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THE FLUVIAL SYSTEM ON THE EAST EUROPEAN PLAIN: SEDIMENT SOURCE AND SINK

ABSTRACT. The modern fluvial system on the lowland East European Plain is of depositional type. Sediment transport to the seas is only a few percent of the total erosion, and the main part of eroded material is accumulated in the channels. The recent deposition of suspended sediments is caused by accelerated soil erosion on the arable slopes, which led to a high rate of lateral sediment input and deposition at the river headwaters and on the floodplains. The process of accumulation is facilitated by the unfilled “negative” volume of the net of dry valleys formed during the Late Glacial catastrophic erosion event. Such events of catastrophic erosion of the sediments deposited in the lowland fluvial systems occur with a frequency of 100-120 thousand years. In the conditions of both scarce vegetation and extremal surface runoff, the entire fluvial systems become the area of intensive erosion, with the deep incision of gullies and of the river channels. Therefore, despite the modern intensive deposition, delivery ratio for the fluvial systems on this lowland territory is close to one in the long-term perspective.

KEY WORDS: The fluvial system, delivery ratio, recent accelerated erosion, sediment deposition, Late Glacial catastrophic erosion event, East European Plain

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INTRODUCTION

A fluvial system is the cascade of connected or disconnected linear depressions (channels) with catchments, formed by modern and ancient water flows, having long history of morphological evolution (Makkaveev 1955; Schumm 1977). These flows, generally directed by the gravity force from upper to lower reaches, interact with the surface layer of the lithosphere, being one of the main denudation agents.

The erosion and deposition in the fluvial systems are well investigated (Gregory and Walling 1976; Schumm 1977; Meade 1996

etc.). Erosion by water produces sediments – particles of different size and weight. These sediments can be transported through the fluvial system only when and where transport capacity of the flow is higher than sediment load. The ability of the fluvial system to deliver sediments to the lowermost point is well described by the ratio between the amount of sediments arriving at the outlet of a fluvial system and the total eroded sediments within the catchment, i.e. delivery ratio Dr . The fluvial system can be of erosive type, when delivery ratio is high and of depositional type, with low delivery ratio. The boundary can be appointed at $Dr=50\%$ (Sidorchuk 2015).

The modern global fluvial system delivers annually to ocean and internal seas about $19 \cdot 10^9$ ton of sediment particles (Milliman and Farnsworth 2011). This is only a part of the global relief destruction by erosion. Annual soil erosion by water only from the global farmland (about 10% of the global terrestrial area) is estimated in a broad range from $172.1 \cdot 10^9$ (Ito 2007) to $22.2 \cdot 10^9$ ton (van Oost et al. 2007). In any case, the modern global delivery ratio is lower than one, and sediment sink in the fluvial systems (mostly at the lowlands) is one of the significant geomorphological processes. The alluvial and non-alluvial sediments, deposited in the fluvial systems, together with channel morphology, represent the memory of the system (Knighton 1984).

The Late Glacial period was characterized by extremal surface runoff, typical at least for the Northern Hemisphere (Dury 1965; Volkov 1963; Sidorchuk 2003). However, for this period the type of the fluvial systems on the lowlands, erosional or depositional, is not well investigated. The main goal of this paper is to show the differences, as well as the similarities, in the processes of the fluvial systems on the East European plain during these two highly contrasting periods of erosion: the period, dominated by human-induced accelerated erosion, lasted about 300 years, and the Late-glacial period about 2-3 thousand years long, with the natural extremal erosion.

The rivers of the East European Plain

The East European plain is a large lowland covering an area of about $4.0 \cdot 10^6$ km² (Alayev et al. 1990). The largest European rivers: Volga, Don, Dnieper, drain its southern megaslopes. The headwaters of these rivers on the main water-divide of the plain have maximum altitudes of about 250-300 m. Therefore, the inclinations of the main rivers 1900-2700 km long are not more than 0.13-0.14‰. The inclinations and lengths of river basin slopes vary in the broad range with highly negatively asymmetrical distributions. The multiple values of the *LS* factor of USLE (Wischmeier and Smith 1978), calculated on the field scale using slope length and inclination, are

typically less than 7 with 80% in the range of 0.1-1.0 (see Fig. 2.14 in Litvin 2002).

The drainage density of the modern permanent rivers and streams with the length more than 1 km on the southern megaslope of the East European plain is 0.36 km/km²: 150717 rivers totally 574414 km long belong to the Volga River basin (1360000 km²), 13012 rivers totally 90416 km long belong to the Don River basin (422000 km²) and 31954 rivers totally 163467 km long belong to the Dnieper River basin (504000 km²) (Domanitskiy et al. 1971). This is only the part of the fluvial system within the study area. The net of dry valleys with a density of 0.4-0.6 km/km² dominates the physiography of the erosion landscape (Fig. 1). These dry valleys (called "balka" or "sukhodol") typically have lengths of 1-10 km. These systems drain water mostly during snow thaw period or after intensive rain. Dense vegetation usually cover their bottoms and slopes, so the modern erosion here is negligible in the pristine conditions. The bottom width of dry valleys is much larger than the width of the flows in these valleys, and the ratio of these two width increases with basin area decrease. The same effect is typical for small and median river valleys. Dokuchaev (1878) was the first describing this phenomenon and addressing it to the history of fluvial system evolution.

The Late-glacial period of extreme erosion

Climate-induced episodes of accelerated erosion occurred repeatedly during periods of deglaciation of the continental ice-sheets (Vandenberghe 1995). The large rivers of the Late Glacial time were formed during these episodes of high surface runoff and were first described by G. Dury (1965) and I. Volkov (1963). The reconstructed mean annual surface runoff was 2-4 times greater on the East European plain for the Late Glacial time about 16-18 ka ago, and the maximum discharges were 5-6 times greater (Sidorchuk et al. 2001, 2008). The river channels were then wider than the modern ones, long and deep gullies dissected slopes of the valleys, and the permanent watercourse net was

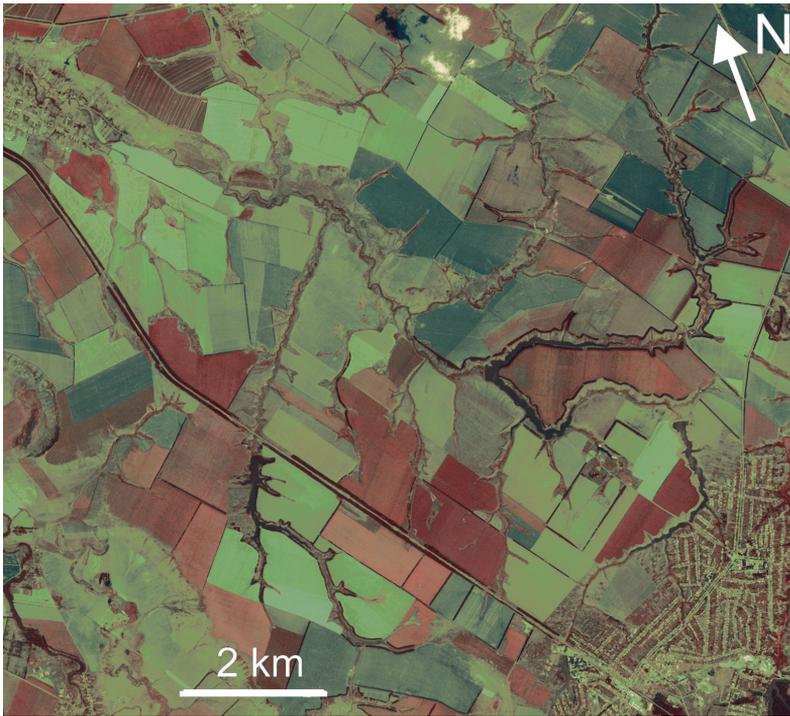


Fig. 1. The dry valley net at the Khoper River basin. The part of SPOT image ID 5 119-246 07/07/30 08:26:01 2 J, central point lat. 51.5° N, lon. 41.92° E (provided by MSU Geoportal)

much denser. The volume of the linear erosion during this geologically rather short episode (2-3 thousand years) was extremely high.

For example, the Khoper River basin (the tributary of the Don River) with an area of 61,100 km² has a recent total length of the permanent flows and dry valleys of 36,000 km. The permanent river net (267 rivers with the total length of 9000 km) consists of the streams equal and more than 10 km long. The dry valleys (some of them with permanent springs) are shorter than app. 10 km length and form the erosion net with a total length of 27000 km, which dissects the basin slopes.

The "negative" volume of these dry valleys can be estimated from the valley volumes with known number of the valleys. The negative volume of a dry valley V_b (km³) depends on its length L (km) and the difference between the upper and lower points of its longitudinal profile H_0 (km). Measurements in the Khoper River basin led to the relationship:

$$V_b = 0.007 H_0 L^2 \quad (1)$$

H_0 vary in the Khoper River basin in the range of 20 to 85 m with a mean value of 45 m.

The number of dry valleys with the length less than 10 km can be estimated from the data on the structure of the fluvial network. This structure is well described by the magnitude – frequency function (Fig. 2). It is convenient to use the length of the dry valley L as the magnitude, and the sum of the lengths of the valleys ΣL with the length greater than L as the frequency:

$$\Sigma L = M L^{1-D} \quad (2)$$

The variables in formula (2) correspond to the terms of the fractal approach. The exponent D can be called the fractal dimension of the valley network, and the coefficient M is a measure of the structure of the network, equal to the total length of all valleys with the length more than 1 km. The formula (2) is empirical and dimensional. therefore all lengths in formulas (1)-(6) are in the same units (km).

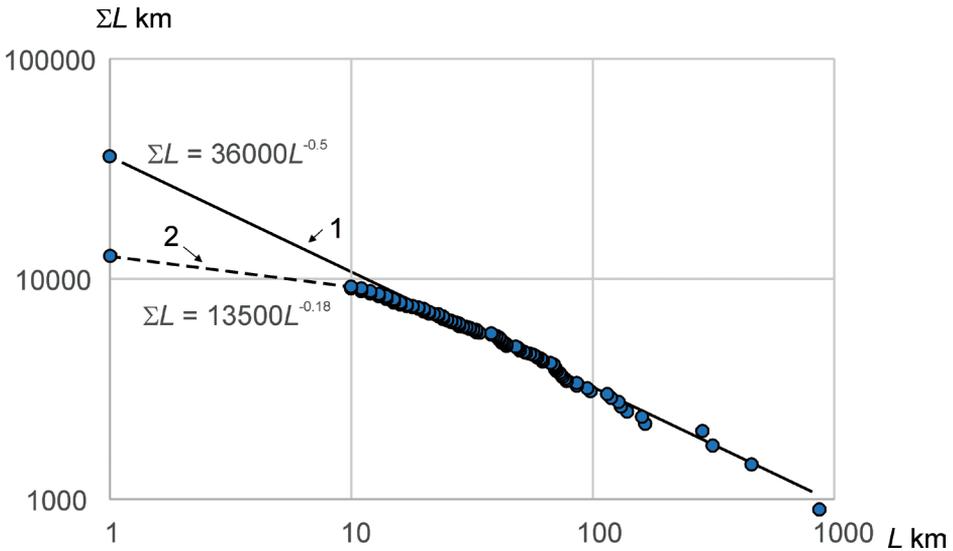


Fig. 2. The relationship between the stream length L and total length ΣL of the streams, equal and longer than L . Key: 1 – the relationship for the recent streams ≥ 10 km long and the Late Glacial streams < 10 km long.; 2 – the relationship for the recent streams < 10 km long

To estimate the number of dry valleys $N_{\Delta L}$ in a given range of length ΔL for a certain j -th catchment area, it is necessary to construct a regional function (2) in the differential form:

$$N_{\Delta L} = \frac{\Delta \sum L}{L_{0mean}} = M_j (1 - D_j) L_{0mean}^{1-D} \Delta L \quad (3)$$

In this formula M_j is regional total length of the network of streams more than 1 km long, D_j is regional fractal dimension, L_{0mean} is the length of a dry valley $(2L_o + \Delta L)/2$. Since the fractal dimension can be calculated with sufficient accuracy only for a limited number of catchments, the linear relationship was obtained between the fractal dimension and the density K (km km^{-2}) of the entire network of streams:

$$(D - 1) = 0.89K \quad (4)$$

The regional M_j value can be calculated with the region area F_j (km^2) and the network density K_j (km km^{-2}):

$$M_j = aK_j F_j \quad (5)$$

Here the coefficient a is equal to 1 and was used to keep dimension of M (km^D). The total volume V of the dry valley network for each region in the Khoper River basin is calculated

by the formula

$$V = \sum_{L=1}^{L=10} N_{\Delta L} V_b \quad (6)$$

The regions with similar density of the stream net K_j and similar dry valley relief H_o in the Khoper River basin were identified on the map «Erosion hazard in the territory of the USSR» compiled in the Institute of Geography of the Russian Academy of Science. The volume of the dry valleys with the lengths of 1-10 km was calculated for each region and for the entire basin with formulas (1-6). In the basin of the Khoper River, the total recent “negative” volume of the dry valleys is 24 km^3 .

During the period of extremal surface runoff 16-18 ka ago all valleys, that are now dry, were deep intensively eroded gullies (Eremenko and Panin 2011). In average they were about 30% deeper compared to the modern erosional forms (Fig. 3). The total “negative” volume of the ancient gully erosion at the Khoper River basin, according Eq. 2-4 was then about 31 km^3 .

The main rivers were also over-deepened during this extreme surface runoff episode along the total length of their channels.

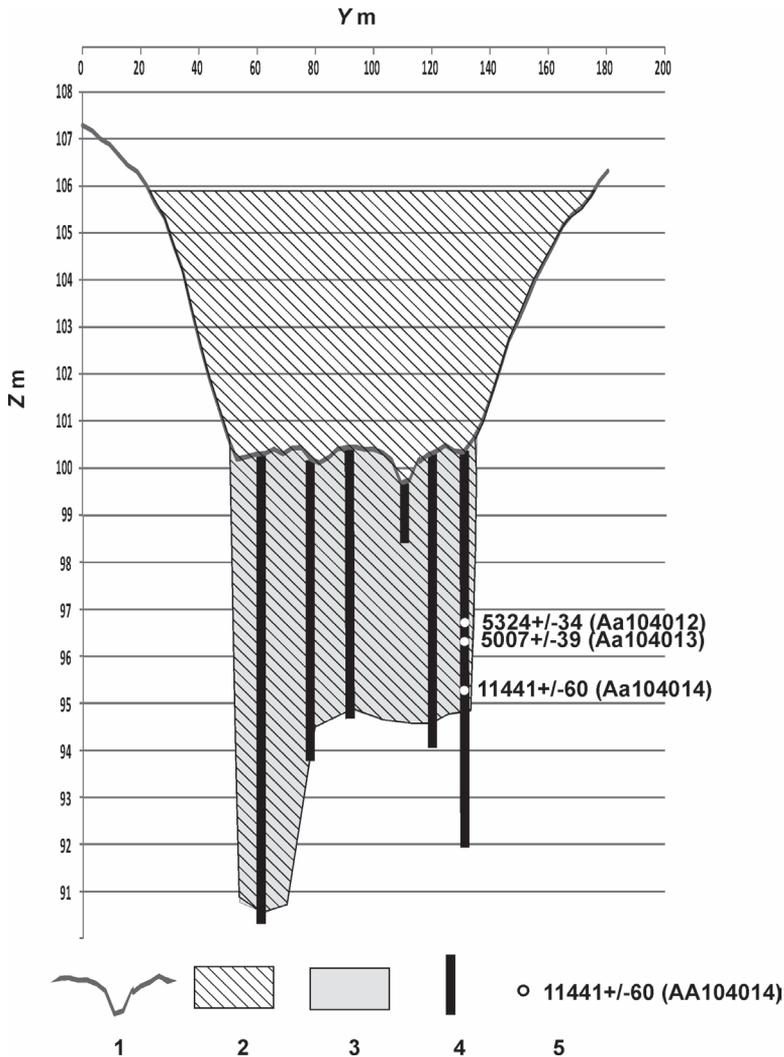


Fig. 3. The cross-section of Perepol'ye dry valley (the Khoher River basin, lat. 51.2° N, lon. 42.32° E), cored by the author and his colleagues in 1997. Key: 1 – the recent dry valley bed; 2 – the cut formed during the Late Glacial catastrophic surface runoff; 3 – the Late-Glacial/Holocene sediments; 4 – cores; 5 – ^{14}C dates (AMS)

Calculations with the equation, similar to 2-6 shows that about 7.5 km^3 were eroded at the Khoher River valley. This process was typical for all rivers on the East European plain (Sidorchuk et al. 2001).

The episode of extreme erosion was relatively short, about 2000-3000 years. The mean rate of gully and river-bed erosion was app. $250 \text{ t km}^{-2} \text{ a}^{-1}$ at the central part of the East European plain (Fig. 4). Such rate is extremely high for the lowland environment in the natural conditions.

The delivery ratio of the fluvial system on these lowland territory was presumably close to one during the event of catastrophic erosion. All sediments eroded on the slopes and within the river channels were delivered to the river mouths and to the seas. The distinct maximum of sedimentation rates was reported for the period 16-18 ka ago at the Black sea (Bahr et al. 2005). The large volume of Khvalyn sediments of the similar age (so called chocolate clays) was deposited in the Caspian Sea (Leonov et al. 2002).

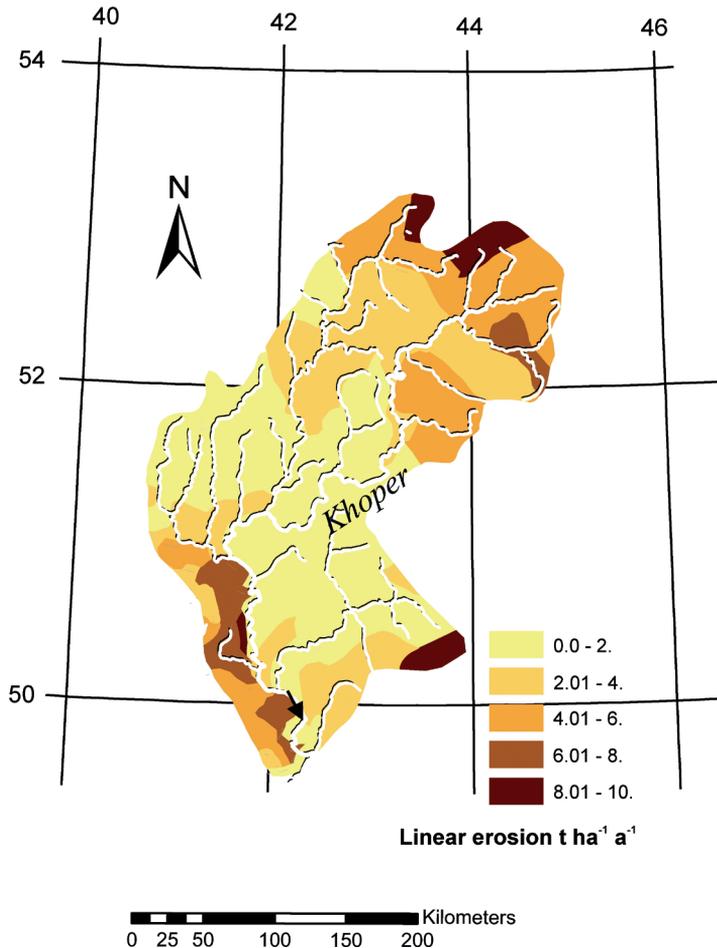


Fig. 4. Annual rate of linear erosion ($\text{t ha}^{-1} \text{a}^{-1}$) during the event of catastrophic surface runoff 16-18 ka ago, calculated from the “negative” volume of dry valleys at the Khooper River basin

The post-erosion deposition on the East European plain

After the episode of catastrophic erosion, the surface runoff generally decreased (with periods with higher and lower discharges) and reached the modern values at the beginning of the Holocene (Sidorchuk et al. 2008). This decrease of discharges in the wide channels led to a transport capacity decrease and to sediment deposition. The maximum rate of deposition in the Khooper River valley estimated for the cross-section shown in Fig. 1 in Sidorchuk (2003) occurred within the period from 8 to 14 ka BP. The deposition rate during the Holocene was lower (Fig. 5).

A potential for deposition is still very high in this environment. In such river valleys with a high potential for collecting the lateral sediment input “inherited” floodplains were formed (Sidorchuk 2003). The deposition in the gullies (now dry valleys on the slopes) was less effective: in average only about 25-30% of their “negative” volume was filled. The total volume of deposition in the fluvial system at the Khooper River basin was about 13 km^3 and this process lasted ~13-14 ka. The average annual erosion rate on the slopes (taking the modern delivery ratio for this basin) was $20\text{-}25 \text{ t km}^{-2}$ during that period, being more intensive at the beginning of the process and with the significant decrease of this rate up to the

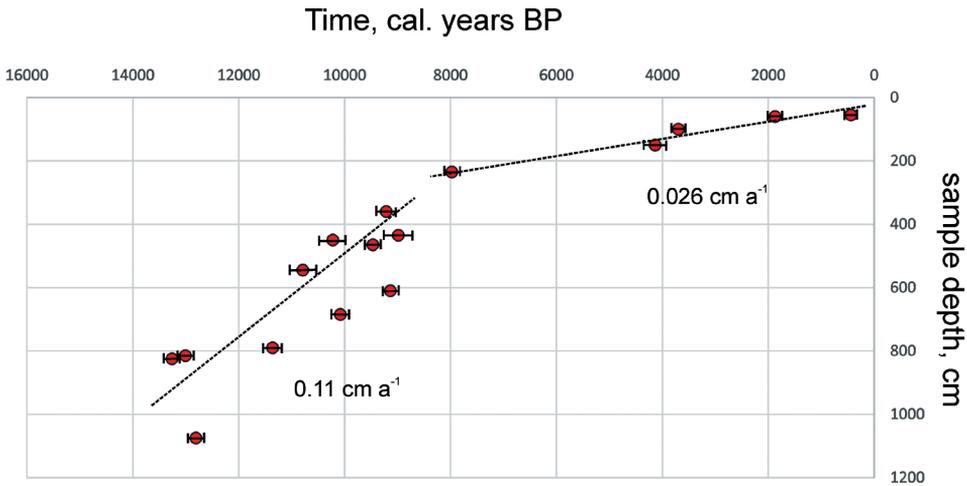


Fig. 5. Rate of deposition in the Late Glacial channels at the bottom of the Khoper River valley (cross-section at lat. 51.22° N, lon. 42.43° E), based on calibrated ^{14}C dating

time of intensive agriculture on these lands. The long lasted natural morphological evolution of the fluvial system on the East European plain after the catastrophic surface runoff event 16-18 ka ago slowly formed a graded channel network. The averaged hydrologic and morphometric characteristics of the rivers of different size and order were estimated by Rzhantsin (1985) (Table 1, columns marked with "x"). The additional information about averaged channel width W (m) and depth d (m) for the bankfull discharge Q_{bf} ($\text{m}^3 \text{s}^{-1}$) conditions (not inundated floodplain) was obtained from the measurements of the Russian Hydrological Survey at about 400 stations ($R=0.85$ for W and 0.6 for d):

$$\begin{aligned} W &= 3.5Q_{bf}^{0.59} \\ d &= 0.84Q_{bf}^{0.24} \end{aligned} \quad (7)$$

Sediment transport rate T (transport capacity of the flow in kg s^{-1}) for fine sediments was calculated with the formula of Zamarin (1951), which was calibrated for the lowland rivers of the East European plain

$$T = 0.22Q_{bf} \left(\frac{U}{\omega} \right)^{1.5} \sqrt{Sd} \quad (8)$$

Here U is flow velocity (m s^{-1}), S – flow surface slope (m m^{-1}), ω – particle fall velocity (m s^{-1}).

The sediment transport rate T for the flood period increases along the average fluvial system (Table 1), therefore the lowland rivers at the East European Plain were able to transport all suspended sediments without significant deposition in the conditions of low rate soil erosion on the slopes. The column of the Table 1 with T_{cr} shows the critical sediment supply to the channel from the slopes during the flood period t . When this value is exceeded, then deposition in the channel can occur. The pre-agriculture sediment yield at the forest-steppe and steppe zones of small rivers of the region was about $4.4 - 17.0 \text{ t km}^{-2} \text{ a}^{-1}$ (see tables 2.11 and 2.15 in Dedkov and Mozherin 1984). This is one-two orders of magnitude lower than the critical transport capacity, therefore rivers of all sizes and orders were capable to transport this amount of sediment.

The other situation is for the dry valleys, where post-erosion "negative" volume is still very large. These valley bottoms are dry the main part of the year and are flooded only during the snow thaw period and after intensive rain. The stream channel with the well-defined banks is rarely evident at dry valley bottoms, and only at the lower sections. The usual discharge in such valleys during rainfall exceeds the bankfull discharge and flood the wide valley bottoms, covered with the grass and

Table 1. The averaged hydrologic and morphometric characteristics of the permanent watercourses (mostly, rivers) on the East European Plain

N^*	L^* km	F km ²	Q^* m ³ s ⁻¹	t^* days	S^* m m ⁻¹	W m	d m	U m s ⁻¹	T kg s ⁻¹	T_{Lcr} ha ⁻¹	Dr	E t ha ⁻¹
1	0.8	0.4	0.5	2	0.134	2.4	0.7	0.3	1.6	7.1	0.61	12.1
2	1.5	1.2	1.12	2	0.0492	3.8	0.9	0.3	2.9	4.2	0.48	9.0
3	2.8	3.6	2.51	2	0.02	6.1	1.0	0.4	5.5	2.6	0.39	7.1
4	5.1	10.7	5.6	2	0.0089	9.8	1.3	0.4	11.0	1.8	0.31	6.0
5	9.3	31.6	12.6	2.08	0.0042	15.9	1.5	0.5	23.0	1.3	0.25	5.3
6	16.9	92.5	28.2	4.7	0.00216	25.5	1.9	0.6	51	2.2	0.20	11.0
7	31	275.6	63	7.2	0.00114	41.0	2.3	0.7	111	2.5	0.16	15.4
8	57	825.0	141	10.1	0.00063	66.0	2.8	0.8	250	2.6	0.13	20.2
9	104	2435.2	316	17.5	0.00036	106.2	3.3	0.9	570	3.6	0.11	33.8
10	190	7205.0	710	21.5	0.00021	171.3	4.1	1.0	1330	3.4	0.08	40.5
11	338	20320.1	1590	29	0.000129	275.6	4.9	1.2	3160	3.9	0.07	56.7
12	620	60559.2	3560	40	0.000079	443.4	6.0	1.3	7490	4.3	0.06	77.3
13	1140	181260.7	7950	52	0.0000495	712.3	7.3	1.5	17900	4.4	0.04	99.9
14	2090	539682.3	17800	70	0.000031	1146.0	8.8	1.8	42906.4	4.8	0.04	134.7
15	3810	1590522.5	40000	90	0.00002	1847.8	10.7	2.0	104920.6	5.1	0.03	178.4

(N is watercourse order, L is river length, F – basin area, Q – mean maximum discharge, t – flood duration, S – channel slope, W – channel bankfull width, d – bankfull depth, U – mean flow velocity, T – suspended sediment transport rate, T_{Lcr} – critical sediment lateral input from slopes – Tt/F , Dr – sediment delivery ratio, $E = T_{Lcr}/Dr$ – critical erosion on river basin slopes. Columns with “*” are after Rzhanitsin (1985)

shrubs. Therefore, most of the sediments, eroded on the slopes, are deposited on the dry valleys bottom surfaces.

The end of this long period of predominantly depositional processes in the fluvial system of the East European plain was characterised by some activation of linear erosion. Gullies were formed on the steep slopes of the river valleys and in the lower parts of the dry valley bottoms (Panin et al. 2009). This linear erosion was caused by some increase of precipitation and surface runoff about 5–6 ka ago and was not related to human activity.

The modern fluvial system of the East European plain

The main characteristic of the modern processes in the fluvial systems of the East European plain is the accelerated soil

erosion on the slopes and rapid deposition of these eroded sediments in the river net headwaters. The calculated annual amount of fine (silt and clay) sediments (Litvin 2002), washed out in the recent human-influenced conditions (see, for example, Fig. 6) is $880 \cdot 10^6$ ton on about $1.43 \cdot 10^6$ km² of arable land.

The average erosion rate is about 6.2 t ha⁻¹, with the maximum of 25 t ha⁻¹. On over 22.7% of the arable land, the annual rate of erosion is less than 0.5 t ha⁻¹; on 24.1% it is in the range 0.5 – 2.0 t ha⁻¹; on 23.5% it is in the range 2.0 – 5.0 t ha⁻¹; on 12.6% it is in the range 5.0 – 10.0 t ha⁻¹; on 9.9% it is in the range 10.0 – 20.0 t ha⁻¹; and on 7.2% of the arable land the annual erosion rate is more than 20.0 t ha⁻¹. In total, the calculated volume of accelerated erosion on slopes in the river basins of the southern mega-slope of the East European Plain ($2.2 \cdot 10^6$ km²) during the period of intensive agriculture (the last 300-

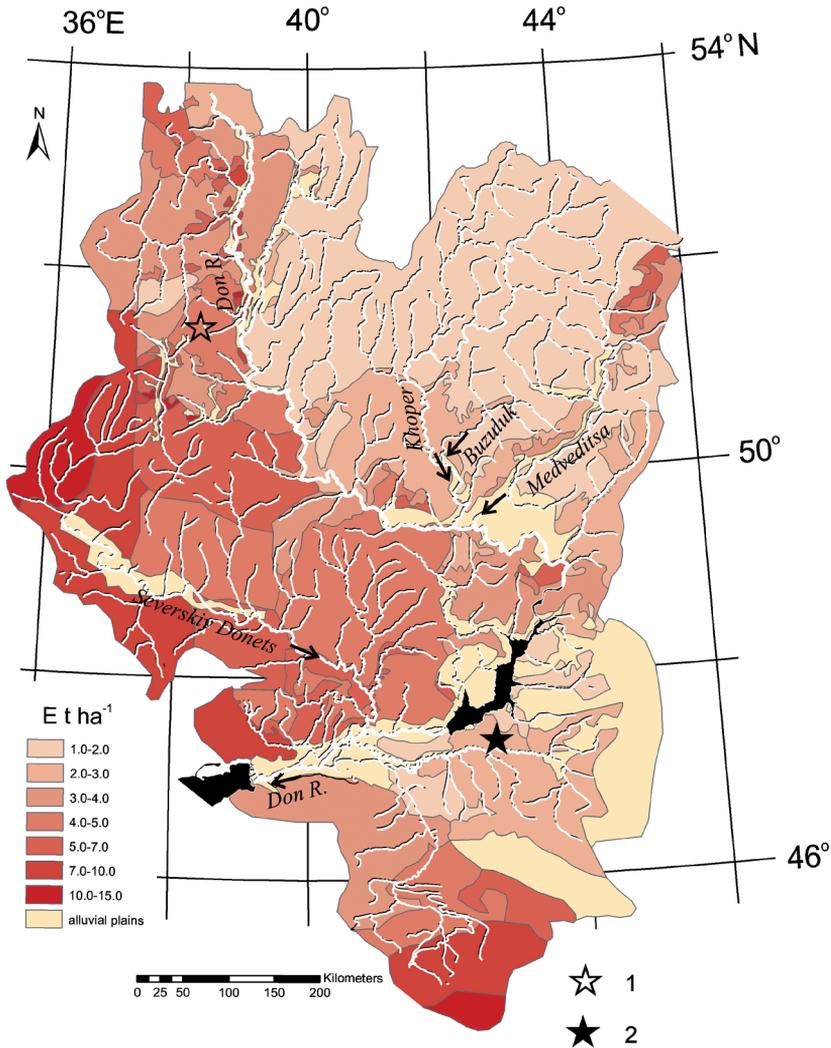


Fig. 6. The fragment of the Soil loss map of the East European Plain (Litvin , 2002) for the Don River basin. The stars show the positions of gauging stations, used on Fig. 7

400 years) is about $76 \cdot 10^9$ ton (Sidorchuk and Golosov 2003).

The second important source of eroded material on the East European Plain is related to gully systems. There are about $1 \cdot 10^6$ gullies with a length over 70 m and a total volume of $3.5 \cdot 10^9 \text{ m}^3$ (Litvin et al. 2003). These gullies were formed mainly during the period of intensive agriculture. The rate of gullies formation reached its maximum in the years 1860-1910 after the agricultural reform of 1861, when $\sim 24\%$ of now existing gullies were formed (Sidorchuk and Golosov 2003).

Sediments washed away due to soil erosion are delivered from the slopes to the water flows of different size. The comparison of calculated slope erosion E and measured sediment transport rate T for 343 river basins with hydrological stations at Volga, Dnieper and Don River basins allows the calculation of the sediment delivery ratio Dr (Golosov et al. 1991). Usually in the lowlands it decreases with basin area $F \text{ km}^2$:

$$Dr = \frac{T}{E} \approx aF^{-b} \tag{9}$$

The exponent b and the coefficient a vary in the broad range at different river basins. For example, for the Don River basin, where T values were measured at small catchments (Resources... 1973), $a=0.23$, $b=0.32$ (Fig. 7).

In the conditions of accelerated soil erosion the critical amount of sediment T_{Lcr} which can be delivered from the slopes during floods without deposition (i.e. the amount equal to the specific transport rate) decreases along the flows with lengths of less than 10 km (Table 1). Such flows are potentially vulnerable to sedimentation if lateral sediment input from the basin is high enough. All dry valleys belong to this class. The last column in the Table 1 shows the critical erosion rate on the slopes $E = T_{Lcr}/Dr$. If the actual erosion on the slopes is more than critical value, the delivered to the watercourses amount of sediment is more than flow transport capacity. Therefore, according to Table 1, the permanent streams with the length 3-10 km can be depositional sinks in the condition of average annual soil erosion rate (6.2 t/ha), and at the areas with soil erosion rate of 25 t/ha even medium-size river with the length 50-60 km can be silted.

Measurements in different regions of the East European Plain (the Middle Oka, the

Upper and Lower Don, the Lower Volga, the Ural River and Stavropol' Region) show that the thickness of sediments at the bottom of dry valleys with basin areas of 5-40 km² ranges from 1.0 to 2.8 m. The mean aggradation rates for the period of intensive agriculture vary within the range 3 to 38 mm a⁻¹ (Golosoov et al. 1991). About 60% of 76 10⁹ ton of eroded material on the southern mega-slope of the East European Plain was deposited in the valleys less than 25 km long and about 90% of it in the valleys less than 100 km long (Table 2). The measurements in the deltas of the major rivers for the period before large reservoirs construction show that only 3-6% of eroded matter was transported to the sea, while its main part was sequestered in the fluvial systems (Sidorchuk 1995).

DISCUSSION AND CONCLUSION

The main geomorphic function of the global fluvial system is the land surface lowering by dissolution, erosion and sediment transport. It is one of the main sources of mineral matter, delivered to the oceans. This process is not continuous: sediment deposition in the channels accompanies erosion, therefore sediment transport occur in form of waves of different amplitudes and periods (Langbein and Leopold, 1964).

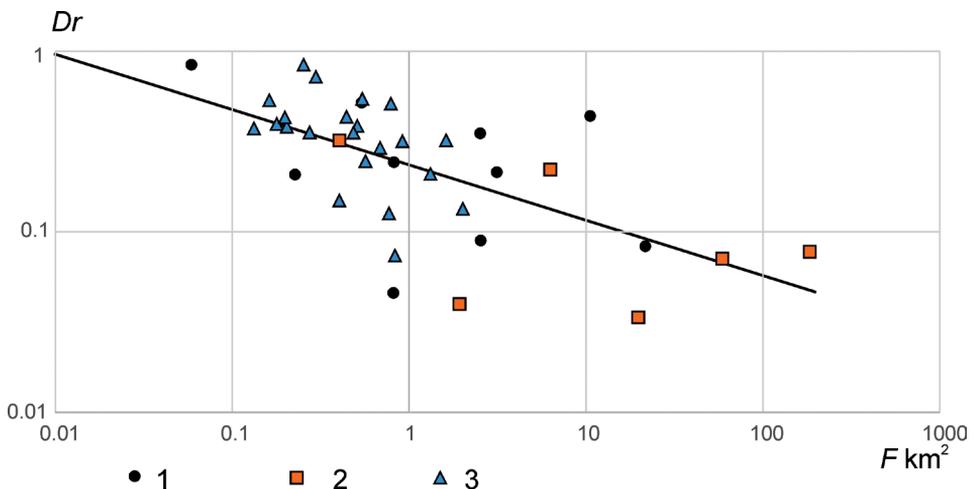


Fig. 7. Changes of the sediment delivery ratio Dr along the the rivers of the Don River Basin. Data from: 1 – gauging stations at Nizhne-Devitskaya water budget station (N 1 at Fig. 6); and 2 – gauging stations at Dubovskaya hydro-meteorological station (N 2 at Fig. 6); 3 – ponds infill in Buzuluk and Medvetitsa river basins

Table 2. Deposition of sediments, eroded from slopes in the river valleys less than 100 km long on the East European Plain

The river basin	F km ²	E t ha ⁻¹ a ⁻¹	E_{agr} 10 ⁹ t	Dr_{100}	D_{agr} 10 ⁹ t
Dnepr upper Pripyat'	106000	2.10	5.2	0.07	4.9
Pripyat'	114300	2.10	5.6	0.04	5.4
Desna	88900	1.90	3.7	0.07	3.4
Dnepr lower Pripyat'	154700	3.60	9	0.05	8.6
Don upper Severskiy Donets	257000	1.30	5.3	0.20	4.2
Severskiy Donets	96250	2.20	4	0.05	3.8
Don lower Severskiy Donets	53025	1.30	0.6	0.05	0.6
Volga upper Oka	265200	1.20	8.4	0.05	8.0
Oka	245000	1.80	11	0.08	10.2
Sura	67500	2.40	3.1	0.30	2.2
Verluga	39400	0.90	0.9	0.08	0.8
Vishera	31200	0.40	0.2	0.30	0.1
Belaya	142000	0.90	1.3	0.30	0.9
Vyatka	129000	2.50	6.1	0.10	5.5
Kama without Vishera	204800	2.80	6.7	0.30	4.7
Volga lower Kama	224000	1.30	4.7	0.30	3.3
Total	2218275		75.8		66.5

(F – basin area; E – recent mean (for the whole river basin) accelerated erosion rate on the slopes; E_{agr} – amount of erosion during the period of intensive agriculture; Dr_{100} – the delivery ratio for the rivers 100 km long; D_{agr} 10⁹ – the amount of deposition in the valleys less than 100 km long during the agricultural period)

The fluvial system is a sediment source at the reaches with positive balance between particle detachment and particle subsidence. The fluvial system is a sediment sink at the reaches with a negative transport rate change along the flow and/or high lateral sediment input from the basin slopes. Water flow regimen and vegetation cover are the main factors, which determine the periods and the amplitudes of erosion-deposition waves.

The waves of erosion and deposition are typical for the fluvial system on the East European plain. These waves have long periods, because Glacial-Interglacial-Glacial waves of climate change caused them. The Late Glacial event of high surface runoff is the global phenomenon first described by G. Dury (1965) and I. Volkov (1963).

The duration of this erosion episode was about 2-3 ka, but the rates of the erosion on the slopes and in the river valleys usually were 200-400 t km⁻² a⁻¹ and often reached to 800-1000 t km⁻² a⁻¹ in the central East European Plain (see Fig. 4). That is close the modern accelerated erosion from the same territory. In West and Central Europe the headwaters of a great number of streams were over-deepened during the Late Glacial (Starkel 1995). The same evolution of the fluvial relief took place on the Great Plains of North America (Arbogast et al. 2008), Atlantic Coastal Plain (Leigh 2006) and the Gulf of Mexico region (Leigh and Feeney 1995). In Australia, the Riverine Plain was formed by much larger rivers than the recent Murrumbidgee and Darling Rivers (Page et al. 2009). All fluvial systems on the lowlands were of erosional type

and were cleaned of a significant part of deposited sediments. These short events of catastrophic erosion have a periodicity of 100-120 ka (Vandenberghe 2003) and in spite of this the long-term delivery ratio in the lowland fluvial systems is close to one. After this short episode of catastrophic erosion the surface runoff decreased and sediment deposition occur in the huge eroded "negative" volume of the fluvial system. The average erosion rate on the slopes of the central East European Plain was not high (about 20-25 t km⁻² a year), but most of these sediments did not reached the river mouths. "Inherited" floodplains with the remnants of the large periglacial river channels are also widespread there (Sidorchuk 2003). The same is typical for all lowlands, which were affected by late-glacial catastrophic erosion. Lowlands were the territory of significant sediment sequestration, the fluvial systems along the main part of their length were of depositional type.

The morphological changes in the channels, caused by deposition, slowly led to the formation of a new equilibrium between erosion and sedimentation in the fluvial systems. Nevertheless, on the East European plain a dense network of dry valleys (the former late-glacial gullies) remain the sinks for sediments. The same was reported for the western European lowlands (Larsen et al. 2016). The duration of sediment deposition can last thousands of years.

This deposition in the fluvial systems on the East European Plain was refreshed by the accelerated soil erosion on the arable land, accompanied by the high rate of the lateral sediment input.

According to Dedkov and Mozzherin (1984), the mean specific sediment yield in the small lowland river basins in the forest-steppe of Europe and North America in pristine conditions was $\sim 17 \pm 30$ t km⁻². The mean

specific sediment yield from the river basins of the same type in the forest-steppe areas used for agriculture is $\sim 88 \pm 29$ t km⁻². In the steppe zone, the difference is even greater: 4.4 ± 3.1 and $\sim 100 \pm 40$ t km⁻², respectively. This is mainly the result of human activity and accelerated erosion on the bare slopes. The calculated volume of accelerated erosion on slopes in the river basins of the southern mega-slope of the East European Plain (2.2 10⁶ km²) during the period of intensive agriculture (the last 300-400 years) is about 76 10⁹ ton. The modern deposition of these sediments is concentrated in the upper reaches of the lowland fluvial systems and on the wide floodplains, "inherited" from the Late Glacial erosion event.

The main difference between the modern accelerated and Late Glacial erosion is the extent of the erosion cut. The main area of the accelerated erosion are the slopes used for agriculture, because of their low protection by vegetation cover. The main area of deposition of eroded soil is the net of dry valleys and small rivers. As the delivery ratio decreases with the basin area (Eq. 9), the deposition rate rapidly decreases along the river length. The Late Glacial short event of catastrophic erosion was caused both by scarce vegetation and by extreme surface runoff. Therefore, the whole fluvial system was the area of intensive erosion, with the deep incision of gullies on the slopes, and channels in the river valleys. These sediments were delivered to the sea basins, and distinct maximum of sedimentation rates was reported for the period 16-18 ka ago for example at the Black sea (Bahr et al. 2005).

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