Investigation of sediment yield of lowland rivers in Ukraine

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Abstract The new map of turbidity in the rivers of Ukraine has been created on the basis of a 50-year data set of sediment yield observed by the Hydrometeorological committee of Ukraine. The trends of sediment discharge have been established. The main causes of increasing or decreasing sediment discharge in rivers of the different regions of Ukraine (Ukrainian Polissia, Podilska and Prydniprovska highlands, Prychornomorska lowland, Donbas, Carpathian Mountains) are explained. Quantitative values of sediment erosion, transit and redeposition in different sections of the catchment system and its flood plain—riverbed complexes have been determined on the basis of a field experimental study of sediment redistribution within the cultivated slope—gully catchment—small river catchment system. The impact of erosion—accumulation processes on small river aggradation has been characterized.

Key words factors; rivers of Ukraine; sediment redistribution; sediments; turbidity

INTRODUCTION

Sediment yield is one of the most important features of the hydrological regime of rivers. It impacts the use of rivers and their hydroecological state. The intensive sheet and gully erosion on the river basin slopes causes the accumulation of sediments in the riverbeds and reduction of the length of the river network. The suspended sediments are a very important factor in the transportation of pollutants and water quality.

These problems have been investigated by many researchers, including Ukrainian scientists. Most of them are members of the “geographical direction-school” of investigation of the river’s regime. The representatives of this direction-school consider the spatial and temporal peculiarities of the sediment yield and its dependence upon different factors: the water discharges, the forestry of the river’s basins, the slope of the riverbed, etc. Drozd was among the first investigators of turbidity and sediment yield in Ukrainian rivers in the 1960s. His work resulted in the creation of the first map of water turbidity. Goretskaia later followed him (Goretskaia et al., 1988). During the last two decades the problems of sediment transportation and channel processes have been studied by Shvebs & Antonova (1988), Bobrovitskaja (1988), Obodovskiy (2001), Grebin (2000, 2002), Kovalchuk (1992, 1997) and Vishnevskiy (1992, 1994, 1997, 2000, 2001).

There are not many representatives of the “hydraulic direction school” in the Ukraine. It is important to distinguish the investigations of Nikitin (1980) and Bazilevich (Bazilevich et al., 1988; Bazilevich & Vishnevskiy, 1994), who worked in the Institute of Hydro-mechanics National Academy of Science of Ukraine.

The other scientists’ studies focus on the transportation of polluted substances on suspended sediments (Linnik, 1999; Voitsekhovich et al., 1997). The documentation of much greater contamination of fine particles for both various chemical substances and
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Radioactive pollution, when compared to larger particles, was the primary result of these works. In particular, a detailed study in a “near zone” of Chernobyl NPP has shown that most pollutants are associated with particles smaller than 0.05 mm (Voitsekhovich et al., 1997; Voitsekhovich, 2001). This fact significantly affected the distribution of pollution by the Prypiat’ River across large distances from Chernobyl NPP.

In spite of many investigations completed during the last decades, some questions were not solved. Among them is the distribution and quantification of natural (not changed by the human impact) turbidity of water.

**DATA**

The basic source of the sediment yield data, including the size of sediments (both bed and suspended) are the results of monitoring by the Hydrometeorological Committee of Ukraine. The duration of the direct observations on many rivers achieved 40–50 years. The number of gauging stations, on which they are carried out, for 1 January 2002 was equal to 119.

These data allow estimation of the spatial and temporal peculiarities of suspended sediments in rivers. However, it is necessary to consider the impact of ponds and reservoirs. There are 63,000 rivers, 28,800 ponds and 1,160 reservoirs in the territory of Ukraine. The total volume of water in ponds and reservoirs exceeds the average water runoff of the Dnepr River or the entire water runoff from the territory of Ukraine.

**RESULTS AND DISCUSSION**

The highest water turbidity (up to 1000 g m$^{-3}$ and higher) is observed in the rivers of the Crimean Mountains, which contain steep slopes and sparse vegetation. The rivers of the Carpathian Mountains and the Podillia region have lower turbidities (200–500 g m$^{-3}$). The smallest turbidity (at a level 10 g m$^{-3}$) is typical for the rivers of Polissia, in the most northern part of Ukraine (Fig. 1).

![Fig. 1 The map of turbidity of water in Ukrainian rivers, g m$^{-3}$ (the shaded region represents areas of the territory containing many ponds and reservoirs).](image-url)
In the main territory of Ukraine, the sediment yield in rivers is decreasing. The main cause is the creation of ponds and reservoirs. After the creation of the Dnister Reservoir (a total volume of 3.0 km$^3$) located between gauging stations Zalishchky and Mohyliv-Podilskyi, the sediment yield at the downstream station has been diminished by 30 times.

It is possible to assume that some impact is associated with the reduction of economic activity, including land use during the 1990s. During this decade the cultivated area decreased by 10%. At the same time, the areas cultivated for sugar beets, which has the highest erosion, experienced a 3-fold increase.

Some impact can be explained by climatic changes. During the 1990s, regional snow cover was minimal. The only exception is the increasing sediment yield in the Carpathian rivers, due to timber harvesting. Another factor is the mining of the channel bottom sediments, including the entire largest particle surface layer (Fig. 2).

The significant part of the suspended sediment yield passes during spring flooding. Sediment yield during floods is responsible for 60–70% of the annual quantity in the northern part of Ukraine and 20–30% in the southern part. During the last decades this trend has diminished. For example, the total suspended sediment yield during spring flooding during 1935–1985 was equal to 76%, and for 1991–2000 it was 64% for the Desna River (hydrological station Chernihiv). This reduction can be explained by the reduced amount of surface water runoff during spring snow-melting. In turn, the reduced runoff is explained by an increase of air temperature in the winter period and the decrease of snow storage on the basin slopes (Grebin’, 2000; Kovalchuk & Shtoiko, 1992).
It is obvious that the presence of suspended sediments in a river flow is determined not only by their supply from the basin area, but also by the conditions of their transportation. The decreased ability to transport sediment in rivers is the basic reason for sediment deposition and reduction of the length of river network (Vishnev’s’kyi, 2000a,b).

It is possible to use the results of some previous investigations to describe sediment erosion and deposition, and to characterize the conditions of sediment transport. The erosion conditions are characterized by the well-known dependence of non-eroding velocity from the size of particles. The conditions of sedimentation are detailed in an investigation by Nikitin (1980). According to these results, the degree of removal of suspended particles by deposition ($S$) is determined by the equation:

$$S = 1.66 + 0.68 \log (\omega / V_{ave})$$

where $\omega$ = hydraulic size of particles, $V_{ave}$ = average flow velocity.

Bazilevich et al. (1988) used the results of these investigations to obtain analytical dependencies that show the boundary conditions of suspended sediments presence in the river flow. These dependencies are:

$$S = 0 \quad \omega / V_{ave} = 0.0036$$  \hspace{1cm} (2)

$$S = 1 \quad \omega / V_{ave} = 0.107$$  \hspace{1cm} (3)

Equation (2) characterizes conditions where sediments do not accumulate ($S = 0$). Hence, when the hydraulic size of sediments is smaller than 0.0036 $V_{ave}$, the particles are constantly supported in a flow. In these conditions, particle exchange with the riverbed does not occur. Equation (3) characterizes conditions where all sediments contained in a flow accumulate ($S = 1$). In intermediate conditions, there is an exchange of sediments.

It is possible to illustrate the lines of equations (2) and (3) and also the graphic relationship between non-erasive velocity (for the depth 1.0 m) for different sizes of sediments on one figure. This enables the delineation of six zones with various conditions of sediments transportation (Fig. 3).

Zone I. This zone is situated beneath the line of non-erasive velocity. It portrays the absence of movement of the bottom sediments. The flow transports all sediments that are present in the flow.

Zone II. The erosion of the bottom sediments does not occur. Only partial sedimentation of suspended sediments occurs.

Zone III. The velocity of flow is insufficient for erosion of the bottom sediments. Complete deposition of sediments that are carried in flow is observed. Such conditions are observed when the rivers enter lakes, reservoirs and seas.

Zone IV. There is partial erosion of bottom sediment and whole transportation of suspended sediment.

Zone V. This zone, as well as previous zones, is characterized by the erosion of bottom sediments. Simultaneously, a portion of the suspended sediment falls on the bottom. These sediments are re-suspended by velocity pulsations.

Zone VI. This zone is characterized by the erosion of bottom sediments. Simultaneously the majority of suspended sediments falls on the bottom. An intensive exchange of sediments is observed (Vyshnev’s’kyi, 2000b).
These results are an addition to the well-known diagrams (particularly Shields criterion) and show the conditions of sediment transport. These results explain the observed sedimentation of riverbeds of small rivers throughout Ukraine. The flow velocity is much less than 0.4 m s\(^{-1}\) in these rivers during the main part of the year.

When the flow velocity is small, and the supply of sediment from the slopes to the river channel is large, the majority of sediment is deposited in the river-bottom (zone II and III of Fig. 3). The spreading of water vegetation in rivers is an additional factor of diminution of the flow velocity. In the rivers of southern Ukraine, most sediment is transported during the warm period of the year. When the hydraulic resistance is great and the flow velocity is small, even fine sediment cannot be transported in suspended form.

The flow’s reduced ability to transport sediment can be explained by the alignment of the interior-seasonal distribution of the river runoff. This is the consequence of climatic changes. Increased winter temperatures observed during previous decades has caused a decrease of the water storage in snow. As a result, the maximal discharges during a spring high water have decreased. At the same time, the runoff during dry periods (both winter and summer) became larger.

Field experimental investigation of sediment transportation was carried out on a small catchment of the Dnister River with the following parameters: area is 17.5 ha, a ratio of width and length of 0.56, relative heights are up to 80 m, hillslope angles are 3–10°, thalweg angles are 2.5–4°, exposure of slopes is western and eastern, cultivated area is 100%, and soils are typically comprised of dark grey podsol eroded to various degrees (Kovalchuk, 1997).

This investigation identified the ratio between erosion, transit, and deposition of sediments in a system: slope–primary watershed–thalweg–flood plain of the small river (I or II order)–channel of the small river–transit part (transportation of sediments to the river of higher rank) for the period of snow-melting and fall of rains. The results are shown schematically in Fig. 4.
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The slope of western exposition
Er. sl. = 37.74 m³
Acc. sl. sed. = 8.21 m³
K ac.sl. sed. = 23.6%

The slope of eastern exposition
Er. sl. = 22.62 m³
Acc. sl. sed. = 3.70 m³
K ac.sl. sed. = 16.4%

The accumulation of sediments from slopes to thalweg water-shed depression = 45.45 m³
K tr. sl. sed. = 79.2%

Accumulation of sediments in thalweg of water-shed 22.03 m³
K acc. t. = 48.5%

Transition of slope sediments throw the thalweg 23.42 m³
K tr. bas. sed. = 51.5%

Erosion of thalweg water-shed depression 6.4 m³

Transition of sediments washing out from thalweg 6.4 m³

Whole volume of sediments, receiving from the water-shed to the flood-plain
K (tr.+er.) = 46.8%

The accumulation of sediments on the flood-plain of the river of I order 23.36 m³
K acc. flood.-pl. = 78.3%

The receiving of sediments from water-shed depression to the river-bed of I order 6.46 m³
K tr. = 21.7%

Redistribution coef. of slope sediments
K acc. sed. = 20.8%

Transit coef. of slope sediments
K tr. sl. sed. = 79.2%

Where: Er sl. = gross soil losses, m³; Acc.sl.sed. = sediment deposition within slope, m³; K ac.sl. sed = part of sediment, deposited within slope; K tr. sl. sed.= transition ratio coefficient;

Fig. 4 The ratio of erosion, transition and redistribution of sediments on the different components of a river-basin system (Podillia Highland, Ukraine).

Of sediment eroded from the completely ploughed slope, 16–24% is accumulated (Fig. 4). That corresponds to a sediment ratio coefficient (the ratio of the quantity of sediment delivered to the rivers to the quantity of sediment eroded from the slopes) of approximately 79%. This coefficient is higher when the slopes are steeper. The further fate of slope sediments is different. Part of them (31–48%) accumulates in the bottom of watershed depressions. Here, an additional amount of sediment (from 14% up to 22%) is formed due to
erosion of the depression thalweg. The sediment transition coefficient for watershed depressions is 51.5%, or 46.8% if taking into account the sediment of eroded from the thalweg. The main part of this sediment (78.3%) accumulates on the floodplain of small rivers (width of floodplain is 120–184 m) and only 21.7% is transported to first order rivers.

The sediment transition coefficient for the small rivers varies from 17.9 up to 28.1%. It depends on the characteristics of the watershed depressions on the slope and floodplains of rivers. The generalization, provided by Golosov (2003), shows that the above mentioned results correspond to the results of other authors.

Our calculations, based on the results of radiocarbon dating floodplain and riverbed sediments of small rivers of the Podilia highland (the Bilka River, Gnyla Lypa catchment – (left tributary of the Dniester River), show that the average rate of sediment deposition ranges between 0.83–1.04 mm year\(^{-1}\) for the last 6.5–7.0 thousand years (according to dating by Marburg Philips University in 1997 (Kovalchuk, 1997). The rate of contemporary erosion from ploughed slopes is 0.3–0.8 mm per season with maximum rates up to 2.9–4.8 mm per season. These data are received as a result of 15 years monitoring of erosion processes on ploughed slopes with inclination 3 – 9\(^o\) at the Bilka catchment.

The change of structure in the river network was investigated using historical and current maps. It was established, that 36–65% of I–III order rivers of the Podilia highland have disappeared during the last 150 years. At the same time, the river length was reduced by 7–31%. Similar results were also obtained by other researchers (Golosov, 2003).

CONCLUSIONS

The following results were obtained from this study:

(a) the new map of turbidity of water in rivers of Ukraine was created;
(b) the anthropogenic impact on water turbidity in the rivers was evaluated;
(c) the modern scheme of sediment transportation in the river flow was obtained;
(d) the characteristics of sediments redistribution in the system of the slope—the watershed depression—the flood plain of first order rivers and riverbed of first order rivers was established.

REFERENCES


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