Sediment Transfer through the Fluvial System (Proceedings of a symposium held in Moscow, August 2004).
IAHS Publ. 288, 2004

Investigation of sediment yield of lowland rivers in Ukraine

I. P. KOVALCHUK[1]& V. I. VISHNEVSKIY[2]
1 *Ivan Franko National University of Lviv, 79000 Lviv, Ukraine*
geomorph@franko.lviv.ua
2 *Central Geophysical Observatory, Kyiv, Ukraine*

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. Goretskaja later followed him (Goretskaja *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 Hydromechanics 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 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 1160 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).

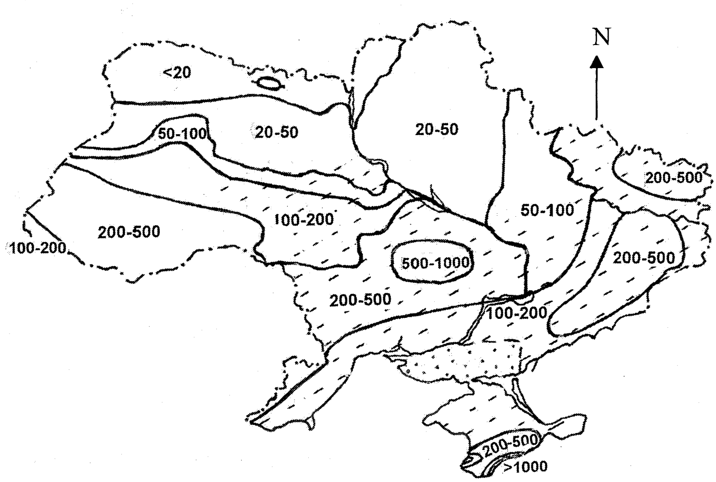


Fig. 1 The map of turbidity of water in Ukrainian rivers, g m^3 (the shaded region represents areas of the territory containing many ponds and reservoirs).

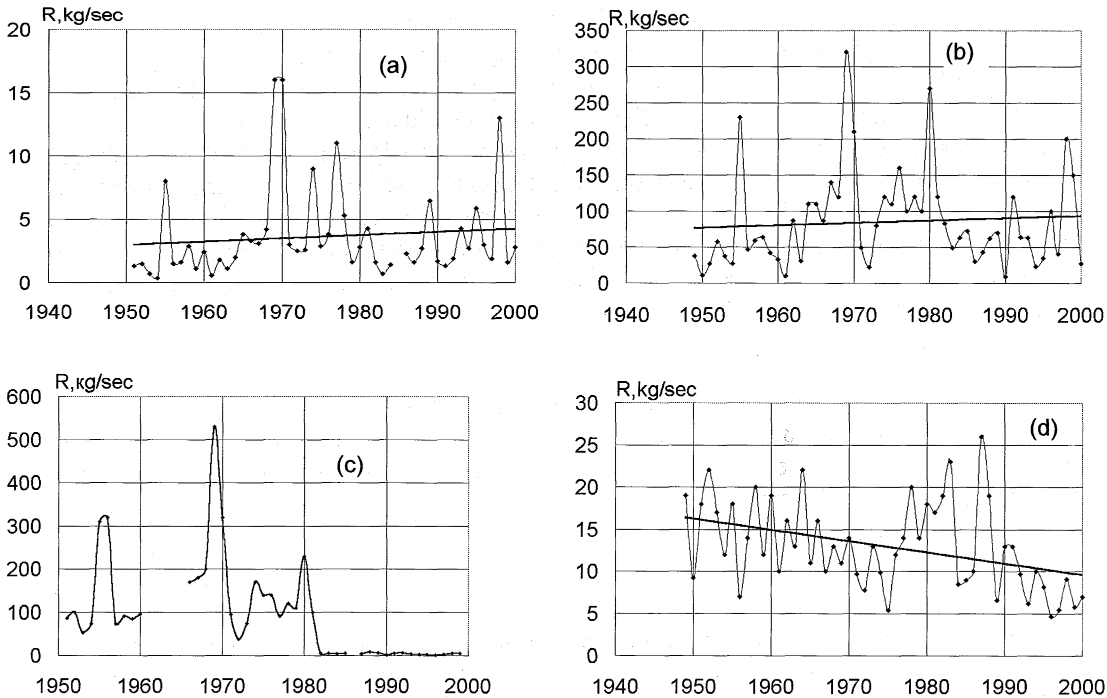


Fig. 2 Long-term changes of suspended sediment yield: (a) Tysa, Rakhiv; (b) Dnister, Zalishchyky; (c) Dnister, Mohyliv-Podilskyi; (d) Desna–Chernihiv.

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 Zalishchyky and Mohylic-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 (Vishnevs'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:

$$S = 1.66 + 0.68 \lg (\omega / V_{ave}) \quad (1)$$

where ω = 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:

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

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

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-erosive 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-erosive 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 (Vyshnevs'kyi, 2000b).

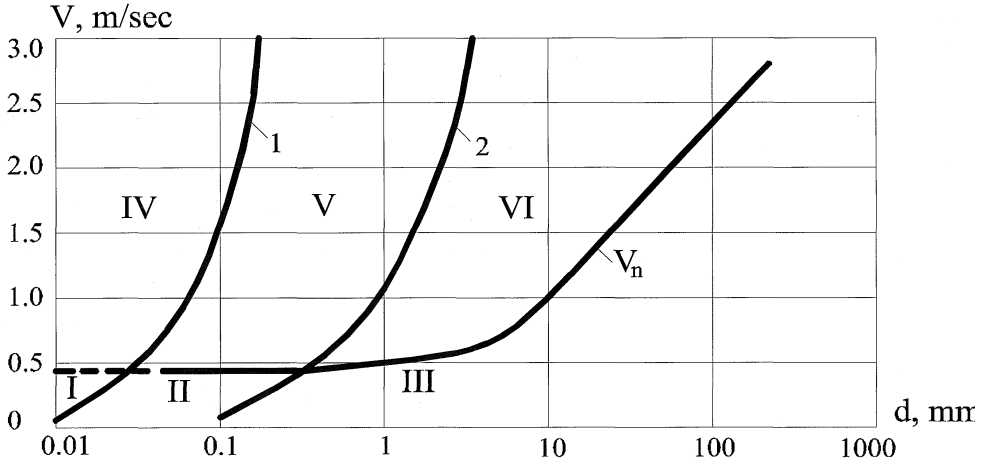


Fig. 3 Distribution of conditions of transportation and deposition of sediments, depending on its size and average velocity of flow: Curves 1 and 2 are plotted from formulas (2) and (3).

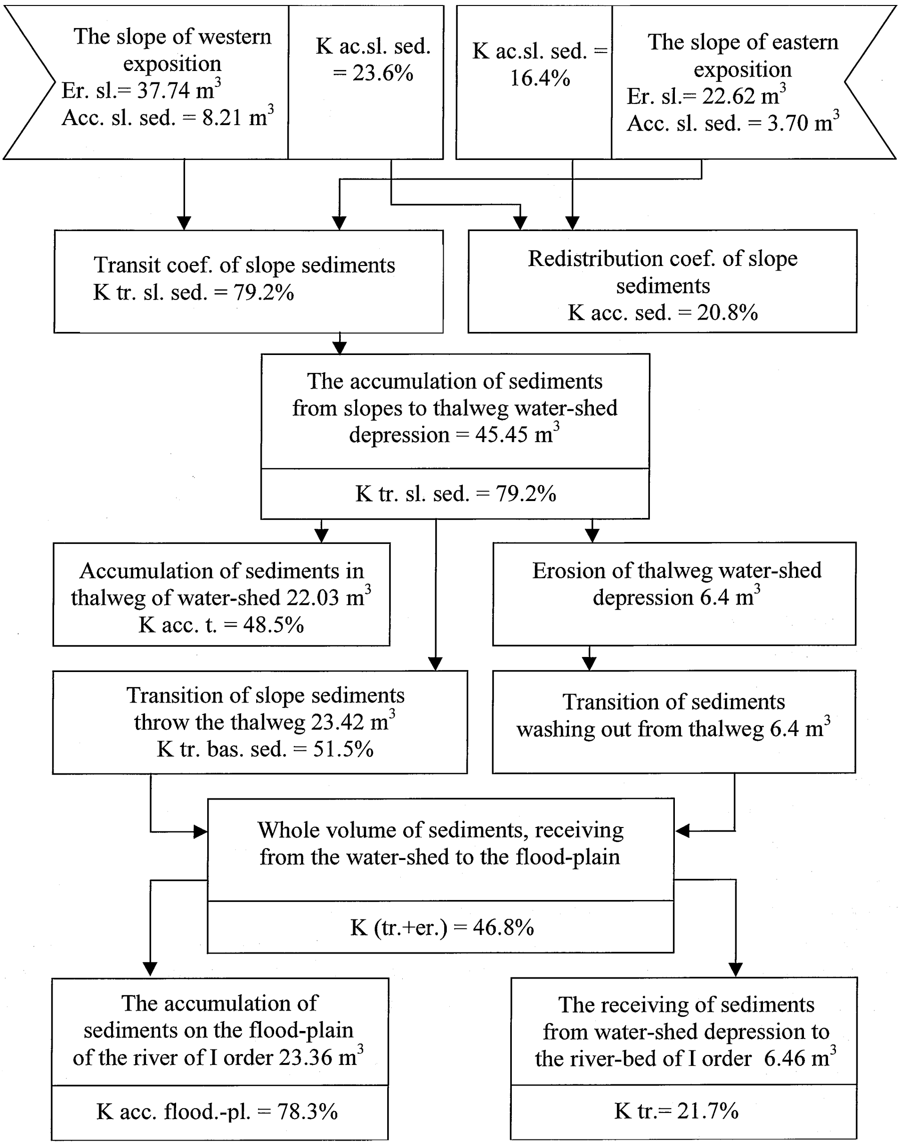
These results are an addition to the well-known diagrams (particularly Shields criterion) and show the conditions of sediment transport. These results explain the observed sedimentation of riverbeds of small rivers throughout Ukraine. The flow velocity is much less than 0.4 m s^{-1} in these rivers during 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.



Where: Er sl. = gross soil losses, m^3; Acc.sl.sed. = sediment deposition within slope, m^3; 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 Podillia highland (the Bilka River, Gnyla Lypa catchment – (left tributary of the Dnister 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 Podillia 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

Bazilevich, V. O., Gribovskaja, N. K. & Kozitskiy, V. V. (1988) Opriedielieniye raskhoda vzvieshennykh nanosov v pieschanykh ruslakh riek (The evaluation of suspended sediments in sandy channels of rivers). *Gidravlika i Gidrotiekhnika* **46**, 32–38 (in Russian).

Bazilevich, V. O. & Vishnevskiy, V. I. (1994) O raskhodie vzvieshennykh nanosov v malykh ravninnykh riekakh (About the discharge of suspended sediments in small plain rivers). In: *Dinamika i tiermika riek, vodokhranilishch i okrainnykh moriey* (Proc. International Conf., 1994), vol. 1, 189–191. Moscow, Russia (in Russian).

Golosov, V. N. (2003) Erozionno-akkumuliativnye processy v verkhnikh zvieniyakh fliuvialnoy seti osvoennykh ravnin umieriennogo poyasa (Erosion-accumulative processes at the upper parts of fluvial network of moderate zone plains). Doctor of Science Thesis, Moscow State University, Moscow, Russia (in Russian).

Goretskaja, Z. A., Manukalo, V. A. & Sokolov S. B. (1988) Opriedielieniye sridniego godovogo stoka nanosov malykh riek stiepnoy zony pravobieriezhnoy Ukrainy po dannym o zailienii prudov (The estimation of the average annual sediment yield of small rivers of a steppe zone of Ukraine based on the database of the ponds' sedimentation). *Trudy UkrNIGMI* **288**, 49–60. (in Russian).

Grebin', V. V. (2000) Otsinka rezhymu nanosiv richok baseynu Dnipra ,v mezhackh Ukrainy (The assessment of sediment yield of rivers in the Dnipro catchment, on the territory of Ukraine). *Hidrologiya, Hidrokhimiya i Hidroekologiya* **1**, 135–137 (in Ukrainian).

Grebin', V. V. (2002) Vykorystannia geografo-hidrologichnoho metodu dlia vyvchennia stokunanosiv (The use of geographic-hydrological method for the investigation of suspended sediment yield). *Hidrologiya, Hidrokhimiya i Hidroekologiya* **3**, 43–48 (in Ukrainian).

Kovalchuk, I. P. (1997) *Rehionalnyi Ekologo-Geomorfologichnyi Analiz* (*Regional Ecological-Geomorphologic Analysis*). Institute of Ukrainian studies, Lviv, Ukraine (in Ukrainian with English summary).

Kovalchuk, I. P. & Shtoiko, P. I. (1992) Izmienieniya riechnykh sistiem Zapadnogo Podolia v XVIII–XIX v. (Changes of river systems of the Western Podillia in XVIII-XIX centuries). *Geomorphology* **2**, 55–72 (in Russian).

Kovalchuk, I. & Zakharchuk, O. (1997) Analiz stoku nanosiv yak integralnoho pokaznyka skhylovoyi ta ruslovoyi eroziyi (The analysis of sediment yield as the index of slope and riverbed erosion). In: *Ukrains'ka Geomorfologiya: Stan i Perspektyvy* (Proc. International Conf., 1997), 117–119. Merkator, Lviv, Ukraine (in Ukrainian).

Linnik, P. M. (1999) Tiazholyie mietally v povierkhnostnykh vodakh Ukrainy: sodierzhaniye i formy migratsii (Heavy metals in surface waters of Ukraine: the contents and forms of migration). *Gidrobiologicheskiy Zhurnal*, **35**(1), 22–41 (in Russian).

Nikitin, I. K. (1980) *Slozhnyie Turbulientnyie Tiechieniya i Processy Tieplomassopierienosa* (Complicated turbulent currents and processes of heat and mass transportation). Naukova dumka, Kyiv, Ukraine (in Russian).

Obodovs'kyi, O. G. (2001) *Hidrologo-Ekologichna Otsinka Ruslovykh Protsesiv* (Na Prykladi Richok Ukrainy) (Hydrological and ecological estimation of channel process (on example of Ukrainian rivers)). Nika-Tsentr, Kyiv, Ukraine (in Ukrainian).

Shvebs, G. I. (1974) *Formirovaniye Vodnoy Erozii, Stoka Nanosov i ich Otsenka* (Na Primierie Ukrainy i Moldavii) (Formation of water erosion, sediment yield and their estimation (on an example of Ukraine and Moldova)). Gidromietieoizdat, Leningrad, Russia (in Russian).

Shvebs, G. I. & Antonova, S. A. (1988) Sovriemiennyye izmienieniya riezhyma nanosov riek Ukrainy (Modern changes of sediment yield of the rivers of Ukraine). In: *Trudy Piatogo Vsiesoyuznogo Gidrologichieskogo Syezda*, vol. 10, part 2, 155–160. Gidromietieoizdat, Leningrad, Russia (in Russian).

Shvebs, G. I. & Bobrovitskaya, N. N. (1988) Eroziya i stok nanosov s vodosbora (Erosion and sediment transportation from the watershed). In: *Trudy Piatogo Vsiesoyuznogo Gidrologichieskogo Syezda*, vol. 10, part 2, 102–125. Gidromietieoizdat, Leningrad, Russia (in Russian).

Vyshnevs'kyi, V. I. (2000) *Richky i Vodoimy Ukrainy. Stan i Vykorystannia* (The rivers and lakes of Ukraine. The state and the use). Vipol, Kyiv, Ukraine (in Ukrainian).

Vyshnevs'kyi, V. I. (2000) Transportuvannia i osadzhuvannia nanosiv u rivnynnykh richkakh (The transportation and the sedimentation of suspended sediments in plain rivers). In: *Naukovi Pratsi UkrNDHMI* **248**, 91–99. Kyiv, Ukraine (in Ukrainian).

Vyshnevs'kyi, V. I. (2001) Zminy klimatu i richkovoho stoku na terytorii Ukrainy i Bilorusi (The change of climate of and river runoff on the territory of Ukraine and Belarus). In: *Naukovi Pratsi UkrNDHMI* **249**, 89–105 (in Ukrainian).

Vyshnevs'kyi, V. I. & Kulachins'ka, L. N. (1999) Tviordyi stok malykh riek Ukrainy (A sediment yield of small rivers of Ukraine). In: *Melioratsiya i Vodnoye Khoziaystvo* **78**, 78–88 (in Russian).

Voitsekhovich, O. V. (2001) *Upravlieniye Kachiestvom Povierkhnostnykh Vod v Zonie Vliyaniya Avarii na Chernobylskoy AES* (The management of quality of the surface water in zone of influence of Chernobyl NPP accident). UkrNDHMI, Kyiv, Ukraine (in Russian).

Voitsekhovich, O. V., Kanivets, V. V. & Vishnevskiy, V. I. (1997) Sediment associated transport of Chernobyl radionuclides in the Pripyat River, Ukraine. In: *Study of Erosion, River Bed Deformation and Sediment Transport in River Basins as Related to Natural and Man-made Changes*. IHP–V. Technical Documents in Hydrology, vol. 10, 155–164. UNESCO, Paris.

Voloshchuk, V. M., Bojchenko, S. G. Stepanenko, S. M. *et al.* (2002) *Globalne Poteplinnia i Klimat Ukrainy: Regionalni Ekologichni ta Sotsialno-Ekonomichni Aspekty* (The global increasing of air temperature and the climate changes of Ukraine: the regional and social aspects). VPC "Kyivs'kyi Universytet", Kyiv, Ukraine (in Ukrainian).

Zubkova, K. M., Petukhova, G. A. & Tkachova, L. G. (1988) Izmienchivost' stoka nanosov i vliyaniye khoziaystviennoi dieyatielnosti na yego kharaktieristiki (Variability of suspended sediment yield and influence of economic activity on its characteristics). In: *Trudy Piatogo Vsiesoyuznogo Gidrologichieskogo Syezda*, vol. 10, part 2, 149–154. Gidromietieoizdat, Lieningrad, Russia (in Russian).