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An investigation into the state of agricultural lands under water erosion conditions

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Abstract. Protecting agricultural land from erosion continues to be the most important task within the overall issue of the protection and rational use of land resources. That is why it is necessary to comprehensively study patterns of development in the erosion processes, and to assess the specific nature and features of their impact upon soil and vegetation, water resources, and landscapes in various natural conditions. The work is based on the results of many years of experimental research on problems that are related to soil erosion, and on the accumulation of slope sediments in catchments and in the valleys of small rivers, based on the use of landscape geography, soil morphology, and cartography methods of research. The research methodology that is included the collection covers the analysis of cartographic and experimental materials on the geo-ecological situation regarding an formation and manifestation of spatial and temporal erosion processes in the territory, and, the carrying out of research work which cover the soil washout and erosion processes in key areas of agricultural landscapes. The methodology also includes, the process of conducting a determination of the influence of natural and anthropogenic factors on the intensity of erosion processes, and the cameral processing of results that have been obtained in the field, all of which characterise the erosion and hydrology situation in the basins of small rivers. The paper presents the latest levels of research on the spatial and temporal variability of the features of erosion processes, depending upon their mechanisms of functioning, the complexity of the territory's geomorphological landscape conditions, and the intensity of anthropogenic load on the catchment areas of small rivers. The management of the migration of biogenic elements in agricultural landscapes can be improved if, on the one hand, the share of cultivated land is reduced and, on the other hand, the area of meadow land and small forest plots is increased, which significantly serve to slow down the flow of erosion products, including biogenic elements, into the hydrosphere. It has been established that, with an increase in the share of arable land, the removal of biogenic elements with runoff increases in direct proportion. Therefore, with up to 50% of the territory being cultivated, nitrogen removal was seven times higher - and phosphorus two times higher - than with the same territory under 20% of cultivation. With 80% cultivation, nitrogen removal increases two times and phosphorus and potassium removal increases four times when compared to 40–50% cultivation of the same territory in the catchments.

Key words: agricultural landscape, catchment, environmental monitoring, runoff, soil erosion.

INTRODUCTION

The planet's soils have been undergoing a process of created over millennia under conditions that have since disappeared. Soil destruction has occurred due to human error in just a few years. Over historical time, these losses have amounted to about twenty million square kilometres. For comparison, we note that the entire modern arable area in the world amounts to fifteen million square kilometres (Boardman et al., 1994; hazarika & Honda, 2001; Morgan, 2005, 2006).

Long-term irrational human activity has led to the fact that natural landscapes in a number of the world's regions have been practically destroyed, and the agricultural landscapes that have been created during this process are imperfect and unstable.

Both from an ecological and an economic point of view, it is much more expedient to prevent unfavourable changes in soil cover than to carry out expensive work to restore it or recreate those properties that are responsible for fertility having been lost (Kõlli & Tõnutare, 2020).

Most of the world's soil resources are either in a satisfactory, poor, or very poor condition. In particular, 33% of soil resources have been degraded to a moderate or high degree due to erosion, salinization, compaction, oxidation, and chemical contamination of those soils (Kurdyukova, 2020; Slyusar et al., 2020).

Amongst the most important problems, when it comes to providing a solution upon which the very existence of mankind depends, the erosion of soils and their degradation tops the list. In decisions that have been taken by the UN World Conferences on Environment and Development (Rio de Janeiro 1992; 2012; Johannesburg 2002; New York 2000; 2005; 2008; 2010; 2013; 2015), it was noted that the protection and rational use of soils should be the central theme of state policy, because it is the condition of soils that determines their ability to perform productive and ecological functions which are characteristic of the nature of human life, and any deterioration in that condition also affects the environment.

Soil washout from one shower of rain can affect as much as between 330–350 t ha^{-1} (or 2.5 cm of the upper layer). In this context, flushing away just 1 mm irrevocably removes 76 kg of nitrogen, up to 240 kg of phosphorus, and up to 80 kg of potassium from one hectare of land.

Researchers (Martin, 2002; Hines & Bishop, 2007; Cerdan et al., 2010; Panagos et al., 2014a, 2014b) have noted that, worldwide, more than three million hectares are irretrievably lost every day due to erosion, and in every minute that passes a total of forty-four hectares of land which is suitable for agriculture is taken out of agricultural use.

In the world's scientific community, great efforts are being made to study the processes of soil erosion and to develop effective measures to combat it (Kovář et al., 2012; Tarariko et al., 2017; Kachmar et al., 2018; Brychta & Janecek, 2019; Tarariko et al., 2019). Forecasting and controlling the hydrological erosion processes (HEP) in catchment areas should be based on knowledge of the surface runoff formation processes, and on an assessment of natural and anthropogenic factors and their interaction. Numerous bodies of data exist to show the role of various factors in terms of the formation of runoffs (Baboshkina et al., 2020).

Therefore a change in the structure of land use - that is the ratio between the areas of different categories of land and types of land - leads to the most significant levels of change in terms of the volume of sediments being transported down the slopes and entering the channel network of catchment areas. Therefore the share of agricultural development is one of the main factors involved in the modulus of suspended sediment runoff in lowland rivers (Litvin et al., 2010; Ran et al., 2020).

On slopes that are covered by natural herbaceous vegetation, the intensity of washout and runoff is lower than it is under agricultural crops (Ivanov & Nazarenko, 1998). It is believed that perennial grasses have the highest anti-erosion effect, while annual crops of continuous sowing are much weaker, and row crops are the worst of all. The washout from those areas that are occupied by perennial grasses is between 0.5–2.0 t ha^{-1}, while from plots that have been sown with cereal crops it is between 3–58 t ha^{-1}, from fields that are occupied by row crops it is between 4–264 t ha^{-1}, and from fallow plots it is between 10–475 t ha^{-1} (Ivanov, 2007).

Therefore the diversity of vegetative cover is a prerequisite for a wide range of influences on the processes of the water erosion of soil, while ploughed watersheds are an arena of its intensive development. Sown agricultural crops are significantly inferior to natural vegetation in their soil-protecting properties. In this regard, it is necessary to study natural vegetation as well as its transformed state under the influence of anthropogenic pressure. This information is important in the successful development of effective methods for protecting soil against erosion.

Several studies (Pimentel & Kounang, 1998; Misir, 2012; Ma et al., 2019) have established that woody vegetation is the most effective when it comes to protecting soil from water and wind erosion. The forest regulates snow melting and, therefore, moisture is fully absorbed into the soil, replenishing groundwater levels, while the forest underbrush almost completely prevents the surface runoff of melt water, which is the main reagent of the erosion processes.

The forest has an important regulatory effect on water flow, serving to improve its quality, transferring surface water to subsurface and underground water, smoothing out the peaks of spring floods and water spills after rainfall, and maintaining high water levels (Larocque, 2020). The felling of forests reduces the erosion resistance of landscapes and leads to the impoverishment of soil fertility. Deforestation by 50% of an area increases its annual runoff by between 40–50%, while soil washout increases between 1.2–1.8 times (Kastridis, 2020).

The intensity of the manifestation of soil erosion depends upon the relative degree of cultivation in the area; its share of arable land in the overall volume of agricultural land.

Within the context of the further intensification of agriculture, the question arises regarding the introduction of a system of anti-erosion measures in agricultural landscapes. It is possible to reduce runoff and soil washout from arable land by applying a deep loosening of the soil, leaving stubble on the surface of the field; in this case, the volume of surface runoff water is reduced by between 2.2–5.1 times when compared to the effect that is produced by ploughing (Lyakh et al., 2011). Winter ploughing across the slope with an additional slotting to a depth of between 40 to 50 cm, carried out at different times and depending upon the cultivated crop, also provides a noticeable reduction in surface runoff. The loosening and turning of the upper layer, the cutting of soil horizons by stalks, and the decompaction of the subsurface layer all serves to contribute to the active transfer of runoff water deep into the soil, into the low humidity zone (Belolyubtzev, 2009; de Menezes et al., 2020)

The patterns regarding the manifestation of accumulative erosion processes are largely determined by the features of the territory's relief.

A very important indicator which determines the risk of erosion is the slope's compass direction. In different climatic conditions, the influence of this factor on the development of erosion processes is different (Routschek et al., 2014). It has been proven that on northern slopes the snow reserves and the depth of soil freezing are greater than on southern ones. Therefore, here, as the snow melts, there is a gradual washout of soils, which in quantitative terms exceeds the washout on southern slopes.

Scientific studies have shown that southern, south-western, and south-eastern slopes are characterised by maximum intensity washout (ranging from significant to very strong). Northern slopes are less prone to erosion processes. On these slopes, intensity does not exceed 15 m^3 ha^{-1}.

In addition to the slope's compass direction, the slope's length is also one of those factors that influences the intensity of the erosion processes. It has been established that, with a twofold increase in slope length, soil washout can increase by between 1.4–1.5 times and, with a threefold increase in slope length, the washout rate increases by a factor of ten.

Slopes of up to 500 m in height are characterised by weak flushing intensity, while the maximum possible intensity of soil washout is typical for slopes of 1.5 km or more, where soil loss from a catchment area onto the lower part of the slopes increases significantly (Kovář et al., 2012). On steep, short, and high northern slopes, the intensity of accumulative erosion processes is higher than it is on longer and more gentle northern slopes.

It should also be noted that, in addition to the length, steepness, shape, and direction of slopes, the development of washout is also influenced by the shape of the catchment area, the density of the section that is vulnerable to erosion, the depth of local erosion bases, and so on.

Recently, scientists from various countries around the world have been engaged in the creation of models that will aid in calculating soil washout levels, both during snow melt and during rain showers. In the USA, a special organisation called WEPP (Becker, 1997) was created for such purposes. Japanese researchers have developed a model for determining soil loss depending upon the catchment area's size, and have determined a sediment movement index; scientists from Belgium have created a soil loss model for various landscapes; in Iraq they have prepared a universal equation in order to be able to predict potential annual soil loss rates (Hussein, 1998; Van Oost et al., 2000; Li et al., 2001).

Diagnosing and preventing soil erosion will be a key contribution to achieving the EU's goals.

Washed-off soils have impaired hydrological properties. In turn this affects, first and foremost, the ability of the soil to absorb and retain moisture. Water absorption on strongly washed-off soils is only 55% of the normal maximum when compared to non-washed-out analogues, and the maximum possible reserves of productive moisture are reduced by as much as 40%, which sharply increases surface runoff and impairs water supply to plants, as well as the chemical and physical properties of the soils themselves.

The researchers predict three scenarios that are also being used by the Intergovernmental Panel on Climate Change (IPCC). All of them, when including the impact of climate change and land use in their forecasts, predict increasing water erosion levels in most countries around the world, regardless of climatic conditions. The results that have been obtained indicate that climate change is the main factor that contributes towards the intensification of soil erosion.

Depending upon the simulation scenario being used, soil erosion is projected to increase significantly (from 30% to 66%) by 2070 when compared to the figures for 2015 (FAO, 2015).

Unfortunately, practically all soils can be subject to water erosion under certain conditions.

The optimisation of land use is one of the most important modern problems in terms of the sustainable development of agriculture. It is inextricably linked to the development of theoretical and methodological foundations for managing accumulative erosion processes in order to preserve soil fertility and a favourable ecological state of the environment. Significant advances have already been made in tackling this complex problem. On the basis of the theory of erosion processes, two strategies have been objectively formed when it comes to protecting soil from erosion, these being the balance-based strategy and the energy-based strategy. The balance-based strategy is aimed at achieving a level of permissible soil washout, the intensity of which does not exceed their self-recovery rate. An energy-based strategy for protecting soil against erosion aims to regulate the balance between the energy of water flows and the soil's erosion resistance. But it turns out that it is difficult to achieve 'normal erosion' or 'a non-erosive rate of water flows', because the problem of forecasting accumulative erosion processes with sufficient accuracy in order to be able to solve design decisions is one that remains unsolved.

Therefore there still exists a contradiction between the needs involved in managing accumulative erosion processes and the impossibility of their accurate prediction. This contradiction necessitates the further development of a solution to the problem at the theoretical and methodological levels of research.

The purpose of this paper was the study of regularities in the distribution of accumulative erosion processes on agricultural lands, and an assessment of their impact on the ecological state of the catchment systems of small rivers.

MATERIALS AND METHODS

The methodology being used in the analysis, assessment, and planning regarding the structure of agricultural land use is primarily one that concentrates on ecological land management. Generally accepted methods include experimental field observations and laboratory analyses, morphological comparisons and analogues, the use of ecological landscape axiomatics as a method of cognition, cartographic, balance-based, statistical economic, and computational constructive methods of landscape modelling, and the instrumental determination of the intensity of development of water-erosion processes.

The landscape unit that was chosen in order to determine the size and nature of the influence of agriculture on soil cover and on natural waters, and to study the incoming and outgoing flows of chemical elements, is that of the catchment area of a small river (Kovář et al., 2012).

The nature of conducting a study and the methods in which agricultural landscapes and farming systems can be optimised in the catchment areas of small rivers have been based on the application of a systematic approach to solving the problem, which in turn determined the methodological approach to the selection and determination of the main directions for research (Kurdyukova, 2020).

The first approach covers studies that are primarily aimed at the quantitative characteristics of the geomorphological, soil, and climatic conditions of the catchment area of a small river that is being studied, and its place in Ukraine's physical and geographical zoning, as well as its spatial location.

The second approach is to research the quantitative characteristics of anthropogenic factors, including the organisation of the land use area and the structure of sown areas and crop rotations.

The third approach characterises the complex influence of natural and anthropogenic factors (such as the structure of the agricultural landscape) on the state of agro-ecosystems in individual catchment areas, including the development of erosion processes.

The fourth approach consists of determining the quality indicators of groundwater and surface runoff in terms of their content of biogenic elements, depending upon the structure of agricultural landscapes and applied farming systems.

These four main directions are based on the fact that the study of interaction in a complex system such as the structure of the agro-landscape of a river's catchment area, and of the qualitative composition of water resources (in terms of nutrients), should be carried out, on the one hand, in a broad sense, ie. that it should cover the entire river catchment area and, on the other hand, as a deep and detailed analysis of the role of and interaction between individual natural and anthropogenic factors.

RESULTS AND DISCUSSION

Modern trends in the development of agriculture are associated with a change in the paradigm of nature management, and a gradual rejection of the anthropocentric approach to these, with an orientation towards nature conservation as a priority.

The scientific basis of modern agriculture is a deep knowledge of the ecological regularities of the landscape, and the relationship between agricultural ecosystems and natural ecosystems in the general natural-anthropogenic cycle.

It has already been proven that, at the current stage of the formation of the environmental paradigm in terms of agricultural land use, there is a need to improve existing measures and to develop new comprehensive measures in order to be able to protect soil from erosion, which will be aimed not only at diagnosing disruptions of the ecological state of erosion, but will also determine a differentiated approach to regulating the intensity of destructive processes in agricultural landscapes.

At the same time, the best soil-protective effect (and, in general, environmental effect) is achieved through the use not of separate anti-erosion (anti-deflationary) measures but in their interrelated and mutually coordinated complexes. It is precisely the creation and operation of effective complexes of anti-erosion (anti-deflationary) measures which will ensure the ecological sustainability of agricultural landscapes.

In order to plan and efficiently manage the land erosion control system, it is necessary to use all modern methods of forecasting the erosion processes. However, the large number of mathematical models that are currently available for forecasting and assessing accumulative erosion processes on slopes and in river beds indicates that they are somewhat limited, and that the problem in general remains unsolved. The desire to take into account a larger number of factors in order to improve the accuracy of forecasting erosion leads to a decrease in the credibility of the results that are obtained using the model. Each factor is taken into account with a certain level of probability, and the probability of a simultaneous combination of several independent events is equal to the product of the probabilities of these events.

This increases the relevance of the need for scientific research that is aimed at obtaining new areas of knowledge in terms of managing accumulative erosion processes within catchments along their entire length, from watersheds to channels, on the basis of the mathematical modelling of the structure of erosion geosystems, as a set of their system-forming connections.

We carry out constant monitoring of land use by agricultural enterprises through the means of cartographic and field surveys of the state of land plots, in order to assess the natural resource potential and the conditions for the formation and progressing of erosion processes.

The ratio of rain and melt washout changes significantly in terms of space.

The temperature regime and the depth of soil freezing have a significant impact upon the development of erosion processes during the spring snowmelt period (Fig. 1).

Figure 1. The development of water erosion processes in the snowmelt period.

During the warm part of the year, the development of water erosion on slopes is determined first and foremost by the intensity and duration of rainfall. It is believed that runoff water is not formed when less than 10 mm of rain falls, since this quantity of rainwater is equal to the water-holding capacity of any soil which does not have vegetation.

The quantitative characteristics of the products of soil washout from agricultural land were measured by means of the volumetric water method (Fig. 2).

Figure 2. A full-scale study of soil washout products during a period of heavy rainfall.

The basis for modelling accumulative erosion processes is that of a discrete model of the catchment structure, one which takes into account the spatial hierarchy of its elements and their functional interrelationships through the integral temporary or permanent water-soil flow of the main valley (Kachmar et al., 2018). In order to design environmentally sustainable agricultural landscapes, it is necessary to take into account the spatial structure of the surface runoff, which is the carrier for the system of forming links.

The catchment area is defined here not only as a fundamental geomorphological element, but also as a structural formation unit that reflects the specifics and patterns of the distribution of elementary catchment areas in the lower level; that is, the allocation of functionally integral systems, the elements of which are connected by unidirectional flows of matter and energy and which differ in their natural properties and the degree of their anthropogenic influence.

Small river basins are characterised by the greatest levels of response to anthropogenic impacts. Any change of the load in the natural structure of the basin affects the integral indicators of its functioning, which are liquid and solid flows. Therefore the composition of the water in small rivers is a reflection of the total of the surrounding natural processes and anthropogenic activities in the catchment areas of those rivers.

The research was carried out in the catchments of small rivers that were flowing into the River Dnieper at its midpoint.

Within the catchments of small rivers, elementary catchment areas have been identified which are of the second order and which come with depressions (Fig. 3, a). In order to detail the features of the functioning of geosystems at the local level, and the patterns of processes that occur between them as a result of the lateral movement of matter and moisture, a key site (a cross-section polygon) was set up in one of the micro-catchments (Fig. 3, b).

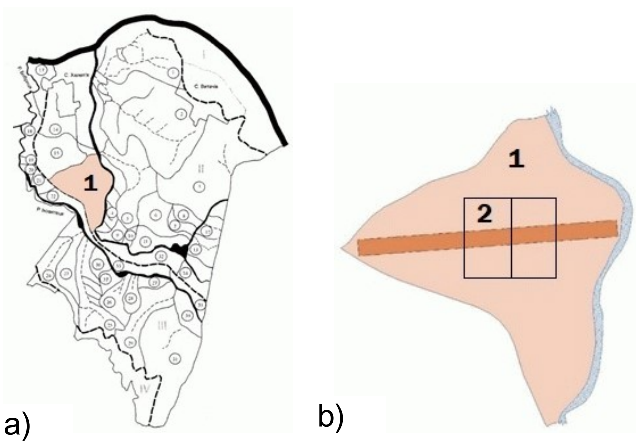


Figure 3. This is the block diagram for monitoring the accumulative erosion processes in small river basins: a) is the schematic map of micro-catchments for the small river basins; and b) is a diagram of the key site (the cross-section polygon).

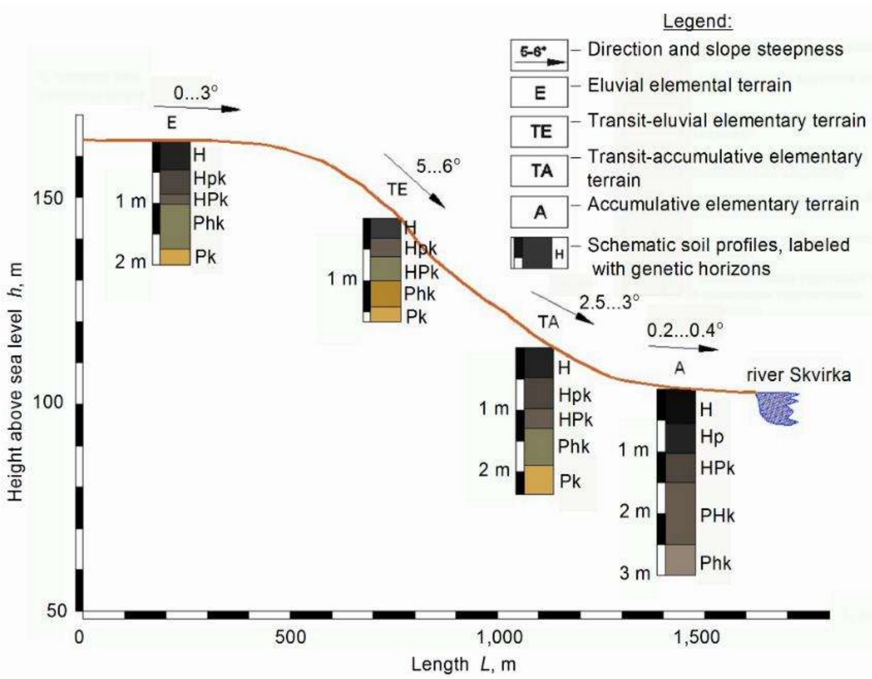


Figure 4. Monitoring platforms at reference sites.

Monitoring sites were laid at the reference plot points for the purpose of carrying out a spatial assessment of the erosion hazard in agricultural landscapes, while also establishing patterns of distribution, intensity, and trends in the development of accumulative erosion processes in the system of a ‘slope element - slope - primary catchment area - river catchment area - channel’ (Fig. 4).

The research solved the problems of a connected biogeochemical analysis of various geosystems of small river basins: soils, rocks, surface and ground water, precipitation, agricultural ecosystems and natural ecosystems, in order to be able to compile the initial ecological erosion characteristics of the territory and the trends regarding their change (Fig. 5).

Figure 5. The object of the research on a topographic base, in Ukraine’s Kiev region.

In order to be able to solve problems that are related to developing design solutions in models that cover the adaptive landscape arrangement of land that remains in use, taking into account their geomorphological features, the use was made of modern forms of technology for monitoring, modelling, analysis, and information processing.

When using the spatial interpolation method, a digital relief model was built of the research area. This relief model is the basis for compiling data on the steepness and exposure of the slopes, as well as the longitudinal and transverse curvature of the slopes, while also serving to make it possible to identify structural relief lines which include the lines of the erosion network and watersheds, while additionally serving to delineate catchment areas (Fig. 6).

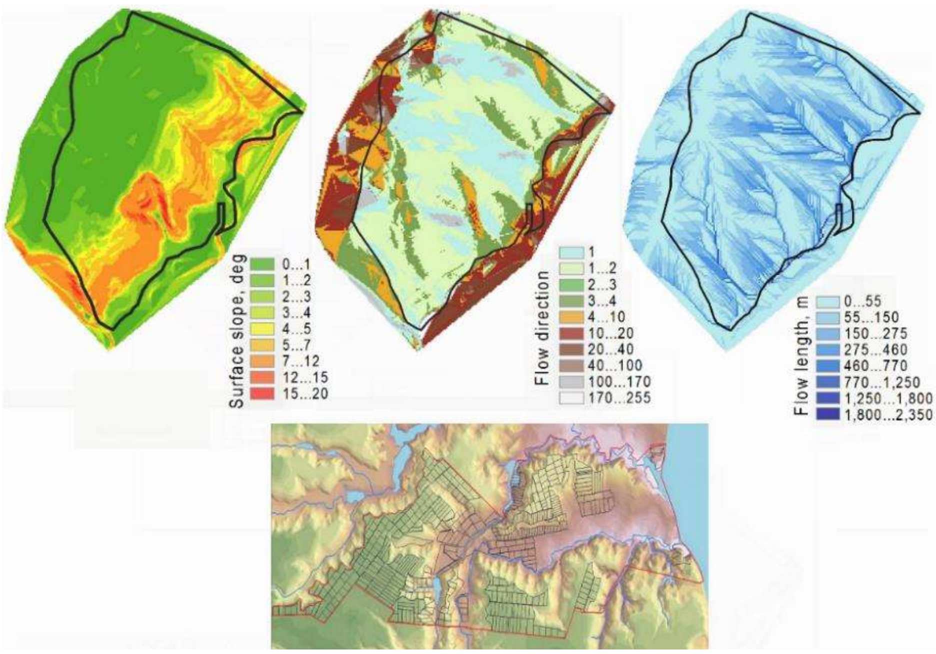


Figure 6. An element in the digital elevation model, by characteristics.

It was determined that the geomorphological characteristics of the terrain relief are necessary in order to be able to determine the elements, forms, and types of relief, the degree of its sectionality, length, steepness, and shape. A quantitative assessment was carried out of the relief of those agricultural landscapes which are at risk of erosion in order to develop a system of anti-erosion measures, while the relief serves as the basis for the rational allocation of agricultural land (Fig. 7). The degree of soil erosion is in direct proportion to the geomorphological characteristics of the territory, especially the steepness of the slopes (Shevchenko & Kolomiiets, 2014; Kaminskyi et al., 2018a, 2018b; Kolomiiets et al., 2019).

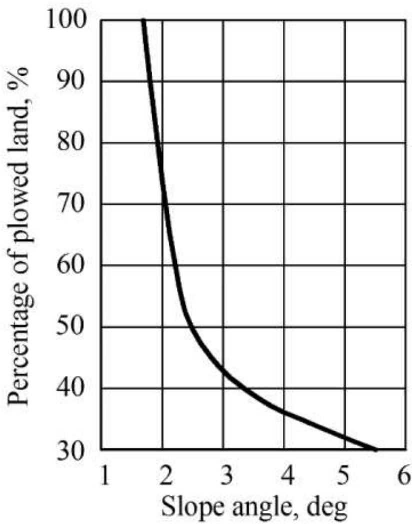


Figure 7. The dependence of the percentage of ploughing in catchment areas on slope steepness.

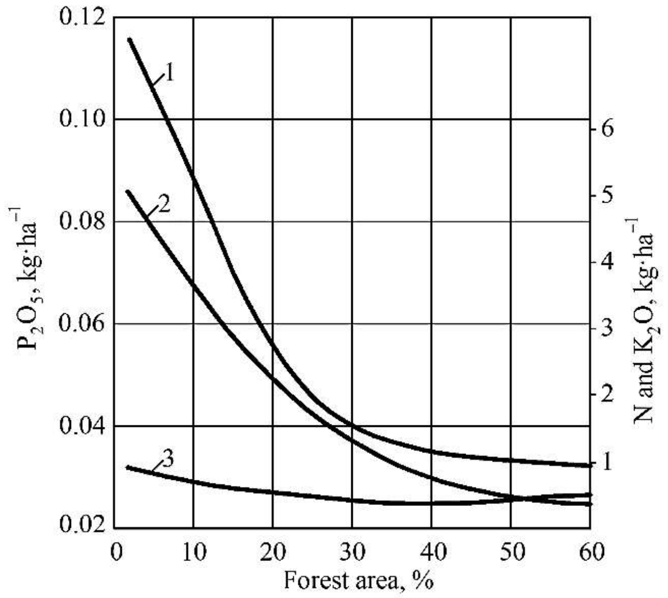
Eroded arable land is not just lost soil cover. It is also tons of lost crops, since the yields tend to be between 10–30% lower than before the soil cover was lost, and the cost of obtaining 1 Kcal of energy is between three and five times higher (Kutzenko, 2012). Therefore it is very important to ease the pressure of intensification on this type of land which provides such a vital means of livelihood.

In order to establish the relationship between the percentage of ploughed catchment area and trends in the development of accumulative erosion processes, low, medium, and high-intensity models were developed by type of anthropogenic load. Within the catchment models with their increased ploughing levels, the amount of soil washout changes during the spring snowmelt and summer rain periods as follows: on catchments with a slope of between 5–7 degrees, which are completely occupied by forest and meadow, the soil washout is insignificant at between 0.4–0.9 t ha^{-1} (Kutzenko, 2012). With a ploughing rate of between 10–20% and an average steepness of three degrees, soil washout increases to 3 t ha^{-1} (Kutzenko, 2012).

It has been established that, with an increase in the specific gravity of arable land, the removal of biogenic elements with runoff increases in direct proportion. So with a ploughing rate of up to 50%, nitrogen removal was seven times higher than with a 20% ploughing rate for the territory in question, while phosphorus removal was two times higher (Litvin et al., 2010). With an 80% ploughing rate, nitrogen removal increases by a factor of two when compared to a ploughing rate of the catchment area of between 40–50%, and phosphorus and potassium removal increases four times (Litvin et al., 2010).

The influence of forest planting on the removal of biogenic elements with surface runoff in catchment areas with between 2–62% forest cover was something that was also studied.

It was found that with a forestation level of only 2%, the removal of nitrogen with liquid runoff was at 5.0 kg ha^{-1}, phosphorus was at 0.12 kg ha^{-1}, and potassium was at 0.91 kg ha^{-1}. With an increase in forest cover to 27%, the removal of nitrogen, phosphorus, and potassium with liquid runoff decreased to 1.96 kg ha^{-1}, 0.04 kg ha^{-1}, and 0.43 kg ha^{-1}, respectively. With a forestation level of more than half the territory (57%), the removal of nitrogen, phosphorus, and potassium with liquid runoff decreased, respectively, to 0.10 kg ha^{-1}, 0.02 kg ha^{-1} and 0.22 kg ha^{-1} (Fig. 8).



a)

b)

Figure 8. The dependence of the removal of biogenic elements with surface runoff on the forestation of the catchment area (a) and a general view of the runoff (b): 1 – P_20_5; 2 – N; 3 – K_2O.

In this way, the integrated nature of information about space and time, and about the functioning of the erosion-denudation systems in general, greatly complicates the search for connections between factors and erosion processes.

However, it should be noted that natural factors (the hydrogeological conditions of the basin and the drainage capacity of the soils) serves to determine the situation regarding ecological erosion to a lesser extent; it depends more on economic activities in the river basin, and especially in the river valley.

CONCLUSIONS

1. The problems have been analysed in relation to the involvement of managing accumulative erosion processes in terms of agricultural lands, which largely determine the ecological state of the basin systems of small rivers.

2. The main methodological principles of geo-ecological landscape research have been studied and implemented at the regional level, which has made it possible to carry out a quantitative assessment of the factors involved in the spatial differentiation of accumulative erosion processes on the basis of the basin approach.

3. A comprehensive analysis has been carried out regarding the effect of erosion on the ecological state of the environment, and a territorial assessment has been provided of the danger of the pollution of ground and surface waters by means of biogenic elements due to soil erosion.

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