

The development of sheet erosion on intensively used soils

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ABSTRACT This paper deals with the processes of water erosion, their control by the type, length, steepness and utilization of the slope, and the influence of relief, soil cover and climatic factors. The depth of snowmelt runoff, sediment particle size distributions within the streams, sedimentation and soil losses in lowland and mountain terrain and the base levels of erosion are described for the main agricultural regions of the USSR. An analysis of the development of mechanical erosion on slopes is presented and the influence of soil erodibility and of the distribution of different crops on the various slope elements on the magnitude of soil loss is also described. The distribution of land and crops within the main natural zones of the USSR, according to their degree of erosion is shown.

INTRODUCTION

There are 2.2 billion (10^9) ha of land in the USSR, of which 72% (1.6 billion ha) comprises tundra, forest-tundra, northern taiga and desert, i.e. regions where runoff is very low or absent. Erosion caused by surface runoff is associated with 608 million ha of agricultural land which includes 225 million ha of arable cultivation (Gaidamaka, 1975). The total runoff, both solid and liquid, is 4384 km^3 , equivalent to $0.2 \text{ km}^3 \text{ km}^{-2}$ (Dolgoplov *et al.*, 1973). The average snowmelt runoff from the arable and other land of the European part of the USSR is $50\text{-}60 \text{ km}^3$. 1.5-1.6 billion tonnes of soil are eroded by this water. About half of this sediment accumulates in the valley bottoms and in reservoirs and 0.5-0.6 billion tonnes enters the rivers. 1.2 million tonnes of nitrogen, 0.6 million tonnes of phosphorus and considerable amount of potassium are transported in association with the sediment and are lost by farmers (Sobolev, 1973).

The overall pattern of water erosion reflects the influence of relief, erodibility, geology, climate, soil type, land use, and the application of control measures (Table 1).

The intensity of soil erosion and of sediment transport and redistribution in agricultural regions is greatly influenced by both the natural conditions and the economic activities (e.g. form, length and steepness of the slopes, type of drainage basin, rainfall frequency and intensity, resistance to soil erosion, base level of erosion, structure of agricultural lands, and the percentage of clear-tilled crops (Lidov *et al.*, 1972)).

TABLE 1 Distribution of soils, runoff, cropping practices and erosion in different regions of the USSR

<i>Region</i>	<i>Soils</i>	<i>Runoff</i>	<i>Cropping practices</i>
<i>EROSION CAUSED MAINLY BY SNOWMELT</i>			
<i>Forest-steppe and northern steppe</i>	<i>Grey forest podsollic and leached chernozem</i>	<i>High, particularly from autumn ploughed land</i>	<i>Autumn ploughed land, horticulture (row crops are cultivated), winter crops, perennial grass</i>
<i>Steppe</i>	<i>Chernozems and chestnut soils</i>	<i>Absent or very low during 7 years out of 10</i>	<i>Winter crops, perennial grass, horticulture, autumn ploughed land (7 years out of 10), old idle land, pasture, small forests in steppe ravines</i>
<i>EROSION CAUSED MAINLY BY STORM RAINFALL</i>			
<i>Southwestern and southern</i>	<i>Chernozems and dark-chestnut soils</i>	<i>High</i>	<i>Bare fallow, spring sown perennial grass, clean-tilled crops, grain-legume crops, early spring crops, winter sown perennial grass, pasture, forest</i>

PATTERNS OF SLOPE EROSION

As a result of investigations undertaken in the European and Asian territories of the USSR, the following patterns of slope erosion intensity were found:

(a) Maximum erosion activity and soil loss take place on convex slopes where steepness, drainage area and the depth of runoff increase towards the foot of the slope.

(b) On concave slopes, especially those with a form close to the profile of equilibrium, erosional activity is very low and erosion loss is replaced by accumulation at the foot of the slope.

(c) Straight slopes are characterized by similar patterns of runoff and soil loss as found on convex slopes, but the erosional activity is less intense. Due to the constant steepness, erosion gradually increases downslope and the maximum erosion occurs on the second part of the slope above the third segment. Within the slope base concavity, erosional loss is replaced by accumulation.

(d) On complex slopes (terrace, convexo-concave and others) the slope steepness and length are of less importance than the ratio of their component elements (convex, concave and straight) with different steepness.

Long-term investigations of the loss and redistribution of currently eroding soils have revealed geographical regularities in the deposition on slopes of different form and age as well as in erosion processes. These have permitted the establishment of a sequence of relief evolution from the straight steep slope at the angle of repose, through the convex slope, to the gentle (1-2° and sometimes up to 3°), straight and concave forms.

The frontal slopes of the young loess terraces of the Dniper, Don, Northern Donetz and Volga rivers as well as those in the north of the Caspian lowland were found to have straight (10-30°) and concave forms with poorly developed basal accumulation. Concave slopes are dominant in the Central Russian upland, although their basal zones and the slopes of the younger gullies are characterized by straight slopes developed on the older landforms during the second stage of evolution.

The slopes of the Privolzhskaya upland are mainly long, straight and gentle (1-2°), but the younger slopes of the second and third order gullies are concave and cut into the straight slopes. In the Zavolzhie region, concave slopes prevail although both straight and convex forms occur at lower levels as a result of dissection. At their foot the convex slopes are replaced by straight slopes of 10-30° which are associated with the younger erosion cycle.

The forest-steppe zone is occupied by the most productive soils, namely chernozems and grey forest soils, which are widely used for agricultural production. The most active erosion activity was found to be associated with the areas of ancient agricultural cultivation. In the central forest-steppe zone, these soils occur in the Belgorod, Voronezh, Kursk, Lipetzk and Tambov regions, in the Povolzhie-Kuibishev, Penza, Saratov and Uljanovsk regions and in the Kaluga, Orel and Riazan regions which are in the central economic area. Erosional activity is promoted by climate, relief and the decrease in the resistance to erosion of the soils resulting from the long history of land cultivation without soil protection

measures which has led to considerable loss of humus (Tregubov, 1976).

In the central chernozem regions where convex slopes predominate and soil erodibility is very high, solid runoff reaches an average of 65-70 mm. In the western areas of the Central Russian Upland the annual soil loss is 25 t km^{-2} , and in the Oka-Don lowland it is $2.5\text{-}5 \text{ t km}^{-2}$. The forest-steppe zone of Povolzhie includes the Uljanovsk and Penza regions, northwest of Saratov, and the northern part of the Kujbishev region. Slopes of 2° occur on the divides but in the valleys they reach $5\text{-}6^\circ$. Leached soils, namely, low-humic chernozems and grey forest soils predominate. Snowmelt runoff from the drainage basins reaches 60 mm year^{-1} , including 30 mm from the autumn ploughed land and 70 mm from the fallow land and fields under winter crops. Storm rainfall occurs in most years. High erodibility, steep slopes and intense spring runoff are responsible for the erosion risk in this area.

The central economic region of the non-chernozem zone is characterized by hilly relief and 50% of the agricultural land is situated on slopes greater than 1° . Podzolic and grey forest soils which are susceptible to erosion predominate. The considerable amount of snow, the deep freezing of the soil and the very low infiltration of melted snow are responsible for the intense soil erosion. The depth of snowmelt runoff reaches 100 mm in some regions. The factors mentioned above as well as unsuccessful erosion control have led to the development of erosional activity which decreases soil fertility and causes economic damage.

EROSION AND TRANSPORT PROCESSES

Laboratory investigations of erosion have demonstrated that the transport distances associated with coarse soil particles on slopes subject to surface wash increase with increasing slope steepness and runoff depth. Particles with a mass higher than the critical threshold are shifted primarily as a result of local scour. The distance of particle transport within the stream channel as well as the particle size distribution of the deposited sediments, and the depth of alluvial deposition depend upon the stream type. An increase in the transport capacity of the stream and in the abundance of sediment finer than that forming the channel, causes an increase in the distances over which larger particles are transported. Particles larger than those forming the channel are deposited close to their origin. The smaller material or particles similar to those forming the channel are distributed more evenly along the stream or in the vertical section of alluvial deposits. During transportation, especially in streams with high roughness, particles with weights close to or heavier than critical are deposited in those parts of the channel with low water velocity. Positive projections as well as deep zones also promote the deposition of these particles. Particles with a plate-like form are transported over greater distances and are distributed more evenly in the vertical profile of an alluvial deposit, than similar particles of isometric form.

THE EFFECTS OF AGRICULTURAL ACTIVITY

In the mountain regions the intensity of sheet erosion is mainly related to the geomorphological characteristics of the terrain (e.g. erodibility of the relief, steepness, length and form of the slopes and the local base level of erosion) as well as soil, vegetation and climatic factors. The intensity of sheet erosion in the zones occupied by different agricultural land varies (Stadnitzky *et al.*, 1972; Tshegllova, 1972).

With cultivated land under conditions of hilly relief, what has been termed mechanical erosion can develop as a result of the rotation of the furrows to one side, and this type of erosion may be especially problematical on short steep slopes. The cultivated layer will move downslope and may lead to exposure and movement of the lower horizons, causing the formation of hollows 0.5-0.8 m deep on the upper part of the slope and banks 1-1.5 m in height on the lower part of the slope, especially with slope angles of 7-12°. To control mechanical erosion, cultivation with upward furrow rotation and the use of ploughs without mouldboards, coupled with proper land management, have been found to be effective (Yazukhno, 1972).

Investigations of slope erosion occurring before construction of reservoirs on the Kama River, showed that sheet erosion led to formation of slopewash deposits which promoted a reduction in slope angles. The rise of the water levels in the reservoir caused the destruction of the slopewash deposits and the concave slopes turned into convex slopes and their steepness increased. In this way erosion activity became one of the main factors controlling the evolution of the banks (Kachenov, 1972).

Intensive land use was found to increase the danger of erosion as a result of the following factors; increase in the loss of humus as a result of agricultural production, decrease in the mechanical stability of soil aggregates, cultivation of crops on the slopes due to the lack of flat terrain, furrow irrigation, and overgrazing of grasslands.

Soil erosion maps have now been compiled for all agricultural regions of the USSR, and land management projects involving complex soil conservation practices, including agrotechnical and hydrotechnical measures, have been developed and put into practice. Agricultural machinery designed to control slope erosion has also been introduced and is now used on more than 60 million ha. Effective crop rotations and fertilizer application systems have been developed which make it possible to speed up the reclamation of the productive capacity of eroded land in all soil-climatic regions of the USSR.

All the measures noted above have made it possible to decrease the annual snowmelt and rainfall runoff to 30-40 mm and the annual soil erosion loss to 8-10 t ha⁻¹ and to provide increased grain yields of 100-150 kg ha⁻¹ from those areas where erosion control measures have been established.

However, it must be mentioned that the planned soil losses are not compensated by the increase in fertility. Thus we are facing the problem of ensuring improved fertility on a large scale by means of new soil protection and fertility improvement measures to ensure management of the snowmelt runoff and proper erosion control.

CONCLUSIONS

Investigations of erosion processes and their controlling factors as well as classification of the eroded and potentially eroded lands according to the intensity of natural and agricultural effects have revealed the complex character of this problem. For example, if doubling of the slope steepness and length was considered to cause a 2.5 and a 1.5 times increase in the soil loss from an agricultural unit, the total slope effect would lead to a 3.75 times increase in the soil loss. On convex slopes where both length and steepness increase towards the base of the slope, erosion energy likewise increases. Conversely, on concave slopes an increase in slope length will produce a decrease in erosion intensity. However, as mentioned above, the influence of slope steepness is also affected by other factors including the degree of soil protection by plant cover, conservation practices, soil erodibility, precipitation intensity and the amount of runoff from the higher land. Combination of these factors leads to an increase in water mass and energy with slope length.

Runoff velocity and turbidity were found to increase with an increase in slope angle. In this way the long upper part of a slope with a low angle of slope may produce a large volume of water which will cause intense erosion and an increase in turbidity and soil transportation on the steep lower parts. When the length of the upper part of the slope and the increase of steepness on the lower part are not large, no increase of soil loss occurs.

The intensity of sheet erosion is greatly influenced by the soil erodibility. The more eroded a soil becomes, the greater are the changes in chemical, granulometric and mineralogical composition, water, air and thermal regimes, physical and biological properties, and other parameters, which together lead to a decrease in soil fertility. Soil fertility may decrease considerably as a result of loss of humus and humic acids. The loss of the upper soil horizons of grey forest soils and leached chernozems promotes an increase in the carbonate ratio, which causes a decrease in phosphate mobility and resistance to erosion of the steppe and desert soils.

Soil adsorption potential also decreases as a result of a decrease in the humus and silt fraction in the eroded soils. In chernozem and other soils a decrease in the bivalent cations associated with the soil exchange complex, especially calcium, also decreases resistance to soil erosion and to loss of nitrogen, phosphorus and potassium, slows down plant development and increases the erosion hazard. The amount of stable structural aggregates decreases considerably in eroded soils, soil density increases, and porosity, water permeability and water capacity also decrease. Erosion intensity and soil loss are also increased.

Erosion activity and the amount of soil loss are greatly influenced by the location of a field and the choice of crops. For example, sowing of perennial grass on the divide and of clean-tilled crops lower down the slope lead to an increase in soil loss and transport velocities. When grass or other direct drilled annual plants are planted on the lower part of the slope and the area of autumn ploughing is near the divide, soil lost from the upper fields is retained by plants or stubble. To reveal detailed patterns of

erosion and sedimentation and to solve problems associated with them it is necessary to use uniform methods of investigation based on experimental drainage basins, representative of the main rivers of the basic agricultural regions of the country.

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