, %) in the boundaries of water catchment sub-basins with potential danger of soil erosion under the influence of precipitation: *a – SAer ratio to arable land, %; b – SAer ratio to the sub-basin area, %***

Table 2. **Distribution of arable land by potential danger of soil erosion under the influence of precipitation on the territory of the Dnieper River basin**

Erosion hazard	Washing away of soil, t/ha per year	Area, thous. ha	Specific weight, %
Conditionally absent	< 0,5	1344,4	47,5
Minimal	0,5–2,0	907,2	32,1
Weak (low)	2,1–5,0	432,3	15,3
Medium	5,1–10,0	67,3	2,4
High	10,1–20,0	54,5	1,9
Very high	> 20,0	24,3	0,9
Total:		**2830**	**100**

Lands conditionally safe against erosion are confined to the plains and buffer boundaries of watershed parts of slopes and make up 79,6 % of the total area of arable land. As a result of spatial modeling, there have been identified about 560 thousand ha of lands at risk of erosion (20,4 % of arable land) on the territory of the transboundary Dnieper basin. About 267 sub-basins mainly located in the upper (forest) area of the Dnieper river have a specific area of less than 5 % of erosion-damaged lands and are characterized by a stable type of agricultural landscapes. The largest number of sub-basins with high erosive-accumulative potential are in the forest-steppe and steppe zones, in the middle and lower reaches of the Dnieper, respectively; the specific area of land at erosion risk in some sub-basins amounts to 47 %. In these areas, it is expedient to introduce anti-erosion adaptive-landscape design with the elements of soil conservation agriculture.

Conclusions and prospects of further research

For the first time there have been made spatial prediction and obtained the results of spatial distribution of potential erosion-caused soil loss in the basin of the Dnieper using a modified empirical and statistical model RUSLE and GIS technologies. Land of erosion hazard makes up 20,4 % or 560 thousand ha of the total arable land area. The largest number of sub-basins with high erosive-accumulative potential are in the forest-steppe and steppe zones, in the middle and lower reaches of the Dnieper, respectively; the specific area of land at erosion risk in some sub-basins amounts to 47 %.

The results of the spatial prediction of water-erosion processes presented make it possible to identify discretely distributed priority needs for the implementation of adaptive-landscape anti-erosion design with elements of soil conservation agriculture on the whole territory of the transboundary Dnieper basin, which include assessing the need to reduce agricultural load on the river basin; using differentiated rotations considering soil conservation efficiency of crops; soil conservation tillage and fertilization systems.

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