Erosion in basin geosystems of the Middle Volga (from a landscape analysis perspective)

OLEG YERMOLAEV

*Faculty of Ecology, Kazan State University, Department of Landscape Ecology, Kremlevskaya,
18, Kazan, 420008, Russia*
oleg.yermolaev@ksu.ru

Abstract Human-induced erosion and accumulation processes on agricultural hillslopes have a number of principal differences from natural erosion. Together with substantially higher rates of the processes, anthropogenic erosion creates a new and higher-level spatial organization of hillslope fluvial geosystems. From the focus-areal type of spatial pattern those transform into belts comprising anisotropic groups of vectorial-organized structures acquiring emergent properties. As a consequence, quantitative evaluation of this kind erosion should be conducted separately from its natural analogue.

Key words basin erosion; landscape; Middle Volga; neural networks; regionalization; regressive model

INTRODUCTION

Multi-factor controls of erosion processes determine the complexity of erosion-affected hillslope geosystem functioning. Relationships between erosion and its major controls change in geographical space, so that slope erosion regimes vary regionally, being determined by landscape conditions. Problems with the quantitative assessment of all types of soil erosion from raindrop to gullies still require a satisfactory solution. In this paper we propose to consider the entire complexity of hillslope erosion processes as a unit termed "basin erosion". The focus of this paper is on the methodological aspects of revealing the roles different landscape conditions play in causing basin erosion.

The Middle Volga basin was chosen as the investigation region due to the wide distribution of a spectrum of erosion processes in the region. It is also where the so-called "Erosion Pole" of European Russia is situated (Fig. 1).

Different combinations of natural and anthropogenic conditions create geocomplexes of different taxonomic levels known as "landscapes". Depending on the degree to which erosion processes are generalized in an investigation, it is necessary to use different geosystem taxon as the basic unit. These may be "landscape zones" for the global analysis of spatial regularities of erosion, or "landscape facies" for the development of empirical models of slope-wash at local or more detailed levels. The significance of the landscape approach is in the complexity of control parameters and the decrease in subjectivity of their choice for multiple classification analysis of erosion processes. This fact is well-understood in the scientific community. The number of published examples of the landscape approach in studying basin erosion is extremely small. The main reason for this are the extremely small number of published large- and medium-scale maps of soil erosion and its factors, the difficulty of their composition and a lack of unified legends.

To evaluate the role different landscape factors play in the development of human-accelerated basin erosion, a landscape map of the Middle Volga region was created. It uses a
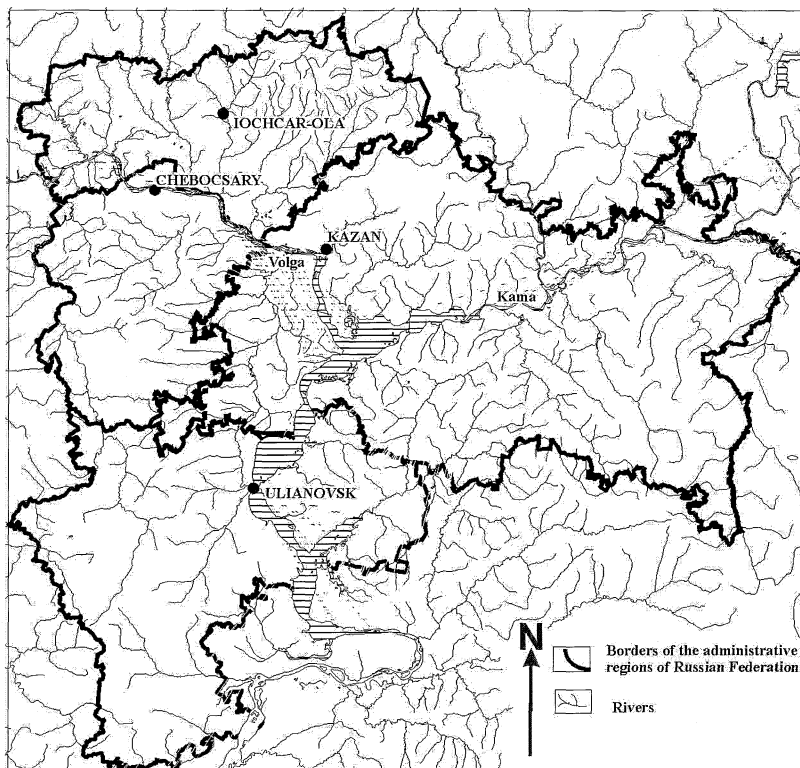
Fig. 1 River network and administrative regions of the Middle Volga territory.

regional level of generalization. Taxons of the landscape region level are presented on the map. The following basic principles were adhered to during the regionalization procedure. Firstly, regions were distinguished based on the most important landscape conditions, their spatial variability being dependent on interactions of both zonal and azonal natural factors. Secondly, for territorial landscape complexes, which must belong to the same taxonomic level, the proportionality requirement was kept at each stage of regionalization. Thirdly, the regionalization was carried out in the "upward" direction, or from individual to general. We chose the most distinctive landscape characteristics because we wanted them to embrace the required range of typical geosystem spaces (Colomitz, 1998), to have sufficient variety of values and to be accessible for measurements aimed at obtaining a massive database. Both zonal and regional factors of landscape differentiation were taken into account with the aim of studying the spatial organization of regional landscape conditions. River basins of the 2–3 order (by A. N. Strahler) have been taken as the basic operational unit of the spatial analysis.

DATA

The total number of parameters used for landscape regionalization comprised more than 50 (including: hydro-climatic, geomorphological, anthropogenic, lithological and landscape-geophysical); 3331 river basins were examined with an average catchment area of 40 km^2.

Examples of the parameters employed are: (a) annual sum of the solar radiation; (b) runoff coefficient; (c) rainfall erosivity index; (d) bedrock lithology; (e) soil texture; (f) slope length and gradient; (g) topographical altitude spectra; (h) landscape primary productivity; (i) soil humus content; (j) annual sum of the positive temperatures; and (k) area of cultivated land, etc.

The study territory is located within the forest, forest-steppe and northern part of the steppe landscape zone of the Russian Plain and comprises more than 130 000 km^2. Information on soil erosion of arable land was obtained for the territory of the Middle Volga, including the basins of the rivers Volga, Vyatka, Cama and Sviyaga. During the last 200 years arable land cover has increased by 40–60% and now comprises about 80–85% of the basins' area. The period of most intensive agriculture in the region began about 200 years ago. According to archive maps, the landscape zones which have experienced the greatest deforestation and subsequent greatest increase in arable areas are the southern forest-steppe and broad-leaved forest landscape zones.

METHODS

As most natural characteristics have continuous spatial distribution, regions with relatively uniform values of parameters were chosen for regionalization by traditionally formal indicators. This formal division leads to creation of artificial borders, loss of information about gradual change of values and, eventually, to incorrect territory regionalization. This is especially true when combined processing of a large number of heterogeneous parameters is undertaken. Modern computer databases storing large volumes of heterogeneous information on spatially distributed landscape characteristics require new methods for their combined processing.

Presentation of all the variety of heterogeneous components in the form of a small set of standard elements should be the best decision in this direction. Application of traditional statistics methods, cluster analysis and regionalization do not allow gradual transitions and connections, common in a real geographical space, to be revealed and visually presented on the map.

In the middle 1990s a new class of non-parametric adaptive algorithms appeared for the analyses of structure distributions—"self-organizing maps of Kohonen" (neural networks methods). The method of "self-organizing maps of Kohonen" (1997) was used as the main approach for automatic regionalization. Effectively it includes a few main stages described below.

In the first stage, 121 classes of units were determined according to a set of landscape characteristics (Yermolaev & Saveliev, 2000; Yermolaev, 2002). Such a number of classes helps to group regions in homogeneous groups presentable for cartographic spatial analysis, by using methods of hierarchical classification. This allows the presentation of topological properties (interarrangement) of distinguished classes in space of characteristics, and therefore a structure of the space of all characteristics for a given territory. This method mainly differs from the others by a large number of degrees of freedom, making it possible to construct any number of precise models. It gives an ability of "self-organizing" to the studied system or an ability to connect and modify its own structure and behaviour taking account of new input data. A valuable property of neural networks is the possibility for generalization, which is expressed in construction of satisfactory models by incomplete or strongly distorted data.

A second stage involved construction of regional mathematical statistics models of natural-anthropogenic modification of basin erosion, the landscape taxons on the last step of hierarchical classification were successfully combined initially into 24, and then into 11 landscape regions. The combination of landscape regions to 11 was pursuing two main targets. Firstly, it was necessary to provide statistically representative samples. In some regions a number of river basins did not satisfy this requirement. Secondly, united regions are close, not only by landscape conditions, but by intensity of basin erosion processes. A further decrease of the number regions is undesirable as it brings to notably distorted accuracy of predictive modelling of erosion results at the accepted generalization level. Supposing that each landscape region has its own specific conditions of basin erosion processes, a general linear regressive model of soil erosion index was constructed for every region. So, equations were obtained for landscape regions of the Middle Volga 11 and for the total territory a piecewise-linear model was made up (in cooperation with S. S. Mukcharamova).

Additional models were constructed during the third stage, aimed at determining the role of factors influencing the intensity and spatial pattern of human-accelerated erosion. Factors were combined in thematic groups: hydro-climatic, geomorphologic, anthropogenic, lithological, landscape-geophysical, and a whole array of factors used for erosion analysis. Separate regionalization of these factor groups by using artificial neural networks with 121 classes was also conducted. It has been found that all these cases have statistically significant (with 99% of confidence probability) correlation between arguments of soil and gully erosion and other variable models. The significance level for each of the factors included in the model is not less than 5%. Therefore none of them can be neglected. However, it does not mean that all the considered regressive models are adequate or possess good forecasting qualities. Characteristics used for evaluation of such qualities: R, coefficient of multiple determination; σ, standard error of estimation; *MAE*, mean absolute error of samples, are given in Tables 1 and 2. The higher the coefficients R^2, R and the lower the values of errors σ and *MAE*, the better and more adequately the model describes processes of basin erosion.

Table 1 Estimation of prognosis accuracy of soil erosion development.

Regionalization by conditions of soil erosion processes' development	"Piecewise-constant" model on the basis of classification of neural networks				"Piecewise-linear" model			
	R	R^2 (%)	σ	*MAE*	R	R^2	σ	*MAE*
Hydro-climatic	0.64	41	0.354	0.279	0.59	0.35	0.373	0.300
Geomorphologic	0.57	32	0.379	0.302	0.50	0.25	0.415	0.334
Anthropogenic	0.54	29	0.387	0.317	0.43	0.18	0.419	0.348
Lithologic	0.61	37	0.365	0.287	0.52	0.27	0.394	0.322
Landscape-geophysic	0.69	48	0.334	0.256	0.68	0.46	0.338	0.264
All indices	0.70	49	0.328	0.250	0.69	0.48	0.330	0.256

Table 2 Characteristics of gully erosion prognosis model quality for the total Middle Volga.

Types of models	σ	*MAE*	R^2 (%)	R
"Piecewise-constant" model on the basis of regionalization by landscape regions	0.689	0.539	52	0.72
"Piecewise-linear" model on the basis of regionalization by landscape regions	0.566	0.42	67	0.82

The fourth stage involves the choice of independent variables (regressors) to be included in a regional model. A number of variables exceeded 50. It should be noted that there is no common statistical procedure for choice of the best subset of regressors. Therefore, a certain subjective decision is always needed. Two opposing criteria exist. On the one side, to provide reliable forecasts the model must include the largest number of variables. On the other side, taking into account efforts for data collection, the equation should include the least number of regressors (Seber, 1980). The choice of "the best subset" is the compromise between these two extremes. With this aim the procedure of regression construction was developed by sorting all possible regressors and accounting expert opinion. At every procedure run, the measure for comparing the forecasting usefulness of different models was calculated.

Earlier, the determination of the coefficient R^2 was used as a measure of agreement between regression model and given data. However, difficulties appeared at the comparison of regressions with different regressors number, because introduction of additional regressor leads to an increase in R^2. We used a different, more suitable measures of model quality called the corrected determination coefficient R^2_c. $R^2_c = 1 - [1 - R^-][N/(N - p)]$, where p is the number of regressors plus one. Regressors making the largest contribution to soil erosion pattern of the given landscape region were distinguished.

RESULTS

The erosion models developed witness the presence of considerable regional differences in control factors. Differences not only concern values of the factors themselves, but also direction and degree of their influence on erosion. Variable complex combinations of landscape conditions and spatial patterns of sheet and rill erosion and gullies on slopes of river basins result in advancing one or other factors to the leading role. For example, for gully erosion in some cases these are geological and geomorphological characteristics (bedrock lithology, soil texture, slope length)—regions 1, 4, 9, 10; in others—climate characteristics (rainfall erosivity index, runoff coefficient)—regions 2, 8; anthropogenic impact (cultivated land area, settlement area)—regions 7, 11 etc. (Fig. 2).

The group of anthropogenic characteristics plays a special role in modelling gully erosion development. Most important of those are interrelated arable land area and forest-covered area. The most widespread reason of important index absence is its weak spatial differentiation in the region or dominance of topographic factors of gully erosion.

The analysis conducted shows that relief parameters, anthropogenic and hydro-climatic factors are the most essential contributors to soil and gully erosion development. Electronic vector maps of typological regionalization, modern and predicted, were created on the basis of developed models of soil and gully erosion processes in the Middle Volga region. They demonstrated very good agreement of results. The models developed will add to a better understanding of regional patterns of human-accelerated erosion processes and may become a basis for land-use plan development and design of soil protection measures.

The landscape approach used to investigate accelerated erosion processes at different taxonomic levels made it possible to address this phenomenon in detail accounting principles of territorial unity, genetic and relative homogeneity. Landscape regions (regional level) reflect zonal and longitudinal-sectoral patterns of basin erosion. Spatial analyses of soil erosion and gullying intensity in the study region based on available information allows
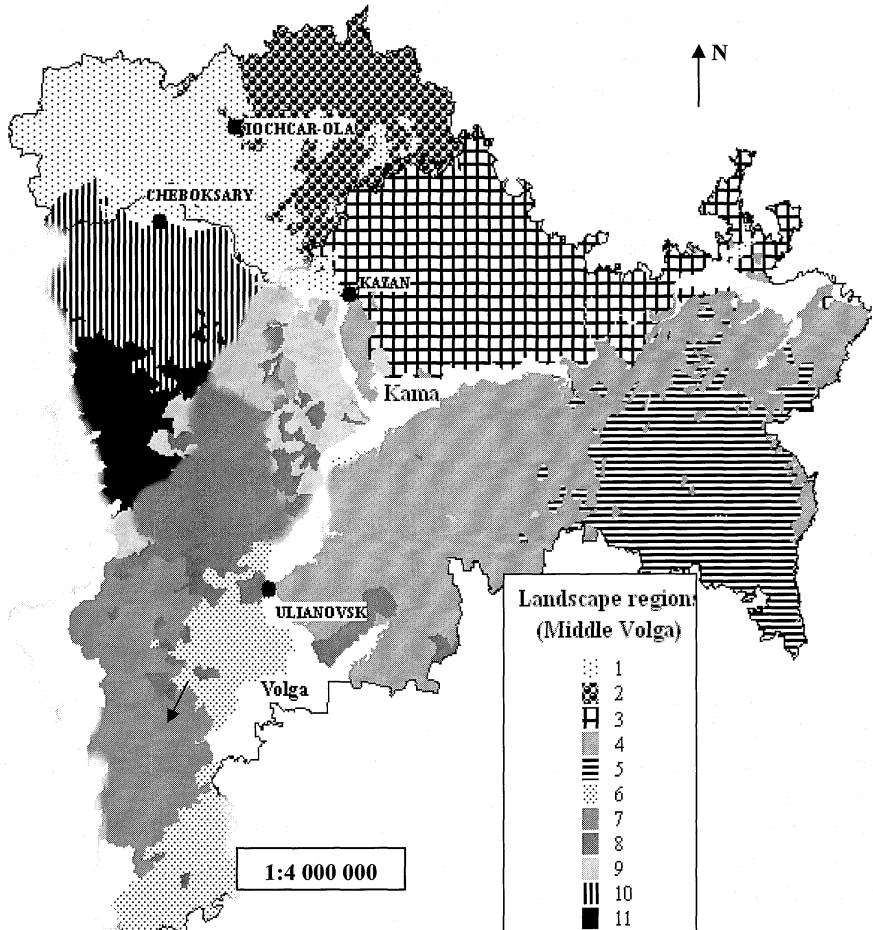
Fig. 2 Landscape regions distinguished by the method discussed of the Middle Volga territory.

us to conclude that: (a) maximum basin erosion is characteristic for upland landscapes of broad-leaved forest zones (Sub-boreal) and the southern part of mixed forest zone; (b) its intensity decreases in both western and eastern directions; (c) to the north and to the south from upland landscapes of broad-leaved forest zones we can also observe lowering of basin erosion intensity; (d) in the north it happens because of lower agricultural activity, and to the south it is due to development of chernozem soils more stable to erosion; and (e) zonality is typical for soil erosion processes. The gully erosion process, on the contrary, is an azonal phenomenon, as it is dependent on the influence of geologic and geomorphologic factors.

The average annual soil losses during the time of agricultural development of territory for different types of soils are in a range of 0.11–0.27 mm year^{-1} (average 0.18 mm year^{-1}). Total denudation losses from gully erosion are lower at least by an order of magnitude.

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