THE VOLGA RIVER BASIN REPORT

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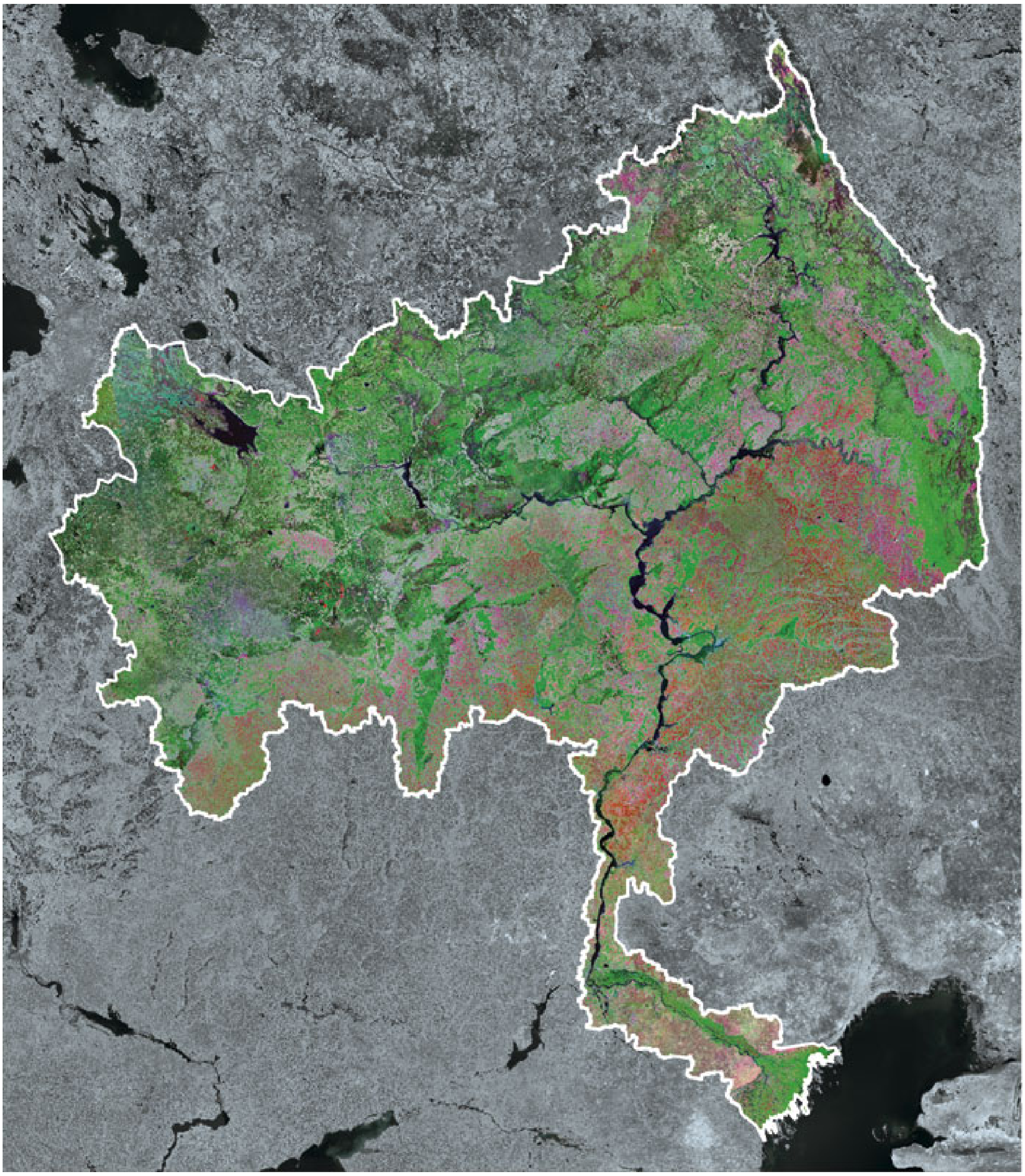

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Photo from front cover page from internet site http://www. Volga River Basin - UNEP-140EWA~Europe Publication Freshwater in Europe.htm

Introduction

The present Volga River Report has been compiled using available books and papers containing information about geographical characteristics of the Volga River Basin (Fig. 1) as well as results of investigations of fluvial sediment redistribution along geomorphic cascades from hillslopes to the Volga River mouth. It is clear that we have not been able to include all the existing data and results of studies concerning the sediment-associated problems within the Volga River Basin in this relatively short report. We therefore have decided to direct main attention to each of physiographic characteristics of the Volga River Basin in the Section 1 of the present report. It contains very helpful and important information for understanding fluvial sediment redistribution processes within the studied river basin as geographical unit. The following sections contain results of some temporal–spatial analysis of sediment fate in different components of geomorphic cascades of the Volga River Basin fluvial system.

Section 2 provides detailed analysis of soil erosion rates on hillslopes within different administrative units of the Volga River Basin paying particular attention to human-accelerated soil erosion on arable land. Dynamic of soil erosion rates during the period of intensive agriculture is also considered. Examples of the two case studies of sediment redistribution within small catchments located in different landscape zones are also included in Section 2.

Gully erosion as a very essential source of sediment in the basin is the main topic of Section 3. Results of quantitative evaluation of total volume of sediment produced by gully erosion within the Volga River Basin are presented. Analysis of gully growth dynamic for last centuries is provided. Regional specifics of the gully network development are also evaluated in Section 3. Results of detailed studies of small rivers and their basins are the main issue of the Section 4. Small rivers are the main part of each fluvial system. Hence we need to pay more attention to sediment redistribution within their basins. Examples of detailed studies of sediment deposition on small river floodplains are included. Results of bank erosion monitoring for some small rivers of the Volga River Basin are also included in that Section.

Figure 1. Location of the Volga river basin in the Eastern Europe, its main cities, rivers and general topography.

Quantitative assessment of sediment redistribution within the large river basin is the key issue for understanding of the fluvial system behavior as a whole. This is the topic of Section 5. Results of quantitative assessment of sediment redistribution within river basins of different sizes are presented. Most of them are based on empirical model calculations. Available field data from different key sites have confirmed correctness of model calculations in general. However some additional field studies still need to be carried out for improving the calculation results. Sediment transport and channel processes in large rivers of the Volga River Basin are the main topic of the Section 6. It is necessary to note that system of reservoirs constructed over the last 60 years along the main channel of the Volga River and its main tributary the Kama River has substantially changed sediment transport within the Volga River Basin main trunks. Information about reservoirs and other anthropogenic impacts on large rivers is also presented. In the end some information about the lower Volga River channel development is included in the Report.

SECTION 1

GENERAL CHARACTERISTICS OF THE VOLGA RIVER BASIN

1.1.The Volga River Basin topography and geology

The Volga River Basin is situated almost entirely within the Russian Plain (or Eastern European Plain), occupying about third of its total area. The basin area is 1380 thousand km^2. The Volga River length is about 3700 km. This is the only large river basin in Russia completely disconnected from the oceans. Main direction of the Volga River flow is also rather unusual for most of the World large river basins, because it flows from peripheral part towards central part of the Eurasian continent. The basin has a tree-like planform (Fig. 1.1) with typical dendritic pattern of hydrographic network (Fig.1.2). In the Volga River middle reaches its basin is almost isometric. In the lower reaches it becomes very narrow with main water divides being located as close as about 50 km from the main river channel.

The Volga River Basin is dominated by plain landscapes. Mountainous terrain occupies no more than 5% of the total basin area. Plain landscapes of the Volga River Basin are in turn represented by alternating uplands and lowlands of different origin. Up to 80% of the total basin area is characterized by elevation not exceeding 200 m above the sea level (a.s.l.). In uplands elevation can reach 300-400 m a.s.l.. Within the Ufimskoe Plateau and the Beleebeevskaya Upland territories local topography in some locations exceeds 400 m, while within the Kara-Tau Ridge it nearly reaches 700 m.

Main rivers of the Volga River Basin are incised to 50-200 m depth relatively to main interfluves in most parts of the basin area. In uplands incision depth of the main rivers can reach 150-200 m. However, dominant topography range between main interfluves and river valley bottoms is 50-100 m. Within waterlogged lowland areas of the Volga River upper reaches, Mecherskaya, Oksko-Donskaya and Prikaspiyskaya Lowlands incision depth of the main river valleys decreases significantly. That is a natural reason for poorly developed surface drainage and widespread waterlogging in the areas considered.

Figure 1.1. General map of the Volga river basin.

Generally even large-scale pattern of the Volga River Basin topography is determined by its location mainly within the Eastern European Platform area. The Eastern European Platform is characterized by long history of geological evolution and at present represents a tectonically stable continental-scale structural unit. Very important stage of the Eastern European Platform evolution for the Volga River Basin geological and geomorphic structure was formation of a vast tectonic depression – the so-called Moscow Syneclise – during the Early Carboniferous. By the end of the Hercynian orogeny that depression had already been infilled by sedimentary rocks, predominantly limestones, marls and dolomites. However, general directions of the Carboniferous strata dip towards the Moscow Syneclise central part has been preserved until present. It determines major large-scale topography features and spatial pattern of hydrographic network of the upper Volga River and Oka River Basins. The Carboniferous age sedimentary rocks are most widespread along the quasi-latitudinal line of the Volga River Basin western boundary, on gentle north-aspect slopes of the main water divide between the Volga and Don Rivers. In that area the Carboniferous sedimentary strata are represented mainly by calcareous rocks originated from marine sedimentation. In contrast, the eastern part of the Volga River Basin (on a left side of the Volga River valley from the Kostroma City down to the Samara City) is dominated by continental, lagoon, lagoon-marine, terrigenous marine and calcareous evaporite sedimentary rocks of the Permian and Triassic ages. At present those strata are widespread on a left side of the Volga River valley only in its middle reach. Presence of such specific bedrock types effects chemical composition of groundwater, widespread karst processes and xerophyication of landscapes.

Figure 1.2. The Volga River Basin hydrographic network structure.

Clayey sedimentary strata are also widespread within the Moscow Syneclise. Those were deposited mainly during the Jurassic period marine transgression. Another transgression took place in the Cretaceous period, resulting in deposition of predominantly loose sands or weakly lithified sandstones. The Cretaceous age deposits represent the surface material mainly in basins of small right tributaries of the Volga and Oka Rivers. Marine deposits of the Cenozoic age are found only in the southern part of the Volga River Basin. Those are represented by clays, sands and more consolidated siliciclastic deposits.

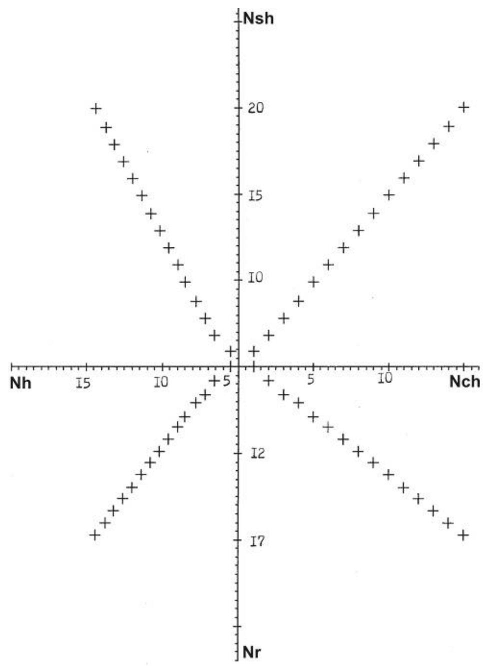

Figure 1.3. Coaxial relationships between stream orders in different coding systems: Nh – Horton, Nsh – Shaidegger, Nch – Chernyh, Nr – Rzhanitsyn.

1.2. Structure of the Volga River Basin hydrographic network

According to the Hortonian dichotomic stream order system, the Volga River has the maximum order of 13 downstream from its confluence with its largest tributary, the Kama River. The Volga River order in other stream order systems can be determined from the diagram shown in Fig. 1.3. The Volga River Basin area is by 1.5-2.0 times lower than the typical average value of basin area for 13th Hortonian order rivers (Simonov et al, 1998). This discrepancy can be explained by comparatively larger density of hydrographic network within the basin. Large number of tributaries determines rapid downstream increase of the main river Hortonian order. There are totally about 830 7^{th} order rivers, about 250 8^{th} order rivers and 60 9^{th} order rivers within the Volga River Basin. More than 40% of the basin area is drained by rivers of 7^{th} Hortonian order and lower. Typical length of such watercourses does not exceed 50 km. There is an anomalously high number of 8^{th} order and 9^{th} order rivers in the Volga River Basin hydrographic network structure. Rivers of the Hortonian order of 10 (N=10) and higher typically have length exceeding 200 km. Such watercourses are commonly considered as medium and large rivers, while those with N<10 can be regarded as small rivers.

1.3. Geomorphic subdivision of the Volga River Basin into typical sub-basins

Joint analysis of the Volga River Basin topography, geology and spatial structure of its hydrographic network allows its subdivision into few typical sub-basins separated by boundaries of the 11-12^{th} Hortonian order tributary basins (Table 1.1):

1. Right (western) part of the lower Volga River Basin. Rivers of the territory downstream from the Kama River confluence flow into the Volga River having N=13.
2. Right (western) part of the middle Volga River Basin. Rivers of the territory between confluences of the Oka and Kama Rivers flow into the Volga River having N=12.
3. The Oka River Basin (N=11).
4. The upper Volga River Basin (upstream from the Oka River confluence) with N=11.
5. Left (eastern) part of the middle Volga River Basin. Rivers of the territory between confluences of the Oka and Kama Rivers flow into the Volga River having N=12.
6. Right (western) part of the lower Kama River Basin. Rivers of the territory downstream from the Belaya River confluence flow into the Kama River having N=12.

7. The Kama River Basin upstream from the Belaya River confluence (N=11).
8. The Belaya River Basin (N=11).
9. Left (eastern) part of the lower Kama River Basin. Rivers of the territory downstream from the Belaya River confluence flow into the Kama River having N=12.
10. Left (eastern) part of the lower Volga River Basin. Rivers of the territory downstream from the Kama River confluence flow into the Volga River having N=13.

Table 1.1. Characteristics of sub-basins distinguished within the Volga River Basin.

No	Characteristics of rivers	Numbers of regions and correspondent values of characteristics									
		I	II	III	IV	V	VI	VII	VIII	IX	X
1	Number of 9th order rivers	2	5	8	6	1	7	12	8	2	7
2	Average area of 9th order river basins (F), 10^3 km^2	29.4	12.8	12.1	21.4	58.4	8.8	9.8	11.0	11.5	7.5
3	Average length of 9th order rivers (L), km	42	110	85	82	384	29	88	107	60	55
4	Ratio of drainage area to main river length for 9th order drainage basins (F/L)	21.6	20.6	21.8	40.4	32.3	18.9	26.4	24.3	63.4	25.1
5	Percentage of basins with increased area comparatively to 'normal':										
	N=7	40	60	35	17	100	40	25	50	0	29
	N=8	60	20	15	33	0	60	17	12	0	13
	N=9	0	0	25	33	0	0	17	12	50	29
	'normal'	0	20	25	17	0	0	41	26	50	29
6	Percentage of basins with increased length comparatively to 'normal':										
	N=7	40	50	33	50	100	40	30	26	100	46
	N=8	60	17	11	38	0	50	15	12	0	36
	N=9	0	33	23	12	0	0	60	50	0	18
	'normal'	0	0	33	0	0	10	0	12	0	0
7	Ratio of drainage area width to its length	0.62	0.60	0.59	0.71	0.35	1.22	0.64	0.46	0.42	0.51

It is obvious that environmental conditions at the main trunks of the Volga River Basin hydrographic network are largely dependent upon situation in small tributary rivers and their catchments. Spatial scale of this influence is mainly associated with morphometric and lithological characteristics of the 9th Hortonian order rivers basins (Table 1.1). In the Volga River Basin those typically have relatively elongated planforms, larger areas, main river lengths and slightly lower average long profile gradients comparatively to the 'normal'. In a contrary, tributaries of 9th order rivers under such circumstances are characterized by shorter lengths and higher average long profile gradients comparatively to the ’normal’. As a result, network of watercourses with $N \leq 8$ in the Volga River Basin responds to variations of flows of matter and energy as the so-called ***basins-ejectors***. This term is used in Russian fluvial geomorphology to characterize a river basin that exports more sediment through its outlet than is delivered into it by its smaller tributaries, as a result of dominance of erosion and sediment transport and absence of significant sediment sinks within it. The more such tributary basins-ejectors is present in a larger river basin the faster changes of sediment production in their catchments will affect the main river. That is also true for changes of runoff and water quality caused by human impact on natural landscapes of small valleys and their catchments.

There are 5 principal factors influencing transformations of flows of matter and energy during transport through catchments comprising a 9^{th} Hortonian order river basin. Firstly, important control is exerted by the drainage basin planform. The more elongated is it, the larger is negative effect of vegetation cover disturbance within a basin. Loss of natural vegetation cover causes acceleration of surface erosion rates. Sediments mobilized by hillslope erosion processes are the most rapidly transported to a 9^{th} order basin outlet in elongated basins. Rates of sediment transport through a basin are also to a certain degree controlled by its ***bifurcation index***, which is the ratio of a number of rivers of the Hortonian order N to that of N+1. The higher is the bifurcation index, the more individual smaller tributaries can affect environmental conditions of the main river.

Lengths of small watercourses is also an important factor influencing conditions of matter and energy flows, which differ on rivers of the same Hortonian order having different lengths. In general, longer (comparatively to the ‘normal’) rivers have lower average long profile gradients. Relative decrease of long profile gradients, in turn, results in lower rates of transport of sediments and associated pollutants and, in the opposite, their more intensive redeposition in alluvial (or other) sediments sinks. Ratio of a tributary drainage basin area to length of a main river section it affects is termed ***the potential specific impact*** (***PSI***). It characterizes possible environmental pressure on a main river section considered caused by negative environmental changes in a tributary basin. On the other hand, it can also illustrate potential contribution of a tributary basin in dilution of polluted flow of a main river providing that a tributary itself is characterized by high water quality. Higher values of the PSI and a main river basin area determine lower susceptibility of a main river sections to negative impacts of environmental changes in tributary basins.

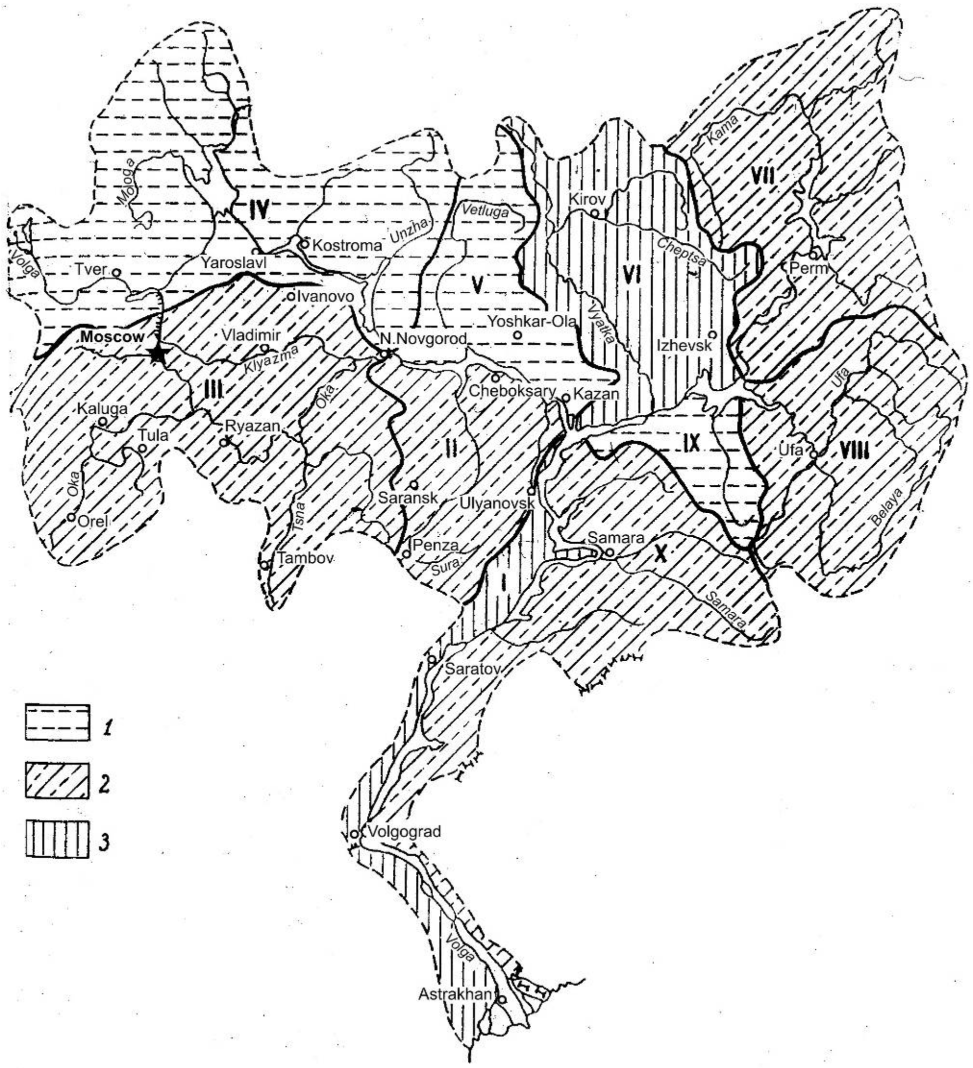

Figure 1.4. Sub-basins distinguished within the Volga River Basin classified according to the degree of environmental resistance of small rivers: 1) low resistance; 2) medium resistance; 3) high resistance. For numbers of sub-basins see the text above and Tables 1.1 and 1.2.

Data presented in Table 1.1 make it possible to compare a degree of resistance of small rivers ecosystems between the sub-basins distinguished within the Volga River Basin associated with differences of their geology, geomorphology and structure of hydrographic network. In order to summarize that information for spatial analysis and visual cartographic presentation (Fig. 1.4), it has been necessary to make a semi-qualitative grading according to specially developed scale of scores (Table 1.2). The score 3 corresponds to characteristics rendering the sub-basins to be considered as territories with the least resistant small river ecosystems. The score 2 marks the sub-basins with moderate degree of resistance of small river ecosystems. The score 1 is given to sub-basins with small river ecosystems characterized by relatively high resistance to potential or existing changes of mater and energy flows caused by either natural processes or anthropogenic activities.

Table 1.2. Qualitative evaluation of environmental resistance of 9th Hotonian order river basins in previously distinguished sub-basins of the Volga River Basin.

No.	Name of sub-basin	Parameters of the river environmental resistance				
		Basin shape	***Bifurcation index***	River length	***PSI***	Basin area
1	Western part of the lower Volga Basin	2	1	2	2	1
2	Western part of the middle Volga Basin	2	2	3	2	2
3	The Oka Basin	2	2	2	22	2
4	The upper Volga Basin	1	2	3	3	3
5	Eastern part of the middle Volga Basin	3	3	2	2	3
6	Western part of the lower Kama Basin	1	2	1	1	2
7	The Kama Basin upstream from the Belaya River mouth	1	2	3	2	2
8	The Belaya Basin	2	2	2	2	2
9	Eastern part of the lower Kama Basin	2	3	2	3	2
10	Eastern part of the lower Volga Basin	1	2	2	2	2

The Fig. 1.4 shows that the Volga River Basin sub-basins distinguished notably differ in terms of potential environmental resistance of the 9th Hortonian order small river basins associated with geological, geomorphological and hydrological factors. Highest susceptibility of small rivers to negative environmental changes is observed in areas of the middle Volga River Basin left (eastern) part, upper Volga Basin and left (eastern) part of the lower Kama River Basin. Lowest degree of potential transformations of environmental conditions in small river ecosystems characterizes areas of right (western) parts of the lower Volga and lower Kama Basins. Obviously, in cases of potential significant natural or anthropogenic environmental changes, the most rapid negative effects on small river ecosystems will be observed in the most susceptible parts of the Volga Basin listed above.

1.4. Climate of the Volga River Basin

Most of the Volga River Basin is located within the so-called ***Atlantic-continental European climatic region*** (Myachkova, 1983). Distinction of this region can be explained by the fact that, in addition to major influence of dominant eastward drift of air masses from the northern Atlantic Ocean, this area (especially its more southern parts) is also affected by continental air masses from the Europe and Asia (particularly from the southern Europe and the Kazakhstan) as well as locally formed air masses. As the sun radiation input increases southward, there also grows a recurrence frequency of anticyclonic weather conditions. That, in turn, leads to the general increase of continentality of the climatic conditions, dramatic decrease of average annual precipitation (Table 1.3) and resulting presence of semi-desert and even desert landscapes in the Astrakhan Region and along the Caspian Sea shores (Isaev & Paramonov, 1998).

The Volga River Basin can be subdivided into three parts according to the general climatic background characteristics: northern (from northern margins down approximately to the Saratov City latitude), central (approximately from the Saratov City latitude to the Volgograd City latitude) and southern (approximately from the Volgograd City latitude to southern margins along the Caspian Sea shores and the Kazakhstan border). Boundaries of these three zones generally coincide with those between forest and forest-steppe landscapes in upper and middle parts of the basin and with those between steppe and semi-desert landscapes in its lower part. There are also intrazonal local climatic provinces such as the Volga-Ahtuba climatic province (Physiographic…, 1961).

Average annual air temperature changes from 3.0°C at the north up to 9.0°C at the south. The degree of climatic continentality rises southward from 30% to 80%, while average annual precipitation falls down from 750 mm to 150 mm. Average depth of snow cover decreases from 60 cm at the north to about 3 cm at the south, and duration of its persistence – from 240 to 30 days. Periods with air temperature above 0°C last for 110-180 days (in southern and northern parts of the basin respectively), vegetational periods – 150-220 days. Despite the significantly longer vegetational period, total productivity of agrolandscapes for actual atmospheric regime in lower parts of the Volga River Basin is by 2.0-2.5 times lower than in its upper and middle parts (Table 1.3) because of moisture deficit.

Table 1.3.Average air temperature (°C) and precipitation (mm) in January (I), July (VII) and annual; potential atmospheric pollution (PAP), total productivity of agrolandscapes (t/ha) for actual (TPa) and optimal (TPo) atmospheric regimes in selected regional administrative centers of the Volga River basin.

Location	Average air temperature			Average precipitation			PAP	TPa	TPo*
	I	VII	Year	I	VII	Year			
Tver	-10.4	17.2	3.3	36	83	612	2.5	5.2	12.3
Yaroslavl	-11.6	17.2	2.7	32	69	546	2.6	5.8	14.6
Nizhniy Novgorod	-12.0	18.1	3.1	31	71	527	2.7	5.2	13.7
Kazan	-12.8	20.0	3.6	27	58	459	2.8	5.2	13.7
Samara	-13.8	20.7	3.8	33	50	449	2.8	6.6	14.9
Saratov	-12.7	20.8	5.3	27	43	414	2.9	5.2	13.7
Volgograd	-9.5	24.3	6.8	24	30	344	3.0	2.8	15.7
Astrakhan	-6.8	25.3	9.4	13	16	182	3.2	2.2	16.9

**Values of TPa and TPo taken from (Sirotenko & Abashina, 1992).*

The following important features of the climatic circulation influencing the potential atmospheric pollution must be noted. Routes of cyclones coming by different trajectories are often crossed in the upper part of the Volga River Basin. Recurrence frequency of anticyclonic weather conditions leading to atmospheric inversions and near-surface air stagnation is by 2-3 times higher in southern parts of the basin (to the south from the Volgograd City) than further northward. Therefore, evaluation of the potential atmospheric pollution from surface sources provided in Table 1.3 shows values from a category of increased and high potential (*PAP*>3.0) for lower parts of the basin and values from a category of moderate potential (*PAP*=2.5-2.9) for its upper parts (Climatic conditions…, 1983).

Transport of atmospheric pollutants is mostly associated with large-scale movements of air masses. Therefore, wind direction and velocity not only at land surface, but also within the 1.5 km thick mixture layer of the troposphere is an important control for redistribution of atmospheric pollutants between river basins. In the Volga River Basin western and south-western winds, i.e. eastward drift of Atlantic air masses dominate the upper and middle parts for most of the year. Rates of the eastward drift are commonly such that pollutants derived from the Western Europe reach the Volga River Basin in 2-3 days (Paramonov, 1994). In southern parts of the basin, however, dominant wind direction changes, making possible the occurrence of natural atmospheric pollution by dust from semi-desert or desert landscapes. For example, in area nearby the Baskunchak salt lake dust blows can be observed during up to 50-60 days per year.

1.5. Hydrology of the Volga River Basin

The Volga River is the largest (by average annual discharge) river of the Europe. Its hydrological characteristics are studied in details. Highest average annual discharge is observed near the Volgograd City (8380 m^3/s). Downstream increase of average annual discharge along the Volga River until that point is almost directly proportional to increase of the drainage area. Maximum contribution is given by the two largest tributaries – the Kama River from the left (4100 m^3/s) and the Oka River from the right (1170 m^3/s). Downstream from the Volgograd City to the delta outlet the river discharge decreased by 2% even before its artificial regulation by large dams and reservoirs. At present the discharge is decreased by almost 10% already nearby the Volgograd City.

Spring snowmelt waters contribute most into the Volga River annual discharge. In different parts of the river basin its contribution varies from 50% to 65%, being about 60% on average for the entire river basin. Groundwater source provides about 30% of annual flow, rainfall – about 10%. As a result of that proportion, under natural conditions the Volga River regime was characterized by sharp and high spring snowmelt flood and low-water periods in summer and winter. Influence of artificial regulations by construction of large dams and reservoirs resulted in decrease of spring snowmelt flood discharge and subsequent slight increase of discharges during low-water periods. In general, annual amplitude of water levels in the Volga River has also decreased substantially. Under natural conditions annual range of water levels in the upper Volga River varied on average from 4 to 8 m, in the middle – from 10 to 11 m, and in the lower – up to 5 m. At present it does not exceed 5-6 m even in the middle reach.

The Volga River Basin water balance general characteristics correspond to its location mostly within the moderate humid climatic belt. Average annual precipitation for the entire basin is 662 mm, while runoff is 179 mm. Average runoff coefficient calculated for the entire Volga River basin is equal to 27%.

The entire length of the Volga River can be affected by ice cover formation in winter. Under natural conditions stable ice formation commonly occurred in November over a period of 10 days on average. Ice cover persisted on average for 120-140 days. After creation of reservoirs ice began to form 3-5 days earlier, and period of its presence also increased by a few days. Maximum ice cover thickness in reservoirs is also larger than in natural river channel. Over the last 10-15 years ice cover persistence and thickness has become notably lower due to generally warmer winter weather conditions. However, it is believed that observations are not long enough at the moment to determine whether it is a long-term tendency or a short-term climatic fluctuation only.

Under natural conditions, the Volga River annually exported into the Caspian Sea large volumes of transported matter, approximately equal to 26×10^6 t of suspended sediment and 45×10^6 t of dissolved materials. Respective area-specific yields are 19 t/km^2/year for suspended sediment and 33 t/km^2/year for dissolved materials. At present sediment entrapment by large reservoirs has resulted in decrease of the suspended sediment yield at the basin outlet to 8×10^6 t/year. At the same time, general increase of water pollution caused dramatic increase in dissolved material yield to $65\text{-}70\times10^6$ t/year.

Suspended sediment yield is mainly formed in agriculturally developed drainage basins of the forest-steppe and steppe zones where local area-specific suspended sediment yield can be as high as 100-200 t/km^2/year and even more, with average values in a range of 20-40 t/km^2/year. In drainage basins of the forest zone less affected by agriculture area-specific suspended sediment yields rarely exceed 5-10 t/km^2/year.

Natural flow of dissolved materials is largely originated from areas where lithological conditions (presence of easily dissolved sulfate and calcareous bedrock close to the surface) promote karst development. Such areas in the Oka, middle Volga, left part of the Kama River basins are characterized by local area-specific yields of dissolved materials up to 150-300 t/km^2/year. In other parts of the Volga River Basin this value generally varies from 10 to 20 t/km^2/year.

1.6. Soil cover of the Volga River Basin

Water quality conditions in rivers of the Volga Basin are substantially affected by magnitude and frequency of various surface processes in the drainage basin areas. Main fluxes of matter (water runoff, sediment flux, dissolved matter flux, pollutants, etc.) are formed on hillslopes of small catchments, from where they reach small streams and influence background water quality conditions. Characteristics of these matter fluxes depend to the large extent on soil formation processes and soil cover conditions, as different natural settings determine specific types of migration of water and solutes in soil profiles and along elementary slopes. Each soil type is characterized by specific characteristics of acidity. That in turn affects the mobility of different chemical elements and substances, some of which can be detrimental or even toxic for biotic elements of aquatic ecosystems when reaching small streams or rivers. Obviously, soils of different types are also characterized by various content and composition of humus. Together with local topography, soil grain size composition, vegetation cover, type and degree of human impact on natural landscape that influences intensity of surface erosion processes. Active surface erosion delivers additional volumes of dominantly suspended sediment and associated pollutants adsorbed on sediment particles from eroded hillslopes into rivers. Eventually it results not only in negative change of geomorphic conditions in river channels, but also in their chemical pollution.

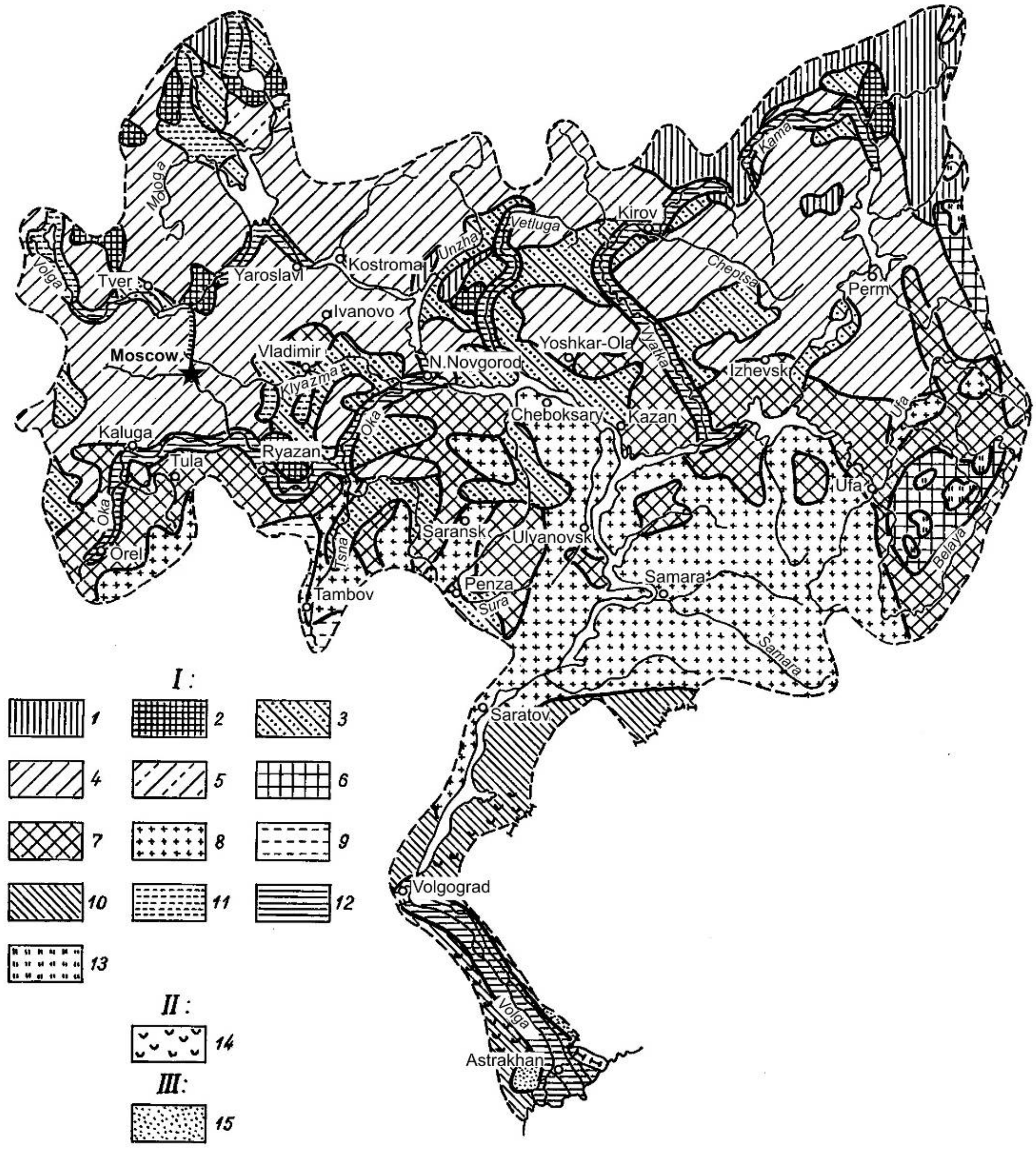

Figure 1.5. Schematic map of the Volga River Basin soil cover. Soil types: 1) ***podzolic***; 2) ***gley podzolic***; 3) ***podzols*** and ***iron-reach soddy podzolic soils***; 4) ***soddy podzolic soils***; 5) ***initially carbonate soddy podzolic soils***; 6) ***brown forest soils***; 7) ***gray forest soils***; 8) ***chernozem soils***; 9) ***dark humus soils***; 10) ***chestnut soils***; 11) ***peat*** and ***peat gley soils***; 12) ***alluvial soils***; 13) ***mountainous dark humus soils***. Soil complexes: 14) ***solonetz soils***. Non-soil surface materials: 15) sands.

The Volga River Basin area can be subdivided into a wide range of zones, subzones and provinces according to dominant soil types (Gavrilova & Bogdanova, 1998). Figure 1.5 shows spatial distribution of main soil types within the territory. The most widespread soil types within the Volga River Basin are those comprising zone of ***gray forest soils***[1] and subzone of ***soddy podzolic soils***.

Typical ***podzolic soils*** occupy well-drained upland interfluves mainly in western and eastern parts of the subzone. In lowlands of its central part ***peat soils*** and ***peaty gley podzolic soils*** are widespread. Most of the soil subtypes within the subzone of ***soddy podzolic soils*** are of limited use for agricultural purposes. Agricultural land occupies separated patches only, total percentage of arable land does not exceed 10%. Arable ***podzolic soils*** are characterized by rapid destruction of weak structure of natural topsoil horizons, causing lumping in wet and surface crusting in dry conditions. On the other hand, ***iron-reach soddy podzolic soils*** has long proved to be the most intensively affected by human activities. At present up to 30-50% of this soil subtype area is cultivated. Near large settlements and industrial centers this value can reach 70-80%. Long-term cultivation has profoundly changed soil profile morphology, leading to destruction or deterioration of the plough horizon structure. On the other hand, it has also had some positive effect, by decreasing rates of ***podzolization*** (leaching) processes.

Typical ***podzolic soils*** are characterized by sharp morphological differentiation of the soil profile and associated contrast chemical properties. There are two morphologically very distinctive diagnostic soil horizons: a bleached ***podzolic*** (eluvial) horizon of lighter texture and a darken compacted illuvial horizon with generally more clayey texture and distinctive compound subangular blocky or prismatic structure with prominent illuviation coatings on ped surfaces. ***Podzolic soils*** are characterized by constantly penetrating water regime. Presence of peaty litter or mosses with high water-absorbing capacity on top of the soil profile causes periodical waterlogging and subsequent gleying of upper soil horizons. In spring there is usually a

[1] Here and further in the text soil taxonomy terms are taken from the Russian soil classification system (Russian soil…, 2001).

temporary upper groundwater horizon forming within the eluvial and above the illuvial horizon. Periodical presence of reductive chemical conditions increases mobility of iron-organic and other metal-organic compounds in the soil profile, which migrate in forms of sols and chelates. Relatively high stability of the latter results in high probability of their transfer into surface runoff or groundwaters from the soil solutes. As a result, chemical composition of small river waters in the taiga forest subzone is characterized by high content of iron-organic compounds giving waters dark brownish stain.

Relatively high infiltration capacity of loamy and clayey parent materials on which the soils are formed together with their relatively low permeability determine slow filtration of soil solutes. Main passages for soil solutes movement in compacted and clayey illuvial horizons are relatively large vertical cracks, pores, roots and routes of earthworms. Eluviation processes are commonly more active and concentrated around those more permeable pathways. Upper horizons of typical podzolic soils are characterized by very acid conditions (pH=3.5-4.5), high exchange and hydrolytic acidity. However, degree of the soil solutes reaction acidity usually decreases down the soil profile. ***Podzolic soils*** commonly have low humus content (<2%) dominated by fulvic acids. Properties described determine mobility of calcium compounds, which usually become transported away from the soil profile and influence chemical composition of surface waters. The latter, together with high organic compound content, usually contain high concentrations of calcium bicarbonates and silica dioxide.

The ***iron-illuvial humus podzols*** are characterized by a presence of a relatively thin humus-illuvial horizon where relatively mobile aluminum fulvates are accumulated. Fulvic humus content in that is 1-3%. Soil horizons are often characterized by irregular wedged (***glossic***) appearance of their boundaries. Sometimes soil horizons are connected with upper temporary groundwater horizon or other groundwater horizons, becoming within-soil drains for soil solutes transport with high content of iron-organic compounds. Specific morphology of the soil profile is observed for the subtype of ***humus-illuvial podzols***. It consists of thick peaty layer of litter underlain by strongly bleached eluvial horizon and relatively thick humus-illuvial horizon situated just above the groundwater table. The latter horizon is loose in wet conditions, however becomes very dense and compacted into large blocks upon drying out. That results in additional increase of waterlogging of relatively flat and poorly drained catchments of small rivers in northern and middle taiga forest subzones (Karavaeva, 1982). Humus content in humus-illuvial horizon formed on relatively poor quartz sands does not exceed 2-3%. However, on other parent material with high base content it can reach 5-8%. Specific feature of chemistry of the ***humus-illuvial podzols*** is that only Al_2O_3-humic compounds are accumulated in the illuvial horizon, while more mobile iron-organics are moved further into groundwaters and, eventually, rivers.

The process of formation of ***contacted-eluvial-gleyic podzolic soils*** on contacts between sands or loamy sands with more clayey parent material layers is associated with periodic waterlogging along the geological boundary. It results in periodical occurrence of local reductive conditions of soil solutes with mobilization and partial export of iron. General reaction of soil solutes is however still acid. Soil profiles are impoverished in clay fraction content and relatively enriched in mobile forms of iron. Infiltration capacity and permeability of ***podzolic soils*** are generally low. Substantial proportion of precipitated moisture eventually contributes into surface runoff formation. Dominance of silt fractions in topsoil texture renders all subtypes of ***podzolic soils*** to be susceptible to surface erosion processes.

The ***soddy podzolic soils*** are formed under conditions of constantly penetrating water regime with relatively short period of drying out. Humus accumulation processes become the most typical for this soil subtype in addition to ***podzolization*** (eluviation). Humus content in the topsoil layer of the ***soddy podzolic soils*** increases to 3-4%, while reaction becomes less acid (pH varies from 4.0-4.5 in the topsoil to 6.0-7.0 in the subsoil horizons) than that in the typical ***podzolic soils***. Transfer of iron-organic compounds away from the soil profile also decreases.

On sandy parent material on autonomous landscape positions (on interfluves) ***iron-rich soddy podzolic soils*** are formed. These are characterized by distinctive humus horizon and weakly compacted illuvial horizon. Spatial structure of soil cover retains major catena (toposequence) and lithogenic differentiations, but not as prominent as in more northern soil subtypes. For example, typical toposequence on loamy parent material consists of ***soddy podzolic soils*** on interfluves and upper hillslopes, substituted downslope by ***gley soddy podzolic*** and ***peaty gley podzolic soils*** at hillslope toes and in depressions. General degree of waterlogging in small river catchments gradually decreases southward, although some blanket peat bogs are still present. In turn, typical toposequence on sandy parent material is represented by ***iron-illuvial soddy podzolic soils*** on interfluves and upper hillslopes, substituted downslope by ***humus-illuvial podzols*** in hydromorphic (low slope) landscape positions. Sandur plains are in most cases heavily waterlogged and therefore occupied by ***peaty soils*** typical for blanket, transitional or eutrophic bogs.

Zone of ***gray forest soils*** is stretched in quasi-latitudinal direction as a relatively narrow belt disconnected at places by tongue-shaped expansions of ***soddy podzolic soils*** from the north and ***chernozem soils*** from the south. ***Gray forest soils*** can be divided into three main subtypes: ***typical gray forest soils***, ***dark-gray forest soils*** and ***light-gray forest soils*** (Russian soil…, 2001), differing mainly in horizon thickness and humus content. Central subtype of ***typical gray forest soils*** is the most common within the Volga River Basin territory, while the others two occupy relatively smaller areas. The ***gray forest soils*** are typically formed on parent materials represented by the so-called cover loams or loessy loams. These soils are intensively used for agricultural purposes. That, even under conditions of relatively low topography, results in widespread surface erosion processes. Within the ***gray forest soil*** belt there are also significant areas occupied by ***soddy podzolic soils*** on alluvial and glaciofluvial sands in wide quasi-longitudinal valleys of the Tsna, Sura and Moksha Rivers.

Southward decrease of available moisture determines periodically penetrating water regime of the ***gray forest soils***. ***Gray forest soils*** have prominently and sharply differentiated profile. Its thickness exceeds that for all the other forest soil types. Vertical profile structure reflects a combination of the dominant soil formation processes: eluvial-illuvial differentiation and active humus accumulation. All horizons of the ***gray forest soils*** are characterized under natural conditions by well developed and stable structure. Migration of calcium humates down the soil profile with accumulation in the subsoil horizons is a typical specific feature of the ***gray forest soils***. Short-term waterlogging may occur in spring above the illuvial horizon, causing the transfer of mobile iron in soil solutes. Humus content in the ***gray forest soils*** topsoil horizon is commonly 4-5% with large amount of humic acids in it. Reaction of soil solutes is either slightly acid (in the topsoil) or slightly alkaline (in the subsoil). Eastward increase of the climatic continentality causes typical thickness of the soil profile to decrease in the same direction, while humus content increases.

Relatively low elevation of the Ural Mountains limits development of vertical soil zonation to formation of ***mountainous dark-humus soils*** on the relatively highest summits. The northern Ural Mountains are dominated by the ***raw-humus burozem soils***, with some areas occupied by ***podzolic soils***. The middle Ural Mountains are commonly occupied by ***soddy podzolic soils*** with ***raw-humus burozem soils*** on highest hilltops only. The southern Ural Mountains have ***mountainous dark-humus soils*** on the highest summits substituted by ***raw-humus burozem soils*** on most of the slopes. Gray forest soils occupy lower hilly piedmonts in combination with some expansions of ***dark-gray forest*** or ***leached chernozem soils*** in wide intermountain valleys.

The Oksko-Donskaya Lowland river basins are dominated by ***leached chernozem soils***, less frequently – ***typical chernozem soils*** and various subtypes of ***dark-humus soils*** (on the Tsna River valley left side terraces). There are also significant areas occupied by ***gray*** and ***dark-gray forest soils*** under presently remaining forests. Generally mosaic spatial pattern of the soil cover is made even more complex by a presence of sandy terraces with pine forests on ***soddy podzolic sandy soils*** along the Sura and Tsna River valleys. The ***dark-humus soils*** are characterized by comparatively thick (about 60 cm) upper humus horizon with prominent and stable granular structure and high humus content (8-10%). Lower parts of these soil profiles are affected by gleying process and have heavy texture.

In relatively elevated areas of the Privolzkaya and Obchiy Syrt Uplands ***leached chernozem soils*** occupy topographic depressions. These soils are usually found in complex spatial combinations with ***gray*** and ***dark-gray forest soils***. Hilltops and upper slopes composed of sandstones or more loose bedrock are dominated by дерново-слабоподзолистые ***soddy slightly podzolic soils*** or дерново-лесные ***soddy forest soils***. More gradual midslopes are often occupied by ***gray*** and ***dark-gray forest soils***. Outcrops of calcareous bedrock are occupied by ***thin gravelly chernozems*** and ***secondary carbonate chernozems***. Sandy terraces of the Volga River valley are occupied by ***low-humus leached chernozem soils*** and sandy soils of pine forests. ***Thin gravelly chernozems*** and ***initially carbonate chernozems*** dominate areas with calcareous bedrock outcrops within the Obchiy Syrt and Bugulminsko-Belebeevskaya Uplands. ***leached chernozem soils*** of the Volga River Basin eastern part formed on loessy loams can be characterized as thick, as humus content in those is 10-12%, being equal to that of the typical chernozem soils. The latter occupy areas along the Volga River valley. ***Typical chernozems*** are commonly formed on the so-called ***syrt clays*** (marine clays with salt content) and have slightly thinner humic horizon (45-65 cm) with humus content about 7-9%. Within the subzone of the ***chernozem soils*** average depth of water penetration decreases southward and secondary carbonates begin to penetrate the lower part of humic horizon from below. ***Southern chernozems*** are characterized by even higher presence of secondary carbonate horizon, while lower subsoil at depth of annual water penetration has secondary gypsum accumulations. These soil subtypes are sometimes slightly saline (soluble soils in upper 100 cm of the soil profile) or ***solonetzic*** (indications of alkalinity in the humic horizon and soluble soils in the lower subsoil).

Soluble soils composition is commonly dominated by sodium sulfates, also sodium and calcium chlorides and abundant secondary gypsum accumulations (Rode & Smirnov, 1972). Contents of those sharply increase at depth of about 1.8-2.0 m. Humus content in the ***southern chernozems*** is decreased to 6%.

Usually high percentage of gravel inclusions in ***ordinary chernozem soils*** limits their agricultural use. Therefore many of those have retained their natural high humus content of up to 10-12%. In topographic depressions ***dark-humus soils*** are formed. Largest area occupied by those is located in the Samara and Bolshaya Kinel River valleys in their lower parts. In areas occupied generally by ***southern chernozems***, there is actually high percentage occupied by ***solonetzic chernozems*** and ***dark solonetz soils***. The ***steppe chernozem soils*** subtype occupy limited area of the eastern part of the Volga River Basin on interfluves between the Bolshaya Kinel, Samara and Bolshoy Irgiz Rivers. Within the lowland part of the eastern Volga River Basin ***ordinary chernozem soils*** occupy more or less homogenous areas. Further eastward within the upland part of the eastern Volga River Basin soil cover spatial pattern is more complex. There are many limited areas of ***thin chernozems*** with ***initially carbonate chernozems*** on solid carbonate bedrock outcrops. Lowlands of eastern part of the Volga River Basin are characterized by a very high percentage of arable land, while in its upland parts it is more moderate (30-50%). Relatively long history of anthropogenic impact on soils of the ***chernozem*** zone, mainly intensive cultivation (up to 300-400 years) has resulted in serious soil degradation. Its main negative consequences are dehumification (to 2-3% humus content) and loss of the topsoil structure, both decreasing soil resistance to erosion by water.

Leached and ***typical chernozem soils*** of the Volga River Basin are formed under conditions of periodically penetrating water regime, while ***ordinary*** and ***southern chernozem soils*** – under conditions of constantly non-penetrating water regime. There are serious changes of water regime comparatively to the natural conditions observed in the arable ***chernozem soils***. Those are associated with increase seasonal contrasts and more humid conditions (Kokovina &

Lebedeva, 1986). It is the water regime that determines thickness of humic horizons, depth and morphology of secondary carbonate horizon, presence and depth of saline horizon. Water regime of ***chernozem soils*** is characterized by return upward suction of soil moisture up the soil profile towards the root layer during the active vegetation development seasons, which compensate loss of moisture due to evapotranspiration and governs associated fluxes of a number of important chemical elements and compounds.

The ***chernozem soils*** are naturally characterized by highest chemical stability of humic substances represented by the most stable and least mobile calcium humates of the most complex structure. Abundance of organic colloids and their stable coagulation lead to formation of very stable granular structure creating the most favorable water and air regime for grassy vegetation. Typical natural humus content in ***chernozem soils*** varies from 6% to 10% (rarely up to 12%). In ***typical*** and ***common chernozems*** there is a pronounced spatial trend of decreasing thickness of the humic horizon from west to east, while humus content increase in the same direction. Chernozems are characterized by high base saturation and high cation exchange capacity. Soil reaction is commonly close to neutral in the topsoil and close to alkaline in the subsoil.

The ***chestnut soils*** zone within the Volga River Basin is represented by fragments in eastern part on interfluves of the Ural and Bolshoy Irgiz Rivers. Outer southern parts of the Obchiy Syrt Upland and other uplands of the eastern part of the basin are covered by ***chestnut*** and ***dark chestnut soils*** on slopes composed of salty clays (***syrt clays***). Lower landscape positions in valley bottoms and on terraces of small intermittent streams are dominated by complex soil cover including hydromorphic ***solonetz*** and ***dark-humus soils***. ***Light chestnut soils*** form complexes with ***solonetz*** soils within the Pricaspian Lowland northern part. Zonal ***light chestnut soils*** are rarely found in homogenous areas and commonly comprise complexes with other soils. Despite the generally unfavorable water regime and physical properties, ***chestnut soils*** are widely used for agricultural purposes, most commonly with irrigation. That has caused substantial degradation of these soils. Its most important consequences are secondary salting and increased ***solonetzicity***. Percentage of arable land in zone of the ***chestnut soils*** is 50-80% in its western part and below 50% further to the east. In southern part it decreases to below 5% because of generally unfavorable climatic conditions.

The ***chestnut soils*** are characterized by constantly non-penetrating water regime. Average depth of annual water penetration is 1.5 m (0.5-1.8 m). Easily soluble salts are transported to that depth and accumulate there forming features of the ***solonetzicity*** (see above) typical for ***chestnut*** and ***light chestnut soils***. Humic horizon of ***chestnut soils*** is characterized by depth 30-40 cm and characterized by coarse granular structure, less stable than that of the ***chernozem soils***. Illuvial-carbonate horizon is compacted, with subangular blocky to prismatic structure. In ***solonetzic*** soils it has a tendency of swelling under wetting, dramatically decreasing its permeability for water and air. Gypsum horizon is commonly more loose and contains visible crystals of a secondary gypsum. Humus content decreases southward from 6% in ***dark chestnut soils*** to 2-3% in ***light chestnut soils***. Soil reaction is always alkaline. Content of soluble salts in the subsoil is commonly 0.5-0.8%, composition – chloride-sulfate-sodium. There are widespread salty soils within the ***chestnut soil*** zone, including ***solonetz*** and ***solonchak*** soils. Those can be formed both on salt-rich parent materials and as a result of soil accumulation from evaporating groundwater.

1.7. Natural vegetation cover and its anthropogenic transformations in the Volga River Basin

The Volga River crosses a few distinctively different natural zones on its way from north to south (Fig. 1.6). Therefore, spatial pattern of vegetation cover in its basin is largely controlled by zonal factors (Vegetation of the European…, 1980). Most of the small river basins within the Volga River Basin are however located in its forested part, as a result of its tree-like planform. Nevertheless, vegetation cover of small river basins is characterized by large degree of spatial variability. In the north-eastern part of the basin forests occupy up to 70-80% of the area, while to the south this percentage decreases to 1-5%. But within smaller river basins range of percentages of forested areas can also be very high (Table 1.4). For example, within the Moscow region average percentage of forests is 38.7%. However, southern part of it is almost completely devoid of forests (area percentage does not exceed 1.5%), while in northern parts of the region it can reach 40-65% (the Nudol, Kunya and Polya River Basins). Most of the presently existing forests are of a secondary origin, meaning that their water conservation functions are much different from that of the native forests.

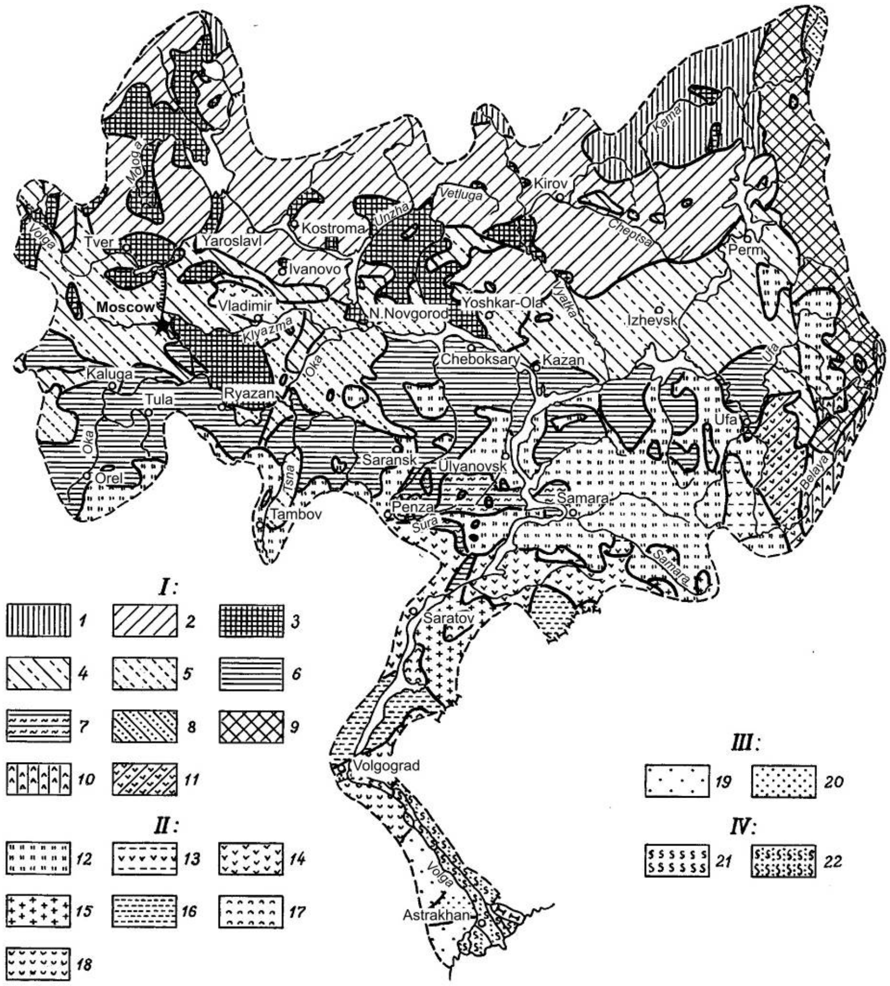

Figure 1.6. Schematic map of the Volga River Basin natural vegetation cover. Zonal types of vegetation: I) Forests: 1) middle taiga fir-spruce and pine forests; 2) southern taiga fir-spruce forests; 3) southern taiga pine and larch-pine forests and blanket bogs; 4) southern taiga fir forests with broad-leaved trees; 5) southern taiga pine grassy forests; 6) broad-leaved lime-oak and maple-lime-oak forests; 7) pine forests with steppe-like grass cover; 8) mountainous cedar-fir and cedar-spruce forests; 9) mountainous fir-spruce and cedar-spruce forests; 10) mountainous pine forests; 11) mountainous lime and lime-oak forests. II) Steppes: 12) grass-cereal steppes; 13) typical rich grassy-fescue-feather grass steppes; 14) typical grass-fescue-feather grass steppes; 15) typical grassy northern dry steppes; 16) typical xerophitic-grassy southern dry steppes; 17) desertified shrubby-grassy northern steppes; 18) desertified shrubby-grassy southern steppes. III) Deserts: 19) cereal-wormwood deserts; 20) wormwood-psammophytic deserts. Floodplain communities: 21) meadows; 22) reed bushes of long-inundated floodplains and lake depressions.

Most of the Volga River Basin area is occupied by coniferous forests (taiga). Northern boundary of the basin practically coincides with the boundary between the so-called middle and southern taiga subzones. Southern taiga mixed forests occupy a belt stretching from the Chudskoe Lake on the west to the Vetluga River on the east. Those are predominantly represented by the European fir communities with birch and aspen. Interfluves between small river catchments are occupied by fir forest with oxalis. Poorly drained flat areas are dominated by fir forest with oxalis and bilberry. Slopes of uplands and richer carbonate soils (the Valday Upland, etc.) are covered by fir forest with oxalis and grasses. Boggy fir forests with sphagnum and long mosses often occupy lowlands and waterlogged flat plains.

Table 1.4. Percentage of forested area in the Volga River Basins separated onto administrative units.

Administrative unit	Forested areas. %	Administrative unit	Forested areas, %
Astrakhan	0-5	Penza	10-30
Bashkortostan	20->80	Perm	30->80
Vladimir	60-80	Ryazan	10-80
Volgograd	1-5	Samara	1-20
Ivanovo	20-30	Saratov	0-20
Kaluga	30-60	Tambov	0-60
Kirov	20-80	Tatarstan	20-30
Kostroma	60-80	Tver	20-60
Mariy-El	20-80	Udmurtiya	20-30
Moscow	30-60	Chuvashiya	10-60
Nizhniy Novgorod	10-80	Yaroslavl	20-60

In upper and middle parts of the Vyatka and Kama River Basins the southern taiga communities are represented by fir and fir-spruce forests. Mountain forests of the Urals are covered by forests with fir, spruce and cedar. In plain catchments of small rivers in the Vyatka and Vetluga River Basins spruce-fir forests with grasses and oxalis are the most widespread. The Ural piedmonts are dominated by spruce-fir forests with oxalis and ferns occupying interfluves and most of the slopes.

Pine forests occupy separated areas mainly on sandy and loamy-sandy soils of plain areas. The most widespread are pine forests with green mosses or lichens on better drained areas and pine forests with long mosses and sphagnum on waterlogged interfluves and river terraces.

Forests of the southern taiga have long been used by men. Large areas of woodland were cut and subsequently used for cultivated land, while on others secondary aspen-birch communities have regrown. Appearance of secondary communities of small-leaved forests was followed by certain negative effects on small river water quality. There is natural acid reaction of soil solutes under coniferous forests maintaining relatively low mobility of many types of pollutants. Substitution of coniferous forests by secondary aspen-birch communities results in shift to more alkaline conditions in soils with increased mobility of a number of chemical elements and compounds.

Main areas of the mixed broad-leaved and fir forests more or less coincide with small river basins of the Smolensko-Moskovskaya, Valdayskaya and Klinsko-Dmitrovskaya Uplands. Three groups of communities are dominant: lime-fir, oak-lime-fir and ash-oak-fir forests with oxalis and grasses. River valleys with conditions of excess wetness are occupied by birch-alder forests with some firs.

Other types of mixed deciduous (broad-leaved) and coniferous forests occupy lower parts of the Vyatka, Kama and Belaya River Basins. Deciduous trees are commonly represented by lime, with oak, maple and elm. These forests are characterized by more complex structure and floristic composition than those of the southern taiga forests. Spruce-fir mixed forests with grasses cover interfluve of the Unzha and Vetluga Rivers as well as hilltops and hillslopes of the Ural piedmont uplands. Mixed forests with broad-leaved trees, fir and spruce are typical for the Ural Mountains western slopes. Pine forests with mixture of broad-leaved trees occupy some areas in the Moscow, Desna and Oka River valleys, on the Privolzhskaya Upland and in the Moksha River Basin.

Belt of the broad-leaved deciduous forests is most evident within the Srednerusskaya and Privolzhskaya Uplands. In eastern part of the Volga River Basin those occupy the Obchiy Syrt and other uplands as well as the Southern Urals lower slopes. Northern parts of the Srednerusskaya and Privolzhskaya Uplands are dominated by lime-oak forests substituted further southward by artificial plantations of the same composition. There are separated areas occupied by oak forests (Russian term ***dubrava***) and pine forests on southern part of the Privolzhskaya Upland. Complex ***dubravas*** occupy the most elevated upland summits. In eastern part of the Volga River basin dominant type of the broad-leaved deciduous forests is represented by maple-lime-oak. Towards the Ural Mountains mono-species oak forests are gradually substituted by mixed lime, maple, elm and oak forests. Pure lime forests can still be found in separated areas of the eastern Volga River Basin uplands, the Western Urals, the Samarskaya Luka natural reserve, on the Srednerusskaya and Privolzhskaya Uplands. Most of the broad-leaved (oak) and small-leaved (poplar, willow, alder) floodplain forests in the Volga River and tributary valleys have important water conservation functions and can be classified to the highest category of water conservation buffer forests.

In different physiographic regions forest vegetation is characterized by various specific properties. Considering its high importance for hydrological regime of fluvial systems, human activities dealing with woodland resources can cause substantial changes in hydrological cycle of forested river basins. The most severe impact on woodland landscapes is of course associated with complete concentrated forest cuttings. Over the last 20 years volumes of timberwood cut in excess of the standard cutting shares were about 2.2×10^6 m^3/year in the Perm Region only. As a long-term result of such treatment of woodland resources, age structure of forests has been changed dramatically, and so is the structure of small river water balance. Devastation of forests by uncontrolled cuttings and forest fires results in dramatic decrease of evapotranspiration. In regions of excess precipitation it results in waterlogging of forest cuttings and fired areas. For example, as a result of the single fire that devastated more than 800 km^2 of woodland in the Unzha River Basin in 1972, percentage of waterlogged areas has grown from 28% to 53% over 15 years (Preobrazhenskaya & Popov, 1989).

Forest cover of river basins has important effect on small river runoff. For example, decreae of forested areas by 30% annual runoff layer decreases by 25 mm (i.e. by 14%) in the subzone of mixed coniferous and broad-leaved forests. Runoff layer from forested basins is higher on average than that from non-forested basins over the summer-autumn period by 16.9 mm (34%) and over the winter period by 6.4 mm (33%). Effective infiltration in basins with larger percentage of woodland areas is higher on average by 25 mm (41%). Forest vegetation, if relatively uniformly distributed within the basin area, exerts positive effect on small river flow by increasing the low-water period discharges and slightly decreasing the spring snowmelt flood discharges (Pimenova & Tsyganova, 1992). Broad-leaved deciduous forests actively transfer precipitation into groundwater flows. That decreases surface runoff, lowers surface erosion rates and protects small river channels from sediment-associated siltation and pollution. In comparison with other forest types, broad-leaved deciduous forests are also the most effective in terms of evapotranspiration from unit area. That has a significant positive effect on general hydrological regime of the territory.

Effects of forest vegetation on formation and passage of fluxes of matter in fluvial systems depends on physiographic conditions in the latter, for example on geological structures. In glaciofluvial landscapes of western parts of the Moscow Region (forested areas occupy more than 30% of the total area) area-specific discharge increases by 0.53 $l/s/km^2$ for each 10% increase of forested area percentage. However, in landscapes formed on glacial boulder clays this effect is less pronounced – area-specific discharge increases by 0.46 $l/s/km^2$ for each 10% of forests (Pimenova & Tsyganova, 1992). Maximum increase of annual runoff volume has been found in small river basins with initial percentage of forested areas above 40% (Paulyukyavitchus, 1989). However, some specialists argue that increased forested areas does not guarantee higher long-term average annual runoff, or even point out to decreased runoff (Voronkov, 1992).

Steppe vegetation is dominant in small river basins of middle and southern parts of the Volga River Basin. Steppes of the southern European Russia are at present largely cultivated. During snowmelt periods or heavy rainfalls arable lands are subject to intensive processes of soil erosion by water. Eroded sediment (dominantly fine fractions) and associated pollutants become delivered into small rivers. Amounts of pollutants closely depend on types of land use, cultivation practices, crop rotations, etc. However, without considering all those factors in details, it can be stated that under present conditions sediment fluxes formed in the steppe zone are much larger than those occurring under natural conditions.

Natural vegetation cover at present remains intact in a few steppe reservoirs or on poor sandy or ***solonetz*** soils. Steppe-like meadows along the Volga River valley alternate with maple-lime-oak forests in transitional forest-steppe zone of the basin. Grass-fescue-feather grass steppes remain intact in separated small areas in western part of the Saratov Region. In eastern part of the basin those occupy narrow strip along interfluve between the Volga and Ural Rivers to the south from the Samara River valley. Dry fescue-feather grass steppes occupy territories to the west from the Ergeni Upland. High terraces of the Volga River and its largest left tributaries (the Bolshoy Irgiz River, etc.) are covered by feather grass-fescue steppes. Desert-like fescue-feather grass, white wormwood-fescue-feather grass, white wormwood steppes cover the Ergeni Upland itself. They often form complexes with black wormwood communities. On Ergeni Upland fescue-feather grass pastures turn into white and black wormwood associations as a result of overgrazing. That effectively means that desertification of the grazing lands is ongoing at present (Terenozhkin, 1947).

Desert vegetation within the Volga River Basin is found only within the Prikaspiyskaya Lowland where there are effectively no small streams and rivers. Desert communities present there are dominated by wormwood. Specific property of the Prikaspiyskaya Lowland desert vegetation is dominance of xerophytes associated with water deficit in the landscape, high saltiness of surface grounds and flat topography.

1.8. Land use history of the Volga River Basin

Agriculture became a permanent part of the economy of the Eastern Slavs towards the late 15th century, as the Muscovite State gained control of most of the Volga river basin. Clearing of forests in the southern half of the forest zone then took place. In the 16th century new territories were opened up and settlement established in the central Volga and central pre-Ural regions. An intensive agriculture developed, with a fallow system in the steppe region, and clearing-burning and fallow systems in the forest-steppe and forest zones (Krokhalev 1960). At the beginning of the 18th century the area of arable land increased rapidly. A three-field system (winter wheat, summer crops and fallow) began to be used in the central regions of European Russia and the area of industrial crops (such as flax) began to increase, although it still remained very small. The most favorable arable land was largely found on the southern slopes of moraine hills with gradients of 2-4° directly adjoining river valleys, along which most settlement developed. Ploughing was restricted to the hillslopes. As a result, the length of the fields did not exceed 150-220 m. At the end of 18th century the settlement of the southern and south-eastern parts of the territory began. As people moved southward into a region with greater local relief, they began to cultivate slightly longer and steeper fields: slopes of 5-7° were cultivated, often 300-400 m long. Ploughing along (up and down) the slopes was retained, as in the forest zone, and promoted gully formation (Sobolev, 1948).

Reliable agricultural data for Russia were obtained during a General Survey in the late 18th century (Tsvetkov, 1957). This period saw a gradual decrease in arable fertility lands as increasing production of cereals for export displaced cattle-rearing. The three-field system of rotation was at this time applied over most of the territory. In the first half of the 19th century, different agricultural systems began to be used. In the Yaroslavl' and Moscow districts, for example, a four-field crop rotation system (fallow, winter wheat, clover, and summer crops) was introduced beginning from the 1820s. Most landowners, however, retained the traditional three-field system. In the south and southeast, a commercial cattle rearing was retained predominant. After the abolition of serfdom in 1861, radical changes occurred in the agriculture of Russia. There was a marked increase in crops specialization, and only the north-east retained the clearing-burning system for cereals. Intensive ploughing began in the southeast and south in the Stavropol' steppes, with the fallow system retained. Flax was now sown over a wide region in the northwest and Upper Volga region as far as Nizhniy Novgorod, being incorporated in the multi-field rotation (fallow-rye-oats-2 year grass-flax-oats). In the rest of the territory, outside the ***chernozem*** zone, eight-field rotations were used, in which cereals alternated with fallow, grass and potatoes. Western regions now began to specialize in beet production, which was included in a ten-field rotation or in an improved cereal rotation (fallow-winter cereals-beet-summer cereals).

Cultivated areas in southern forest and forest-steppe zones of European Russia reached its maximum in late 19th century. It was also a period of increase in numbers of land users who owned small fields: 60% of peasants owned land with an area <10 ha. At this time in both the forest and forest-steppe zones steep slopes of dry valleys, unsuitable for cultivation, were ploughed. Narrow strips along the slope represented the plots of land. These strips were separated from each other by deep plough lines, which concentrated flow and promoted gully formation. The length of the ploughed parts of slopes did not exceed 100-150 m in the forest zone, 200-250 m in the forest steppe and 300-350 m in the steppe.

The area of arable land was reduced during World War I, followed by a period of significant private involvement in agriculture during the 1920s. This period ended with general collectivization beginning in 1928. Crop rotations changed to multi-field, somewhat improving soil protection against erosion by increasing vegetation cover. The area of cereal crops decreased from 80-85% to 70-75%, whereas industrial (sunflower, sugar beet and buckwheat) and fodder crops increased. Field sizes increased because the area of fallow land was reduced, and tractors were introduced. Development began in the virgin lands of the lower Volga and in piedmont of the Urals.

During the World War II the area under crops was again everywhere reduced, by a factor of not less than three. By the late 1950s the area of crops had been restored, due to the use of tractors, combine harvesters and other techniques. A change in the structural and hydrological properties of soils began at this time, resulting particularly from the increased loading by machines, and causing increased runoff and erosion. After the 1950s all arable land in the steppe zone of the territory was used, with the last increase in ploughed area coming about by cultivating floodplains, which had previously been used for pastures. The near doubling of the weight and size of tractors continued the process of making tilled soils more susceptible to erosion. Some reduction in the area of cultivated land in the forest zone and forest-steppe zone occurred in the 20th century, as the most eroded areas were excluded from cultivation and some lands were used for urban development and mining.

The 1970-80s were characterized by year-to-year variations of only 1-2% in the area of cultivation. Disc ploughing of 10-15% of the ***chernozem*** zone increased the resistance of these soils to erosion. Outside this zone, the extensive use of grain-fodder systems with 30-40% perennial grasses in the composition of these crops also increased resistance to erosion by increasing vegetation cover.

After collapse of the USSR, the radical changes in the political situation and economy began. Federal statistics of the Russian Federation (Russia in Numbers, 2002) shows dramatic land-use changes. In 25800 large collective farms and state agricultural complexes, which used 86-93% of the land, the area of arable land decreased by 20%, the area of sowing decreased by 42% during 1990-2004. Statistics show that the main land-user (at least 86% of the land) is still large farms (4000 ha on average) with collective type of land-use. The pattern of the fields (their length and inclination) did not change significantly. About 25% of the fields are not used and covered at present by weeds and scrub. The water erosion is negligible there. The market dictates the crop rotation on the other part of land, and the land conservation methods of management are out of use. Often a mono-crop culture (like sunflower) can be cropped for several years of high prices for this type of production. Water erosion rates on such fields could be significantly higher than in previous years.

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SECTION 2

SOIL EROSION IN THE VOLGA RIVER BASIN

2.1. General overview of factors and intensity of soil erosion in the Volga River Basin

Major sediment fluxes of the Volga River Basin begin to form in small river catchments. Those fluxes determine water quality and aquatic habitat conditions in different parts of fluvial systems, environmental conditions for existence of different natural and complex anthropogenic-natural ecosystems. One of the most important processes giving rise to those fluvial sediment fluxes is water erosion on hillslopes. Most important factors influencing spatial distribution and rates of soil erosion by water are climate, topography, soil cover and land use.

Local events of intensive runoff cause close to catastrophic erosion rates. Medvedev & Shabaev (1991) measured an erosion rate of 53.5 t/ha during spring 1974 on the Privolzhskaya Upland, when rainfall combined with melt-water runoff. About 55 mm of rainfall in the Tula Region during 2 hours on August 10, 1997 brought about soil loss of 22-59 t/ha (Golosov *et al.*, 1999). Such runoff and rainfall events with 10-20 year return period produce 70-80% of the total long-term sheet and rill erosion.

The long-term erosion rates for the entire Volga River Basin were calculated. The Universal Soil Loss Equation (Wischmeier & Smith, 1978) was used to calculate soil loss from rainfall. Soil loss during snow-melt was calculated the model of the Russian State Hydrological Institute (Instruction…, 1979). Both models were modified for European Russia conditions (Larionov, 1993) and combined into a single PC-based package, verified on measurements and showed good results (Litvin *et al*., 2003).

In general, intensity of soil erosion on arable lands within the Volga River Basin varies from <1 t/ha/year to >20 t/ha/year. Spatial distribution of potential erosion rates on arable slopes estimated using the USLE-based modeling approach for the entire basin is presented on Figure

2.1. It is controlled by a number of factors of which the most important is a zonal index of rainfall erosivity *R* (as used in USLE). It varies from 3.5-4.0 in northern part of the basin to 8.0-9.0 on Srednerusskaya Upland (western part of the basin). Further southward values of *R* decrease again being about 1.5-2.0 in lower parts of the basin. Water storage in snow by the beginning of snowmelt period is another important parameter influencing soil erosion intensity during spring snowmelt. This is maximal in northern part of the basin (120-140 mm) and decrease southward to 20-40 mm in the lower part of the basin.

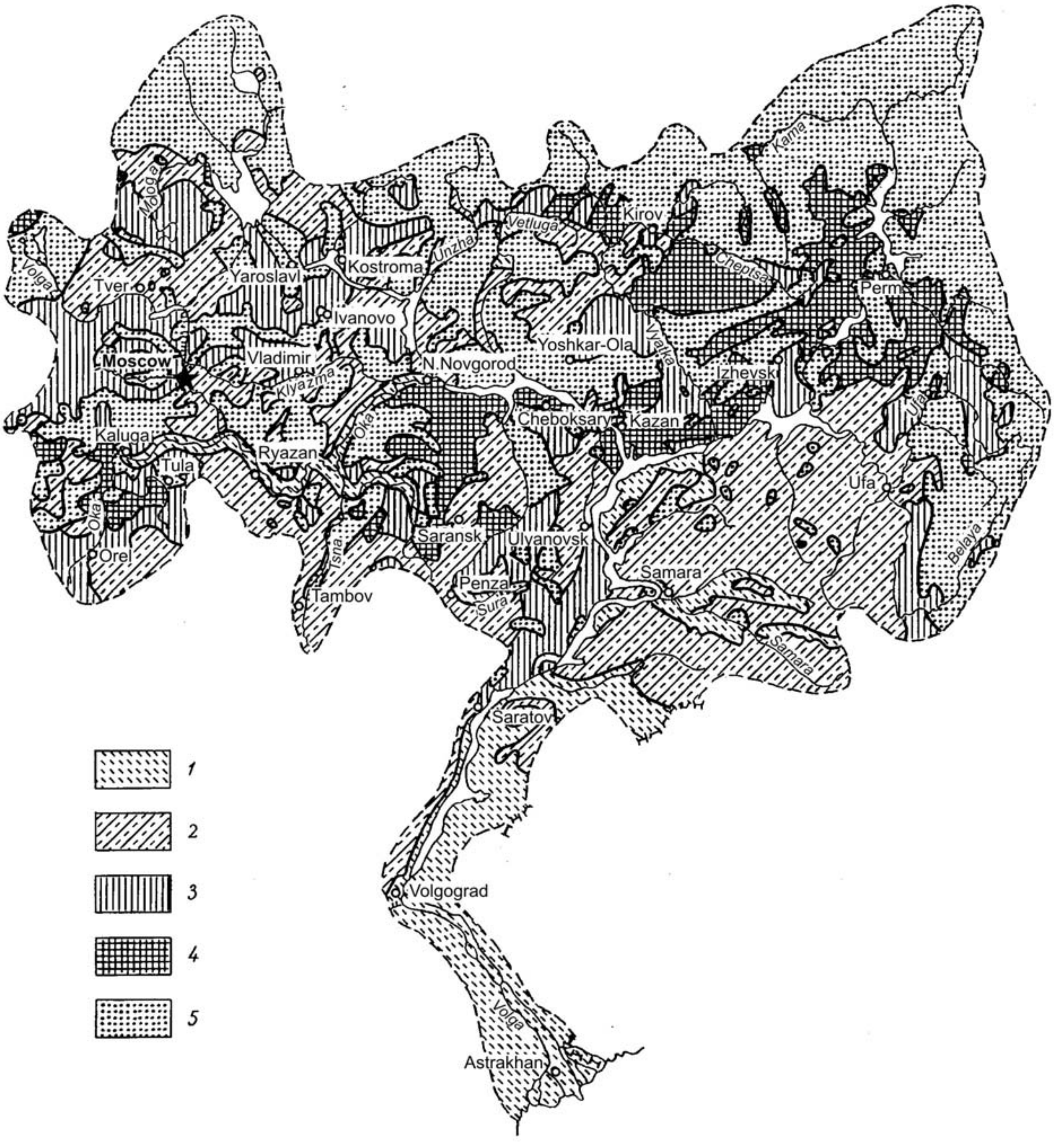

Figure 2.1. Average annual soil erosion rates on arable land of the Volga River Basin: 1) <1 t/ha/year; 2) 1-5 t/ha/year; 3) 5-10 t/ha/year; 4) 10-20 t/ha/year; 5) forests and bogs.

Within climatically uniform territories local topography is the most important factor controlling soil erosion rates. Larges areas with highest potential erosion rates occupy the Smolensko-Moskovskaya, Srednerusskaya, Privolzskaya Uplands and uplands of eastern part of the basin and piedmonts of the Urals. Topography controls on erosion is taken into account in the USLE-based approach by introduction of the *LS* factor incorporating influence of slope length (*L*) and slope gradient (*S*) on erosion rates. Northern parts of the Volga River Basin with arable land dominantly located on uplands and relatively steep valley slopes are characterized by *LS* factor values varying from 1.0 to 2.5. Central part of the basin is characterized by alternation of vast uplands and lowlands values of *LS* factor decrease. In southern part of the basin in the Prikaspiyskaya Lowland uniformly flat topography with very low slope gradients determines extremely low values of *LS* factor – 0.1-0.3.

Soil erodibility *E* is a value characterizing soil susceptibility to erosion, opposite to its erosional resistance, under impact of a unit rainfall erosivity *R*. It varies significantly depending mainly on soil texture, humus content and composition. Easily erodible (highest *E* values of 4.0-4.5) are ***soddy podzolic soils*** on loessy loams. Similar soils on glacial boulder clays are already less erodible (*E*=3.0-3.5). The least erodible soils are humus-rich ***chernozems*** with heavy texture, *E* values being in a range of 0.7-2.0. Erodibility of ***gray forest soils*** varies from 1.5 to 3.0, ***chestnut soils*** – from 1.8 to 2.5. High erodibility characterizes ***light chestnut soils*** with *E*=3.0.

Table 2.1 shows the average calculated severity of sheet and rill erosion and some other information, specified for administrative districts of the Volga river basin. On the glacial landforms in uplands it reaches 10-12 t/ha/year and on glacial-lake and glaciofluvial plains ~2 t/ha/year. Similar relationships are found between soil loss from uplands and lowlands: the Srednerusskaya Upland – 7-8 t/ha/year and the Oksko-Donskaya Lowland – 0.5-2.0 t/ha/year. The lowlands are in general characterized by lowest rates of soil loss, as for the Prikaspiyskaya Lowland – below 0.5 t/ha/year.

Table 2.1. Main characteristics of sheet and rill erosion in the administrative units of the Volga river basin.

№	District name	District area (10^3 ha)	Maximum proportion of arable land (%) / the year when this maximum occurred	Mean annual rate of sheet and rill erosion in the 1970-80s, t/ha (calculated)	Amount of sheet and rill erosion during the period of intensive agriculture (10^6 t) (calculated)
1	Novgorodskaya	5447	12.4/1868	4.5	734.8
2	Vologodskaya	14451	6.2/1950	6.1	802.0
3	Vladimirskaya	2912	43.8/1868	5.5	1134.7
4	Ivanovskaya	2342	43.8/1868	6.5	1218.9
5	Tverskaya	6020	31.7/1868	5.3	1554.9
6	Kaluzhskaya	2978	53.7/1868	7.4	1589.2
7	Kostromskaya	6020	20.6/1868	5.6	1128.4
8	Moskovskaya	4689	39.0/1861	7.7	2413.7
9	Orlovskaya	2465	68.2/1980	5.3	1349.8
10	Ryazanskaya	3961	56.0/1868	3.5	1344.1
11	Smolenskaya	4978	38.1/1868	7.7	2120.5
12	Tul'skaya	2568	74.0/1887	7.5	2324.8
13	Yaroslavskaya	3620	35.1/1868	5.4	1206.3
14	Mari-El	2237	49.6/1887	7.1	1678.6
15	Mordoviya	2613	62.4/1887	6.0	1928.1
16	Chuvashiya	1835	49.6/1887	8.6	1808.4
17	Nizhegorodskaya	7462	42.5/1887	6.7	3913.8
18	Vyatskaya	12035	34.1/1887	6.2	4092.3
19	Tambovskaya	3446	66.5/1980	1.7	685.5
20	Tatarstan	6784	55.4/1980	2.9	3227.1
21	Astrakhanskaya	5303	8.0/1980	0.3	10.1
22	Volgogradskaya	11294	51.7/1980	1.7	822.5
23	Samarskaya	5360	57.8/1980	2.3	950.9
24	Penzenskaya	4335	62.4/1887	4.3	2661.3
25	Saratovskaya	10124	63.1/1980	1.9	1473.7
26	Ul'yanovskaya	3718	53.3/1887	4.4	931.9
27	Bashkiriya	14294	35.3/1980	3.0	1621.2
28	Udmurtiya	4206	36.7/1980	9.7	1829.6
29	Orenburgskaya	12369	36.5/1980	2.1	1156.8
30	Permskiy krai	16024	16.4/1980	12.1	3135.2

In terms of contribution of snowmelt runoff and rainfall into total soil erosion rates, most of the Volga River Basin is characterized by important contribution of both. Snowmelt runoff is responsible for most of average annual soil loss in northern part of the basin and north-western piedmonts of the Urals. To the south from a virtual line connecting the Kazan and Orenburg Cities contribution of rainfall runoff becomes dominant. The lower Volga and surrounding territories are zones with where water erosion in general becomes very low due to low frequency of high-magnitude rainfall events. In those areas wind erosion becomes dominant process of sediment redistribution on slope surfaces.

It is well-known that erosion rates in small river catchments are closely related to percentage of cultivated land. That generally increases from north to south, becomes maximal in steppe zone and decreases abruptly again towards semi-deserts and deserts. In northern part of the basin the so-called ***zone of patchy cultivation*** is located, where cultivated lands form kind of individual separated ‘islands’ in large areas of woodlands. Under such circumstances sediment yield from eroded arable hillslopes does not exert significant effect on suspended sediment concentrations in river waters, though some individual hillslopes can be severely eroded due to presence of eroded soils, sufficient availability of surface water and favorable topography. To the south of the taiga zone intensity of soil erosion on arable slopes remains high, while percentage of arable land increases. In forest-steppe and steppe zones highest percentage of arable land is combined with significant potential erosion rates on cultivated slopes (Table 2.1). Minimal erosion rates characterize the Prikaspiyskaya Lowland and south-eastern part of the basin.

It can be generally concluded that highest impacts on water quality and suspended sediment concentration in rivers is exerted by soil erosion in middle part of the Volga River Basin, while in its northern and southern part this effect is relatively minor.

2.2. Historical review of soil erosion rates in the Volga River Basin

Temporal change of erosion rates in the Volga River Basin over the documented period may to some extent be reconstructed using known modern erosion rates on arable hillslopes and estimates of changes in the principal factors influencing erosion rates: the area under cultivation, precipitation and changes of crop rotations and cultivation practices. Allowing for the relative change in the values of erosion factors, retrospective calculations were made to estimate the intensity of erosion (Sidorchuk & Golosov, 2003). The volume and the rate of soil loss for the entire period of intensive agriculture were thus calculated (Table 2.1, column 6).

According to these estimates for the period from the 18th to the 20th century, erosion was related to the spatial differentiation of erosion factors and the history of the cultivated land expansion in the Volga River Basin. In the 18th century, erosion was highest in the most densely populated and cultivated area of the ***soddy podzolic soils***. Two main areas stand out as having the most intense erosion: in the west, the Smolensko-Moskovskaya Upland region, and in the east, the middle Volga River valley surroundings. In these areas the eroded layer over the studied period reached 20-30 cm on 8-9% of arable land. However, for ***soddy podzolic soils***, where the eluvial horizon does not exceed 15-20 cm and the rate of soil formation is no more than 2-3 cm in 100 years (under natural vegetation), such erosion rates are sufficient to produce moderate to severely eroded soil.

In the 19th century the most severe erosion still occurred in the long-cultivated areas of the ***soddy podzolic soils***. Erosion increased after the landownership reform of 1861 as a result of the ploughing of both land previously deemed unsuitable for cultivation and steeper hillsides. Consequently, by 1887 in the Moscow area of heavy erosion, the eroded layer exceeded 10 cm on 40% of arable land, and on 22% of arable land it exceeded 30 cm. In the middle Volga River valley surroundings, on 63% of arable land eroded layer exceeded 10 cm, and on 14% – >30 cm.

In the 20th century (for our calculations – 1887-1980) the intensity of erosion on long cultivated land on the ***soddy podzolic soils*** decreased substantially. This was connected with a general reduction of cultivated areas, mainly because ploughing has ceased on the most heavily eroded land and on steepest slopes. This accounts for the fact that the total erosion of arable land in the region has increased only slightly. In the ***chernozem*** zone erosion to a depth of >30 cm covered 22% of arable land in the Tula Region.

Calculations show (Sidorchuk & Golosov, 2003) that in general for the European Russia during the period 1696-1796, a total of 5.9×10^9 m^3 of soil was washed away by sheet and rill erosion; in 1796-1887 – 30.8×10^9 m^3; and in 1887-1980 – 33.8×10^9 m^3. The constant increase in the volume of soil loss per unit time (Table 2.2) is due to an increase in the area under cultivation. ***Soddy podzolic soils*** are the most affected, particularly in the Middle Russian and Volga uplands, in the north and south-west of the ***chernozem*** zone. The total volume of calculated soil loss from slopes in European Russia over the period from the 18th to the 20th century inclusive amounts to 70.5 x 10^9 m^3.

Table 2.2. Calculated volumes of sediment mobilized from cultivated hillslopes by sheet and rill erosion (10^9 t) during the period of intensive agriculture (for European Russia).

Period						
1950-1980	1887-1950	1868-1887	1861-1868	1796-1861	1763-1796	1696-1763
12.65	21.1	16.22	1.68	3.54	3.83	2.11

This huge amount of eroded soil resulted in substantial reduction in soil profile thickness, mainly of upper horizons (A+(EB)+B). The spatial distribution of soils with different levels of transformation of these horizons (non-eroded, slightly eroded, moderately eroded, severely eroded, accumulated) is complicated and sporadic, with the distances between spots with non-eroded and severely eroded soil often only 20-40 m. Methods for evaluation of the degree of erosion based on soil profile examinations can be rather subjective. Therefore, several examples cited below belong to the scientists of the same pedological school. On the moraine hills of the Valday Experimental Station in the Novgorod Region the cover layer of silt deposits with ***soddy podzolic soil*** is 25-38 cm thick under the forest. This depth was used as the reference depth of non-eroded or slightly eroded soil. Under the arable land the silt deposits were 3-14 cm deep and in 30% of the area they were completely washed away (Lidov, 1976).

In the Ulyanovsk Region the depth of A+B_1 horizon of non-eroded ***chernozems*** is 80-90 cm on flat interfluves and 55-60 cm on gentle slopes. Mean thickness of these horizons for the complicated sporadic pattern of slightly eroded and moderately eroded soils on the slopes between ephemeral gullies is 30-40 cm. This thickness decrease to 10-20 cm in ephemeral gullies with a density ~3 km/km^2 (Lidov et al., 1973).

At the Ergeni Upland in the Volgograd Region the reference thickness of A horizon of non-eroded ***light chestnut soil*** is 15-20 cm, and that of B_1 horizon is 31-49 cm on relatively stable slopes of the Tinguta dry valley. On severely eroded slopes the A horizon is completely washed away, and the B_1 horizon is only 8-19 cm deep (Lidov & Orlova, 1970). Detailed mapping of soil horizon depth transformation makes it possible to estimate the volumes and rates of erosion for the experimental sites and small catchments with ***chernozem soils*** during the period of intensive agriculture (Table 2.3).

Table 2.3. Soil loss for the period of intensive agriculture, estimated with the method of soil horizon transformation (after Azhigirov et al., 1992)

Basin	Area, (ha)	% of arable land	Soil loss volume, (m^3)	Erosion rate, (mm/a)	District
Malyi Kolyshley River	11775	75	19017	1.26	Saratovskaya
Large Pogromka River	22420	72	10477	0.52	Orenburgskaya

2.3. Detailed case studies of erosion rates within small catchments

Case study 1. Large-scale evaluation of soil redistribution within forest zone of the Volga River Basin: surroundings of the Torzhok City

The forested area of the Volga river basin has been given much less attention in terms of human-induced accelerated soil erosion and sedimentation studies compared to forest-steppe. It was made investigation of soil redistribution within the small dry valley catchment located in the Northern part of Tver region, about 15 km to the southwest of Torzhok city (Fig. 2.2). Relief is characterized by hills and hilly ridges of glacial origin, with mainly convex slopes. Slope length is in most cases insufficient to promote gully formation under local surface runoff conditions. Therefore, sheet and rill erosion together with mechanical translocation by cultivation play a major role in soil and sediment redistribution.

CASE STUDY SITE CHARACTERISTICS

The case study area is located in the northwest of the Volga river basin within the mixed forest zone. Mean annual precipitation is about 600 mm, relatively uniformly distributed within the year. Erosion events can be caused by both intensive snowmelt runoff and occasional summer rainstorms. Rainfall erosivity coefficient of the USLE model is 6.8 estimated for the Torzhok city meteorological station. Soil cover of the region is dominated by ***soddy podzolic soils*** formed on glacial or glaciofluvial deposits.

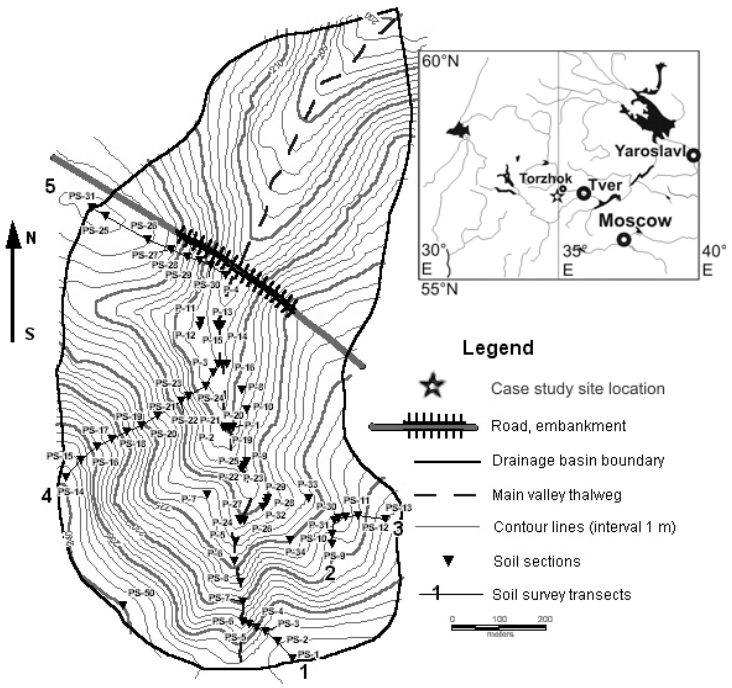

Figure 2.2. Map of the northwest of the Volga basin showing the case study site location and the general study subcatchment scheme with locations of slope transects and soil sections.

The catchment chosen as a key site for this case study has a drainage area of about 81 ha (Fig. 2.2). Catchment slopes have different profile shapes, but convex slopes dominate. Slope gradients are moderate, varying from 0.035 to 0.1. A number of slope depressions separate catchment slopes into sections (Fig. 2.2, 2.3).

The catchment has been intensively cultivated for at least 300 years. Summer rye, oats, barley and wheat were the main crops before 1917, row crops were not cultivated (Pokrovskiy, 1879). During the Soviet times winter cereals were predominant. After 1991, arable area slightly decreased and crop rotation changed from cereal-dominated to perennial grass-dominated, which has substantially lowered land vulnerability to water erosion. Today about 80% of the total catchment area is cultivated.

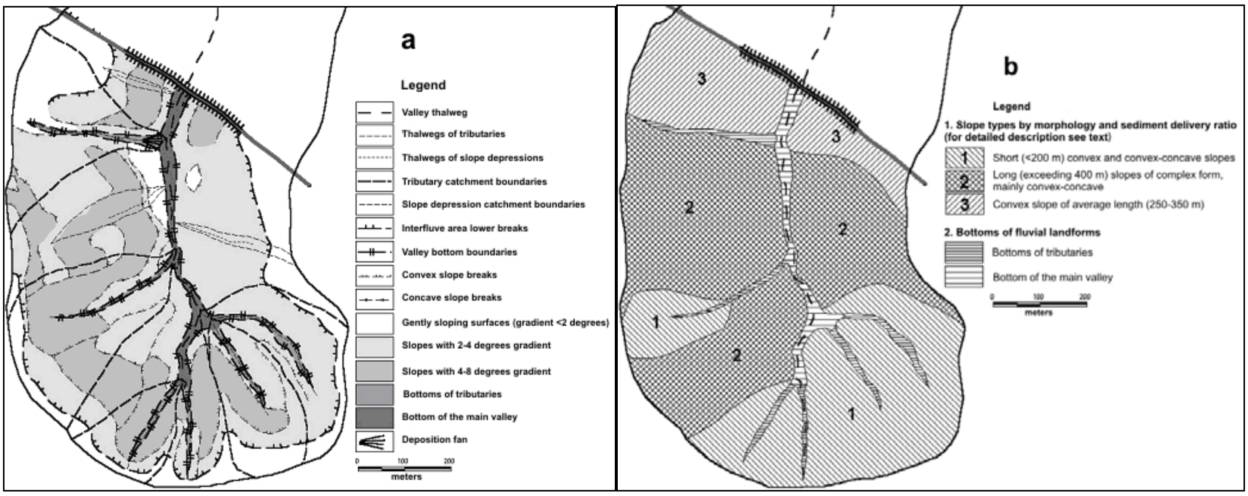

Figure 2.3. Slope gradient map (a) and slope morphological types (b) of the studied catchment part.

METHODS

The upper part of the study catchment (area about 0.54 km^2) separated by a road embankment was chosen for the detailed study (Fig. 2.2). Within this area all major slope types characterizing the entire catchment are represented. Investigations included topographic and geomorphic mapping. (Fig. 2.2, 2.3). Soil survey sections along transects within each of the slope types and on the main valley bottom cross sections were excavated and described in detail on the second stage. From some of those, radionuclide tracer soil sampling was carried out. Integral samples were taken from transect 1 (^{137}Cs) and transect 4 (^{137}Cs and $^{210}Pb_{ex}$). Depth-incremental samples were taken from the reference site section PS-31 (Fig. 2.4). Subsequently samples have undergone preparation and counting in the laboratory with counting times not less than 12 hours.

Methods employed for estimations of soil redistribution rates included soil-morphological method (further – SMM) (Larionov *et al.*, 1973), radionuclide tracers ^{137}Cs (Walling & He, 1999a) and $^{210}Pb_{ex}$ (Walling & He, 1999b), and USLE-based modeling (further – USLE) (Larionov *et al.*, 1998; Krasnov *et al.*, 2001).

RESULTS AND DISCUSSION

Radionuclide tracers reference inventories

Depth distribution profiles of both ^{137}Cs and $^{210}Pb_{ex}$ in soil (Fig. 2.4) at the reference site (section PS-31, Fig. 2.3) together with detailed description of soil structure led us to conclude that this site has not been cultivated since at least 1954. Obtained values of the ^{137}Cs and $^{210}Pb_{ex}$ inventories can therefore be used as characteristic for a baseline fallout input in soil redistribution calibration models. About 93% of the ^{137}Cs inventory is found within the upper 15 cm of the section (Fig. 2.4). Profile shape differs from exponential in the upper part and is characteristic for territories with significant Chernobyl fallout. Modeling of the isotope vertical migration and diffusion (He & Walling, 1997) allowed us to determine its amount as being about 20% of the total inventory. For $^{210}Pb_{ex}$ about 84% of the total inventory is contained within the upper 12 cm of soil. As $^{210}Pb_{ex}$ fallout can be treated as a constant process, annual flux of the isotope from the atmosphere can be calculated from the reference inventory and radioactive decay constant. The value obtained is 260.9 Bq m^{-2} $year^{-1}$, which is in agreement with direct observations of $^{210}Pb_{ex}$ atmospheric flux (Walling & He, 1999b).

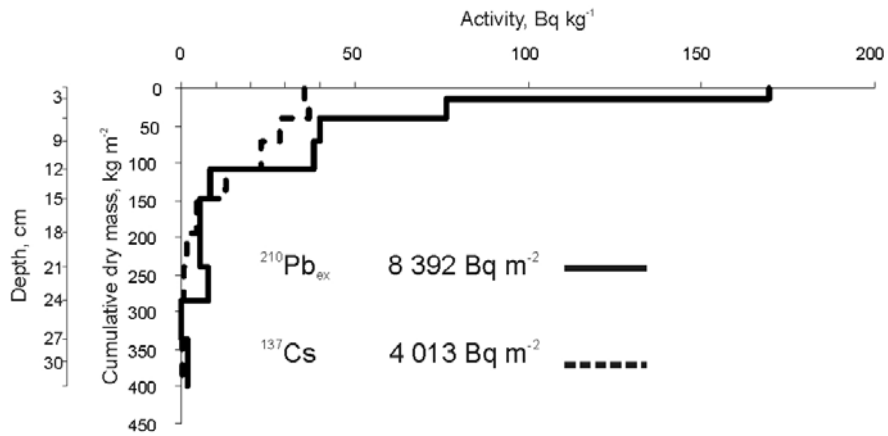

Figure 2.4. Depth distribution of ^{137}Cs and $^{210}Pb_{ex}$ in soil at the reference site (section PS-31).

Soil redistribution on the catchment slopes

Three main slope types have been distinguished according to profile shapes, length and slope break locations (Fig. 2.3b), basing on the morphological map of the studied part of the catchment (Fig. 2.3a). These included: i) short (<200 m) mainly convex or convex-concave slopes (further referred to as Type I slopes); ii) long (up to exceeding 400 m) slopes of complex form with slope breaks and terrace-like surfaces, but generally convex-concave (Type II); iii) intermediate length (250-350 m) convex slopes (Type III). All three types were characterized by soil survey transects along flow lines (Fig. 2.2, 2.5, 2.6).

Slopes of Type I are located in the upper part of the studied subcatchment (Fig. 2.3b). These slopes can in turn be subdivided into 3 subtypes. Shortest (<100 m) convex diverging slopes are located on divides between the main valley and its tributaries. Convex slopes with a flat upper interfluve zone and length of 100 to 200 m characterize the main valley sides. The rest is represented by convex-concave slopes. To characterize all 3 subtypes, 3 soil transects were surveyed (Fig 2.2, transects 1-3). Data obtained were averaged to characterize all Type 1 slopes.

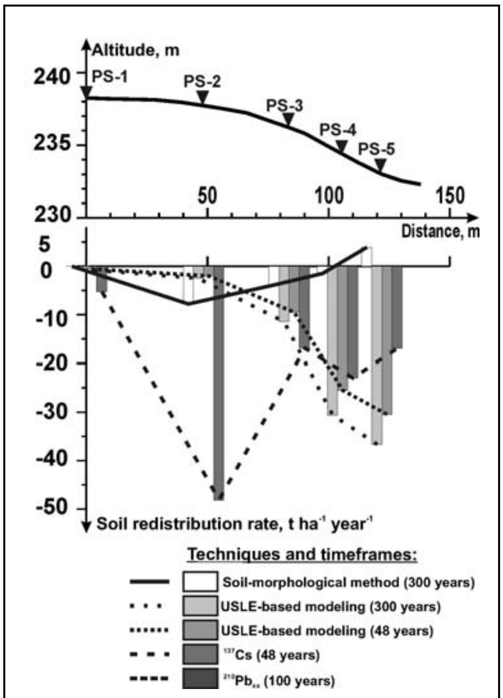

Figure 2.5. Slope long profile along transect 1 and soil redistribution rates estimated by different methods

For transect 1 SMM, USLE and ^{137}Cs methods have been used for soil redistribution rate evaluation (Fig. 2.5). The first two methods yielded relatively similar values of average soil redistribution rates for the entire cultivation period (6.8 t ha^{-1} year^{-1} from SMM and 9.4 t ha^{-1} year^{-1} from USLE). For the 48 year period of ^{137}Cs presence in the environment (since 1954), this tracer gives a value of 22.6 t ha^{-1} year^{-1}, which is almost three times greater than the value (7.8 t ha^{-1} year^{-1}) obtained from modeling.

In general, all three methods employed gave an adequate evaluation of the dominance of erosion on Type I slopes. However, SMM is the only method to detect deposition. Its average rate is estimated to be 3.3 t ha^{-1} year^{-1}, but its spatial extent is very limited. Zones of erosion occupy about 75% of the Type I slope area, whereas detectable within-slope redeposition occurs only on 14%. Sediment delivery ratios for these slopes vary from 68 to 100% depending on the slope subtype. The only important sediment sinks are slope toes.

The Type II slopes are mainly found in the middle part of the studied subcatchment (Fig. 2.3b). These are characterized by a complex profile shape and a very gently sloping gradual transition zone to the main valley bottom. For the Type II slopes, all four methods of soil redistribution assessment described above have been employed (Fig. 2.6A). For the 300-year period SMM estimates an average erosion rate of 6.0 t ha^{-1} year^{-1}, whereas USLE estimates 18.5 t ha^{-1} year^{-1}. Estimation for the 100-year period by $^{210}Pb_{ex}$ (10.0 t ha^{-1} year^{-1}) is essentially close to that from SMM. For the 48-year period, USLE gives an average erosion rate of 15.4 t ha^{-1} year^{-1} and the ^{137}Cs method yields 25.8 t ha^{-1} year^{-1}.

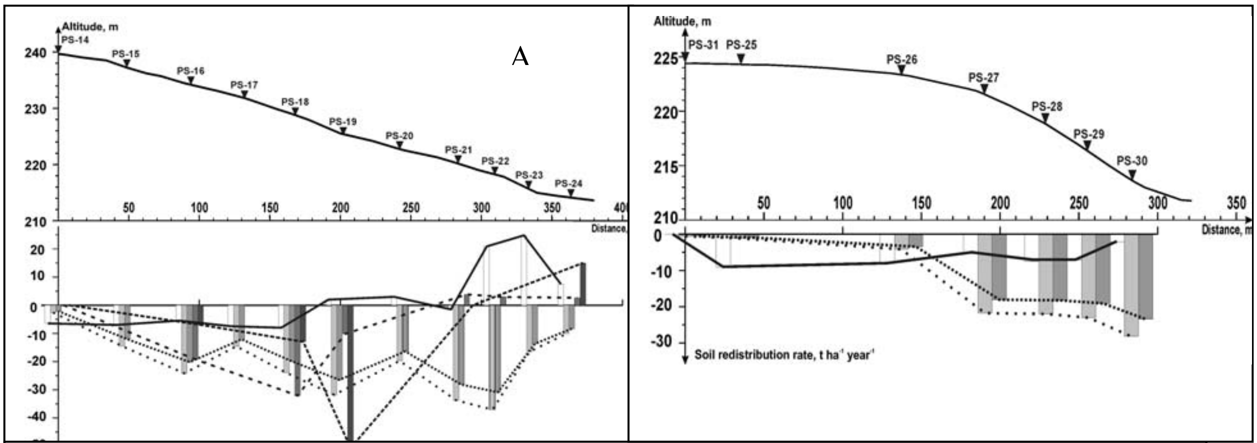

Figure 2.6. Slope long profiles along transect 4 (A) and 5 (B) and soil redistribution rates estimated by different methods (for a legend see Fig. 2.5).

Sediment redeposition within the Type II slopes is again adequately reflected only by SMM. Its average rate is estimated as 8.1 t ha^{-1} year^{-1}. Area of redeposition zones (9.3 ha or 37.6% of the entire Type II slope area) is substantially smaller than that of erosion zones (15.4 ha or 62.4%). The ^{137}Cs and $^{210}Pb_{ex}$ methods most likely underestimate deposition rates. For sections PS-21, PS-22 and PS-23 (Fig. 2.2, 2.6A) presence of accumulation is only confirmed by high activity of both isotopes below the plough layer (comparable or even exceeding that of the plough layer) and an increase in their concentrations in the topsoil downslope, probably reflecting particle size selectivity. Despite this, good agreement is observed in relative area of erosion- and deposition-dominated zones between radionuclide tracers data and SMM. Sediment delivery ratio estimated from SMM is 19%, highlighting the important role of within-slope sediment sinks for the Type II slopes.

The Type III slopes are located only in the lower part of the studied subcatchment nearby the road embankment (Fig. 2.3b). These are characterized by a relatively long (up to 30% of total slope length) flat interfluve section and simple profile shape below with gradient increasing downward and a sharp boundary between slope toe and valley bottom. For the Type III slopes only SMM and USLE have been applied (Fig. 2.6B). Results obtained are between those for the Type I and Type II slopes. Average erosion rates are 6.4 t ha^{-1} $year^{-1}$ according to SMM and 13.3 (300-year period) – 11.0 (48-year period) t ha^{-1} $year^{-1}$ from USLE modeling. Simple morphology determines location of the erosion zone (about 80% of the slope length, except the flat interfluve part) and complete long-term sediment delivery to the main valley bottom (ratio 100%).

Average soil erosion rates on the catchment slopes are moderate – estimations from different techniques vary from 6.4 to 24.2 t ha^{-1} $year^{-1}$. In most cases two zones of intensive erosion can be distinguished: upper slope convexity and the lower third of the slope. The former can be attributed to significant contribution of soil translocation by tillage, whereas the latter is associated with water erosion. It is believed that erosion rates have been decreasing since 1991 when a shift to less erosion-prone crop rotations dominated by perennial grasses began. This decrease is confirmed by the USLE calculations, but has no support from ^{137}Cs data because in our case it has overestimated erosion and underestimated deposition rates. Within-slope accumulation of sediment is believed to be adequately reflected by SMM only. Deposition zones are most often found at slope toes and along boundaries or transition zones between slope and valley bottom. Additional within-slope sediment sinks exist on longer slopes with complex profile. Those can intercept up to 40% of the material eroded from upslope. The employed version of the USLE-based model is unable to account for within-slope redeposition, therefore its applicability for morphologically complex slopes (Type II) is limited.

Case study 2. Large scale study of soil redistribution within slope catchment of forest-steppe zone in area with high level of Chernobyl radionuclide contamination

STUDY AREA

A detail study of soil redistribution using ^{137}Cs technique and other methods was undertaken within intensively cultivated field located in 250 km south from Moscow in the Lokna River Basin, north of the Srednerusskaya Upland (Fig. 2.7). Srednerusskaya Upland is located in the central part of Russian Plain and represents an important topographical barrier for predominant westerly winds. It is the major reason for serious contamination of the north-eastern part of the Srednerusskaya Upland after the Chernobyl accident (Fig. 2.7). The highest inventories of ^{137}Cs fallout have been identified just before the major water divide between the Volga River Basin and the Don River Basin within the headwaters of the Oka River Basin. The study area is located in the middle of the Chasovenkov Verh small catchment. The latter is a dry tributary of the Lokna river (Fig. 2.8). The level of the initial Chernobyl contamination exceeds 300 kBq m^{-2} and the highest contamination identified along the main valley of the Lokna River.

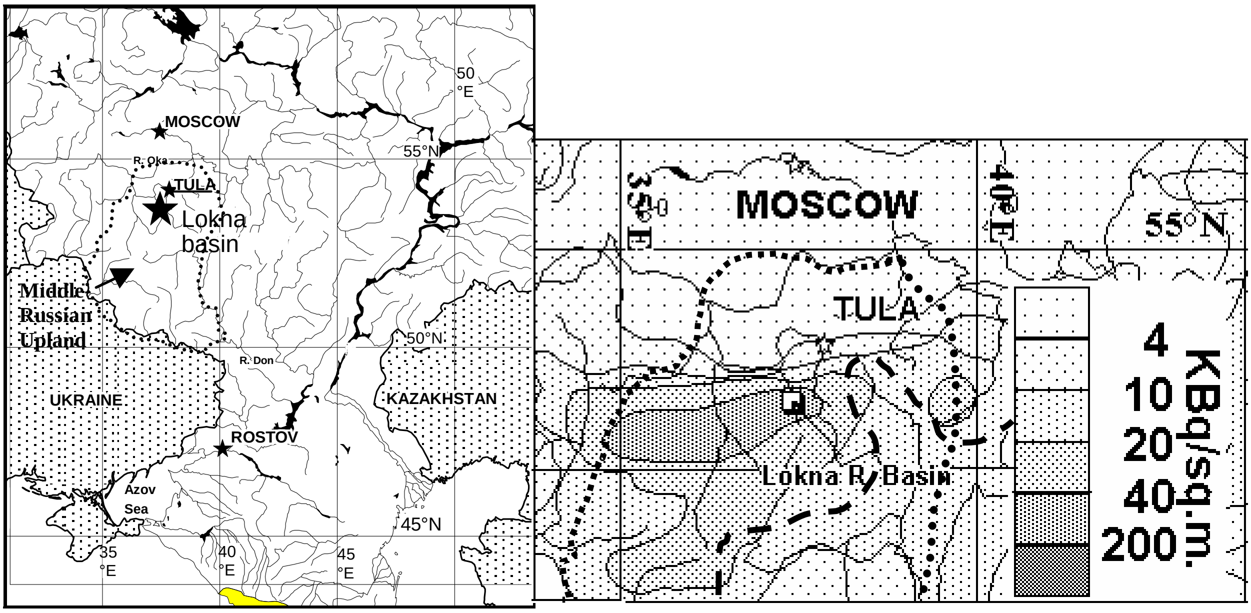

Figure 2.7. Location of the Lokna River basin within the Srednerusskaya Upland and in relation to the regional pattern of the Chernobyl fallout inventories.
Legend: - boundary of the Srednerusskaya Upland; - water divide line between the Volga river basin and the Don river basin.

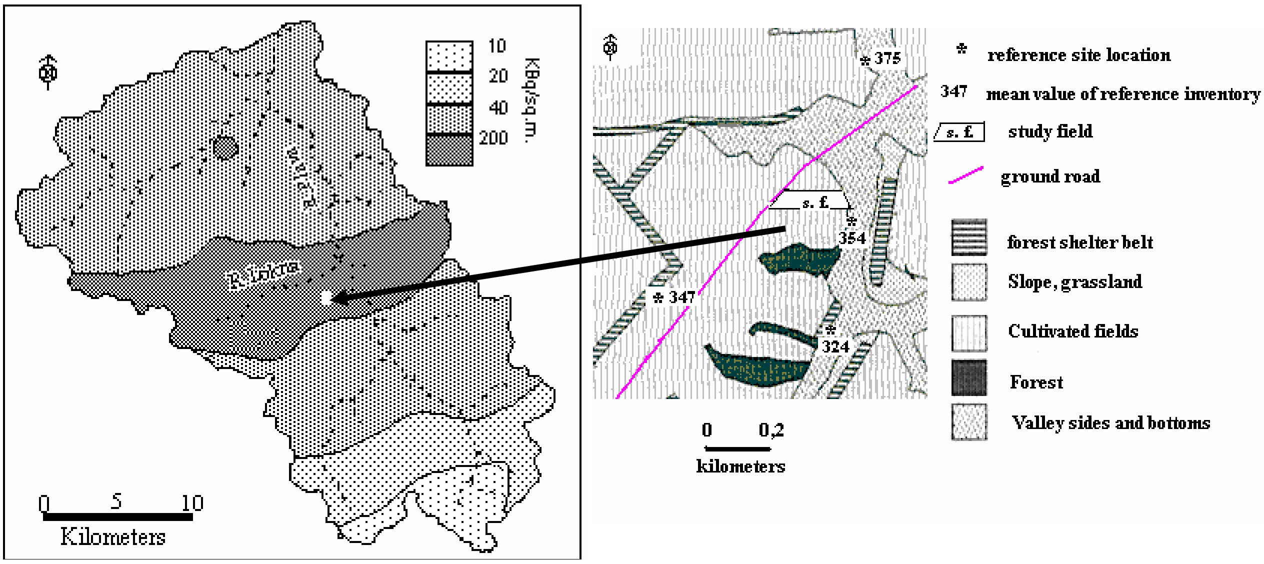

Figure 2.8. Map of Chernobyl ^{137}Cs contamination of the Plava river basin, showing the study area within the Lokna river basin and land management of the middle section of the Chasovenkov Verh balka basin.

The Lokna River Basin is up to 240-250 m a.s.l. and its relative topography range is about 60-90 m. The topography is dominated by a relatively flat interfluve area and mostly convex slopes of different gradients which have been dissected by ***balkas*** (***balka*** – local Russian term for relatively small dry valleys). The local area is underlain by the Carboniferous limestones and dolomites and mantled by the Holocene loessy loams. The most typical soils are ***typical*** and ***leached chernozems*** (Haplic, CHh, according to the FAO classification) with loamy texture, which occupy about 80% of land. According to observations at the local meteorological station, located about 1 km east from the case study field, mean annual precipitation for the period 1986-1997 was 650 mm, and snow comprised about a half of it.

Soil erosion events happen almost each year during the spring snowmelt (March-April) and as a result of heavy rainstorms during the May-September period. Soil erosion during the snowmelt is mostly observed at warmer orientation (southwest), because irregular melting of snow on the most steep convex part of slopes if compare with relatively flat interfluve areas. According to 11-year long field measurements of water and sediment discharges organized at the Kashira field station (Braude, 1976), the mean annual erosion rates during snowmelt are 5.4 t/ha at the "warm" slope catchments. This station is located within northern part of the

Srednerusskaya Upland in area with similar type of relief, but on ***gray forest soils*** with loamy texture (Haplic, GRh according to the FAO classification). Based on long-term field measurements on runoff plots (length 100-150 m; area 0.3-0.5 ha) mean annual erosion rates varied from 0.4 t/ha for the ***gray forest soils*** (Barabanov, 1993) to 1.2 t/ha for loamy ***chernozem*** (Chernyshev, 1976). Differences in values of erosion rates between natural slope catchments and runoff plots have two main reasons: These are the effect of irregular melting of snow on convex slopes (depending on their actual aspect) and runoff concentration in slope depressions (playing crucial role in soil redistribution on natural slope catchments) unaccounted for by erosion plots.

Long-term observations of soil erosion during heavy rains have not been organized at the Srednerusskaya Upland. However, some erosion consequences of the heavy rain observed on 10th of June, 1997 were directly measured for few different arable fields within the Chasovenkov Verh catchment. Volumes of rills and rill fans were independently measured. Average losses from different fields during the rain vary between 28-36 t/ha. Maximum soil losses from the most severely eroded parts of slopes were 200 t/ha.

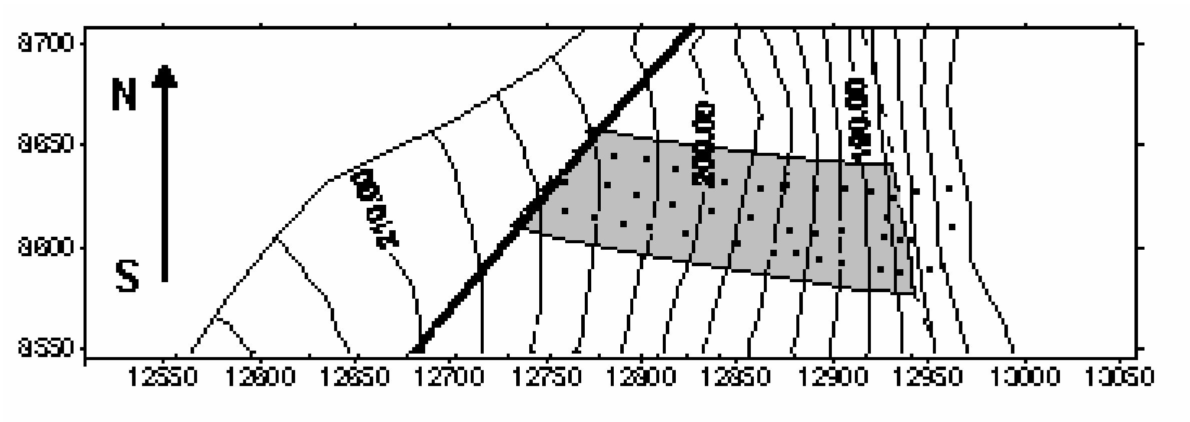

Figure 2.9. The study field topography and sampling points locations
Legend: - study field; . . . – sampling points; - unsealed road

Relatively short slope located in the middle reach of the Chasovenkov Verh balka was selected for the detailed study of soil redistribution (Fig. 2.8, 2.9). This eastern aspect slope has a convex profile, its length is 200-250 m and the gradient 6-15%. An unsealed road forms a local water divide at this slope (Fig. 2.9). Loamy soils contain 2.4-3.8% of humus. They are classified as moderately to strongly eroded soil and, according to the Russian soil classification (Russian soil…, 2001), this means that they have lost about 30% to 50% of the A horizon thickness comparatively to undisturbed soils.

METHODS

Three parallel transects were selected for sampling and in situ measurements of ^{137}Cs inventories, because the sampled field has a quite simple topography (Fig. 2.9). Measurement points were about 20-25 m apart and transects spacing was about 20 m. Four reference sites were chosen at different locations around the study field (Fig. 2.8). Bulk core samples were collected using a 36.2 cm^2 core tube inserted to the depth of 30 cm on the slopes and interfluve. Three cores were taken at each point to decrease the effect of spatial variability. In addition incremental samples from layers 0-30 cm and 30-40 cm were taken on at some points within the interfluve area.

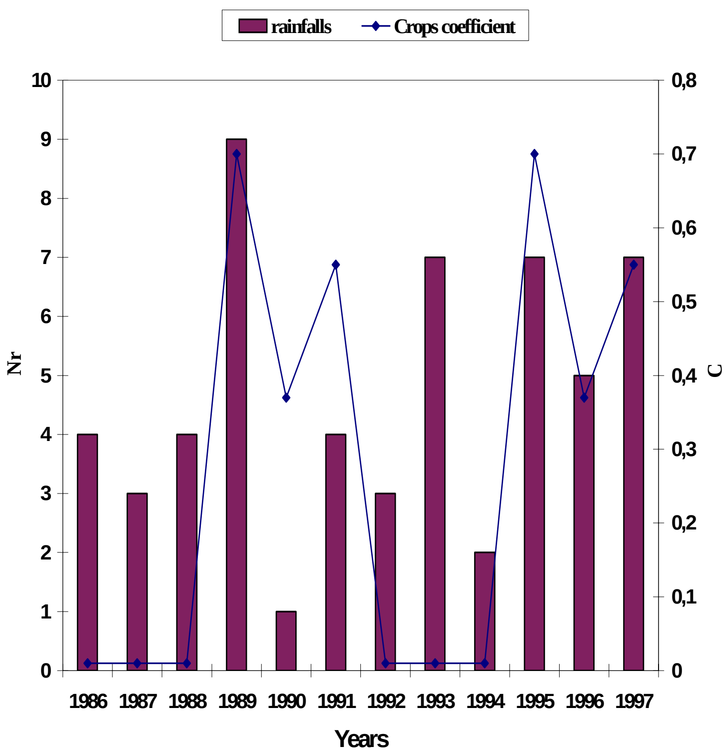

Figure 2.10. Changes of crop coefficient and number of heavy rains for study field during 1986-1997. Legend: Nr – number of rainfalls; C – crop coefficient.

A detailed topographic survey of study slope, as well as sampling points was made using a differential GPS system, that provided height and position records with a maximum error of ±2cm (Panin et al., 2001) (Fig. 2.9).

Information about land management, crop rotation and precipitation for the period May 1986 – May 1998 was collected from local collective farm and meteorological station. Rain-storm related erosion rates on the study slope were calculated using a modified version of the USLE developed by Larionov (1993) and the EPIC (Williams et al., 1984). The EPIC-based calculation of erosion rates were done using the latest version of the MUSLE.

An extreme rain-storm (55 mm for 3.5 hours) on 10 June 1997 caused an intensive runoff and erosion in the study field. Immediately after rain the pattern and volume of rill and rill fans were measured. According to calculations of total soil losses the mean erosion rate over the entire field was 36 t ha^{-1} (3 t ha^{-1} per year for the period 1986-1997) with a maximum loss of 200 t ha^{-1} identified within of 50-100 m strip up from the cultivated slope bottom. The distribution of precipitation during strong rains for the May 1986 – June 1997 period was compared with the dimensionless factor for cover and management (*C* factor) for study field (Fig. 2.10). It was determined that situation similar to that of 1997 were observed at this in 1989 and 1995 (Fig. 2.10). The actual erosion effects of these rains are not known. It is assumed that the soil losses were similar to those observed erosion after the rain of 10 June 1997, i.e. between about 5 t/ha (minimum) and 3.6 t/ha (maximum). This provides a rough indication of mean annual soil losses including erosion during snow-melting for June 1986-1997 period in a range of 4-9 t/ha.

RESULTS

Proportional and standard mass-balance models were applied for the calculation of erosion and deposition rates at the study slope (Table 2.4) using software developed by Walling and He (1999).

Table 2.5 shows mean soil loss rates based on different approaches. The results indicate that Chernobyl-derived ^{137}Cs may already be used for calculation of mean erosion rates for cultivated fields with intensive soil redistribution. The results of the modified USLE version and EPIC models are in agreement with the gross erosion rate estimated from the ^{137}Cs measurements and very close to the upper limit of actual soil losses (Table 2.5).

Table 2.4. Integrated data of soil loss/gain for the study field based on different calibration models.

	Proportional model	Standard mass-balance model
Gross erosion rate (t/ha/year)	11.0	13.1
Eroding sites		
Mean erosion rate (t/ha/year)	18.0	21.6
Percentage of total area	62	61
Aggrading sites		
Mean deposition rate (t/ha/year)	13.3	16.1
Percentage of total area	38	39
Net erosion rate (t/ha/year)	6.1	6.8
Sediment delivery ratio (%)	55	52

Table 2.5. Mean annual soil losses from study for period 1986-1997 established by different methods.

Method of assessment	Mean annual rates, (t/ha/year)
Direct measurements of erosion and deposition volumes combined with analysis of rainfall magnitude and frequency distribution	4-9
Modified version of the USLE model	11.5
EPIC model	12.5
^{137}Cs technique (*in situ* measurement of ^{137}Cs inventory)	
Proportional model:	
Net erosion	6.1
Gross erosion	11.0
Standard mass-balance model:	
Net erosion	6.8
Gross erosion	13.1

Three independent methods have identified the mean annual erosion rates in range 4-11 t/ha/year for the case study field. These results correspond to available information on soil erosion rates for the central and northern regions of the Russian plain. Studies based on evaluation of sediment storage in small reservoirs for arable slopes with similar topography provide erosion rates from 2.0 to 5.7 t/ha/year (Golosov, 1998). Soil morphological methods show erosion rates in the range of 2.0-6.5 t/ha (Rozhkov, 1977).

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SECTION 3

GULLY EROSION IN THE VOLGA RIVER BASIN

3.1. Modern distribution of gully erosion in the Volga River Basin

The territory of the Volga River Basin can be divided (Litvin *et al.,* 2003) into the following four belts according to genesis and density of gullies (Fig. 3.1):

1. The belt where gullies represent extremely uncommon and isolated phenomena (<2 gullies/100 km^2), with no or very low percentage of cultivated land, with flat or rolling relief in the northern (>57-58° N) part of the forest zone or lowlands with weakly incised valleys <10 m deep.

2. The belt of low gully density varying between 2 and 25 gullies/100 km^2 over most of the area. Such areas have relatively low relief range with forested flat interfluves. They occupy the forest zone south of 57-58° N, the flat forested upland areas of the Smolensko-Moskovskaya and Srednerusskaya Uplands and part of the Oksko-Donskaya Lowland. In southern part of the forest zone gully density gullies can reach 25-50/100 km^2. Most of the gullies presently found in forests were formed during the periods of much wider expansion of cultivation on former arable lands.

3. The main belt of gullying in the forest-steppe and steppe zones. The main anthropogenic factor in gully formation here is cultivation of almost the entire area. Gullying is also promoted by favourable natural conditions: substantial volumes of melt water and rainfall, relatively erodible loessy subsoil parent materials and relatively higher topography range. When these areas were first cultivated, intensive tillage led to formation of gully systems of the greatest extent and density, compared to other regions. Topography range and land use pattern differentiate the gully density within the belt. Areas with moderate gully density (25-50/100 km^2) typically occupy relatively flat interfluves and uplands with low topographic range (the Smolensk Hills, the north-western part of the Srednerusskaya Upland), as well as lower rolling plains (the Tambov Range, the Oksko-Donskaya Lowland, western part of the Obshchiy Syrt Upland). Areas of advanced agricultural

development with relatively favourable natural conditions for gully formation are characterised by deeply dissected relief and high gully density: 50-100/100 km^2. Such regions include central parts of the upland country: the Srednerusskaya and Privolzhskaya Uplands. Areas with very high gully density (>100/100 km^2) are found in a relatively small region in the middle of the upland country and along steep slopes of the main valleys, comprising <10% of the entire territory affected by gully erosion.

4. The southern belt with very low gully density. This region includes the greater part of the Prikaspiyskaya Lowland.

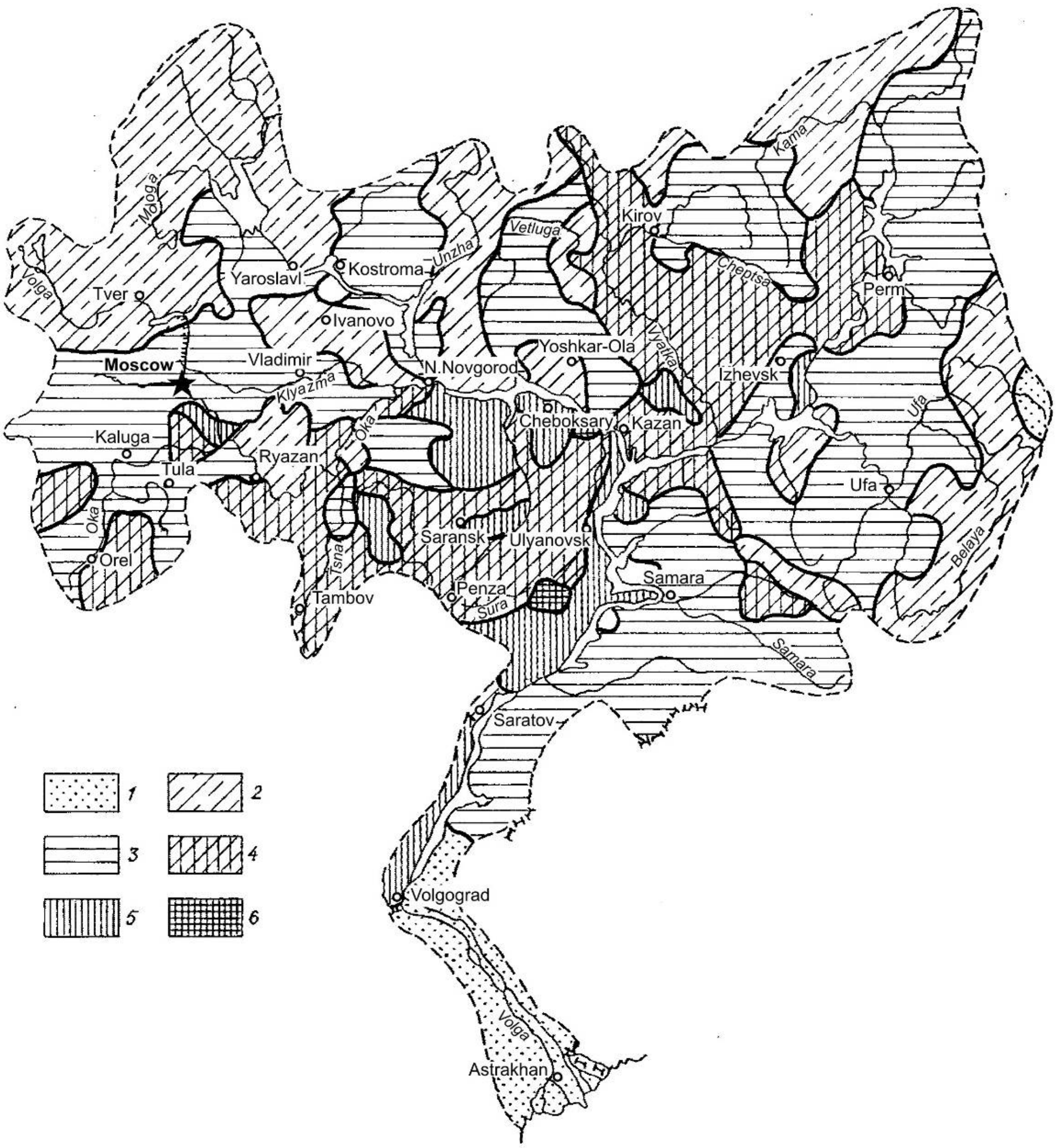

Figure 3.1. Average annual intensity of sediment production by gully erosion in the Volga River Basin: 1) <0.1 $m^3/year/km^2$; 2) 0.1-1.0 $m^3/year/km^2$; 3) 1.0-20.0 $m^3/year/km^2$; 4) 20.0-75.0 $m^3/year/km^2$; 5) 75.0-200.0 $m^3/year/km^2$; 6) >200 $m^3/year/km^2$.

B.F. Kosov (1970) collected more – than 300 measurements of gully growth rates in European part of the former USSR for various land use types (Table 3.1). About 45% of these data show gully growth during 1-5 years, 35% – up to 10 years, the others for longer periods up to 170 years. The gullies on arable land are characterised mainly by medium rate of growth (50% of the gullies have a maximum growth rate <5 m/year). Catastrophic (>100 m/year) rates of gully development are more typical for the areas of forest cutting and industrial development.

Table 3.1. Distribution (in %) of gullies with different growth rates (after Kosov, 1970).

Land use type	The total number of gullies	Maximum annual (seasonal) growth (m)				
		<5	6-15	20-40	50-80	>100
Agriculture	269	50	25	15	8	2
Logging	15	25	18	25	7	25
Road building	17	15	25	30	25	5
Industrial development	19	20	20	25	10	25

3.2. Variation of gully erosion rates during the period of intensive agriculture

In the development of gully erosion the same stages can be seen as in sheet erosion (see Section 2). Using data from the chronicles of the 12-14th centuries and land registries for the 15-17th centuries, Sobolev (1948) noted severe linear erosion in towns and villages of the forest zone. Moryakova (1988) has dated >500 gullies in the ***soddy podzolic soil*** region with the help of organic carbon content in the initial soils in the gullies. These data show five main periods of intensive gully growth with the maximum rate of gully formation in 1860-1910, when ~24% of presently existing gullies were formed (Table 3.2).

Table 3.2. Main stages of gully formation in the ***soddy podzolic soil*** *belt (after Moryakova, 1988, with additions).*

Period	% of the gullies formed during the period	Volume of the gullies in 1970 (10^6 m^3)	The rate of gully formation (%/year)
1970-1910	9.0	16.5	0.15
1910-1860	24.2	44.4	0.48
1860-1730	40.4	74.2	0.31
1730-1600	21.2	38.9	0.16
1600-1500	5.2	9.5	0.05

Period of the most rapid development of gullies within the forest-steppe zone of the Volga River Basin was the second half of the 19th century. Massalsky (1897) used responses to his special questionnaire from correspondents throughout the European Russia to obtain the first overview of the extent of gully erosion in the ***chernozem*** belt. Highest intensity of gullying coincides with the areas of historically earliest cultivation within the ***chernozem*** zone (the Tula Region). Two other periods with formation of numerous new gullies and active growth of the existing ones were registered in the forest-steppe and steppe zones during the late 19th and 20th centuries. They were connected with expanding cultivation of virgin lands, beginning from the end of 19^{th} century and up to the 1950s, and in some areas also with the recommencing of cultivation after the World War II. The tendency towards decreasing gully erosion rates during the second half of the 20th century is noted for all European Russia. According to field observations (Butakov et al., 2000), it reduced 2-3-fold compared to the data for the early and middle 20th century, collected by B.F. Kosov (1970).

3.3. Sediment export from gullies into river valleys of the Volga River Basin

Modern gully erosion in the Volga River Basin is one of significant contributors into sediment yield in rivers. One of the parameters that can be used for characterizing quantitatively a contribution of gully erosion into sediment redistribution within a fluvial system is the area-specific sediment yield W_g, i.e. volume of sediment delivered from a gully mouth over a unit time divided by a gully catchment area (m^3/year/km^2). This parameter characterizes amount of sediment delivered from gullies into larger elements of a fluvial network:

$$W_g = D_g V_g F \qquad (3.1)$$

where D_g – gully density 1/km^2; V_g – average rate of gully headcut growth, m/year; F – average gully cross-section area, m.

Calculation of area-specific sediment yield from gullies (W) was carried out for basins of the 1st order rivers distinguished on the 1:2500000 scale topographic maps. Map of area-specific sediment yield from gullies was created for the Volga River Basin territory using results of that calculation. It is shown on Figure 3.1. The map gives a generalized quantitative characteristic of the present state of gully network and activity of its development. It also allows us to determine types of territories with different intensity of sediment export from gullies.

In order to select appropriate gradations of the map scale, histograms of probabilities of different values of W_g was carried out. The following 6 gradations have been selected on a basis of statistical analysis of the dataset:

1) W_g<0.1 m^3/year/km^2, minimal intensity of gully erosion;
2) 0.1≤ W_g <1.0 m^3/year/km^2, very low intensity of gully erosion;
3) 1.0≤ W_g <20.0 m^3/year/km^2, low intensity of gully erosion;
4) 20.0≤ W_g <75.0 m^3/year/km^2, moderate intensity of gully erosion;
5) 75.0≤ W_g <200.0 m^3/year/km^2, high intensity of gully erosion;
6) W_g >200 m^3/year/km^2, very high intensity of gully erosion.

The map also allows one to observe distinctive relationships of area-specific gully sediment yield values with both zonal factors and regional conditions. Mosaic of geographic areals distinguished on the map according to the area-specific gully sediment yield values consists of a complex combination of territories with different gully densities, size parameters and modern growth rates. Topography range of small slope catchments (depth of local erosion basis for gullies), total precipitation, rainfall intensity and seasonal distribution are the most important natural factors influencing a sediment yield from gullies. Those determine a quantity and, therefore, density of gullies within a given area, as well their size parameters such as length, depth, average cross-section area.

Along the Volga River valley itself within the forest zone values of W_g grow gradually downstream. This tendency is especially evident along the higher right valley slope.

Upper parts of the Volga River Basin, including basins of left tributaries down to the Yaroslavl City, are dominated by slightly rolling forested lowlands. Those are characterized by gully density below 0.05 $1/km^2$ and very low sediment yield (commonly <1.0 $m^3/year/km^2$, rarely exceeding 10.0 $m^3/year/km^2$). From the Yaroslavl City to Nizhniy Novgorod City along the Volga River valley, two types of territories with sharp difference in gully density and area-specific sediment yield can be distinguished: 1) slightly rolling lowlands east from the river; 2) relatively high and dissected uplands west from the river. The former are characterized by minimal values of gully density, sizes and growth rates, determining very low sediment yield from gullies. Only limited parts of the Galich Upland have typical values of sediment yield from gullies reaching 5.0 $m^3/year/km^2$. Uplands to the west from the Volga River, in contrast, are characterized by low to moderate intensities of sediment export from gullies (up to exceeding 20.0 $m^3/year/km^2$). Along the Gorkovskoe Reservoir (the Volga River) banks gully erosion is additionally accelerated by close interaction with active landsliding, both on the reservoir banks and on sides of older larger gullies.

Forested lowlands east from the Volga River between the Nizhniy Novgorod and Kazan cities exhibit very low intensity of gully erosion. Locally increased rates are observed only along the Vetluga River valley at its middle reach, where sediment export from gullies locally reaches moderate values of 50.0 $m^3/year/km^2$.

The Kama River Basin is generally characterized by significant gully density, despite being located entirely within the forest zone. It is a consequence of intensive land use within the basin. The exception is upper parts of basins of the Kama River itself and its main tributaries as well as piedmonts of the northern Ural Mountains. For all those territories gully density is minimal (<0.1 $1/km^2$), and modern intensity of sediment export from gullies does not exceed 1.0 $m^3/year/km^2$. In middle part of the Kama River Basin gullies actively develop mainly on cultivated lands and along the Kamskoe Reservoir banks. Large values of W_g at those areas are associated with interaction of gully erosion with active landsliding in the Pleistocene loessy loam mantle and the Upper Permian (the Tatarian stage) red beds, as well as with active karst processes in areas dominated by carbonate or gypsum bedrock. Moderate values of area-specific sediment yield from gullies (up to 75.0 m^3/year/km^2) are observed in territories of Vyatskie Uvaly and Severnye Uvaly Uplands, spurs of the Verhnekamskaya Upland, in basins of the Siva and Izh Rivers, on slopes of the Kamskoe Reservoir. According to our calculations, highest values 100-200 m^3/year/km^2 and sometimes above 200 m^3/year/km^2 are found along the Kama River valley slopes at its lowest reach and along the Kuibyshevskoe Reservoir slopes.

Almost completely cultivated areas of the forest-steppe and steppe zones are consequently characterized by highest intensities of gully erosion. At present, significant part of gullies within the forest-steppe and steppe zones have already reached its maximum. Despite that, most of those still continue to grow in area and volume. There are also new gullies or new branches of larger gully systems constantly being formed. All the above factors determine generally higher values of sediment export from gullies of forest-steppe and steppe zones comparatively to other natural zones of the European Russia. It is especially evident when one considers upland territories of the Oka River Basin and west of the middle and lower parts of the Volga River Basin (the Srednerusskaya and Privolzhskaya Uplands). In typical case of an upland with local erosion basis depth up to 30-50 m, gullies may form with depth exceeding 5 m, width up to 20 m and cross-sectional area up to 50 m^2. Even for relatively moderate average annual rate of linear growth (>0.5 m/year), intensity of sediment export from gullies averages from 25 to >100 m^3/year/km^2. For example, values of W_g exceeding 50 m^3/year/km^2 are typical for the Srednerusskaya Upland river basins, such as the Zhizdra, Upa, Pronya and Tsna Rivers, as well as for western part of the Privolzhskaya Upland (the Sura and Barysh River Basins).

More localized areas with even higher gully sediment yield (up to 200 m^3/year/km^2) are located along the Oka and Volga River valleys right slopes within middle and lower reaches. The most typical examples of such areas severely dissected by gullies are the Sura, Tsivil and Tereshka River Basins – right tributaries of the middle Volga River. Another locations with very high values of W_g exceeding 200 m^3/year/km^2 are the Volga River valley right slope downstream from the Novocheboksarsk City and the Syzranka River Basin.

In areas with even and lowland topography such as the Oksko-Donskaya Lowland low values of W_g not exceeding 10 m^3/year/km^2 are dominant. In lowest, flat and waterlogged areas such as the Mecherskaya Lowland W_g values <0.1 m^3/year/km^2 are dominant. Similar situation is typical also for the Prikaspiyskaya Lowland.

Interesting information has been obtained by comparison of the present map of intensity of sediment export from gullies with map of typical suspended sediment concentration in rivers compiled by K.N. Lisitsyna based on continuous monitoring data (Sediment yield…, 1977). Certain zonality in intensity of gully erosion and coincidence with characteristics of river suspended sediment yield can evidently be seen. Northern part of the Volga River Basin located within the forest zone is characterized by low values of both suspended sediment concentrations in rivers and area-specific sediment yield from gullies. Middle part of the Volga River Basin, including right part of the Oka Basin and the Vyatka, Kama, Ufa and Belaya River Basins is characterized by considerable intensity of linear erosion and suspended sediment transport in rivers. Highest values of W_g are observed on some parts of the Privolzhskaya Upland and along the high right slope of the Volga River valley itself. At the same locations the increased suspended sediment concentrations (up to 500-1000 g/m^3) are observed in the Volga River itself. This comparison supports the initial statement that gully erosion is one of the important contributors into large-scale fluvial sediment fluxes in the Volga River Basin.

Comparison of volumes of material mobilized on catchment slopes by sheet/rill erosion and gully erosion clearly shows that sediment export from gullies contributes not more than 10% into total volumes of catchment-derived sediment delivered into the medium rivers. On the other hand, when considering small rivers and streams, sediment delivery from gullies dissecting their valley slopes into channels often reaches 100%. At the same time, significant part of sediment flux from sheet and rill erosion on arable hillslopes can be redeposited within stabilized parts of gullies without reaching valley bottoms.

3.4. Modern tendencies of gully erosion development in the Volga River Basin

Published information, results of interpretation of airborne photography (for 1950-1990 period) and results of direct continuous monitoring of gully erosion for different part of the Volga River Basin have been synthesized in this summary in order to give evaluation of general tendencies of gully erosion observed at present (Butakov *et al.*, 2000). Most of information about gully development is represented by measurements of their linear growth, much rarer information on gully area, depth and volume changes is available. Serious problem of data interpretation is arisen from different methods of data acquisition as listed above. Nevertheless, the available large dataset provides some insight on the problem under consideration. Some examples of the largest datasets available in regional and entire basin scales are presented in Tables 3.3 and 3.4.

The longest datasets of direct evidences are available for the two individual gullies. In the end of 19th century on left slope of the Krasivaya Mecha River valley near the Krasnogorskoe village (the Tula region) E.E. Kern described the gully that had been growing already for about 60 years. In 1980 it has been surveyed by group of the Moscow State University scientists (Zorina *et al.*, 1984). Over the first period considered (1831-1891) its average rate of headcut retreat was 7.0 m/year, during the second period (1891-1980) it decreased by 3 times (Table 3.4). Another gully with the longest monitoring history is the Olemetevskiy gully in the Kazan City. Its growth history was reconstructed by Sementovskiy (1940) for the 100-year period (1837-1938). In that gully initial headcut erosion rate for the first 90 years of existence was rather moderate (4.05 m/year), though there may be problem with long-term averaging (gully growth rate at initiation may well have been much larger and decreased later on). Nevertheless, the most intensive headcut retreat took place in short period between 1928 and 1932 – 21.3 m/year, later on it decreased almost twice (Table 3.3). At present the gully has been profoundly modified by urban development and its runoff has become completely regulated. Comparable values of headcut retreat rate over the first 80 years of existence (7.2 m/year) were reconstructed for the gully in the Usa River Basin (the Ulyanovsk Region). In 1967-1977 period that decreased dramatically by 8-10 times (Table 3.4).

Table 3.3. Long-term dynamics of gully headcut retreat in regions of the Tatarstan Republic (the Kama River Basin).

Region	Period	Types of gullies*	Number of headcuts monitored	Average retreat rate (m/year)
Predvolzhie	1958-1980	Slope	145	1.32
		Bottom	427	1.87
	1958-1987	Slope	13	0.33
		Bottom	12	1.61
	1987-1999	Slope	158	0.35
		Bottom	69	0.98
Zapadnoe Predkamie	1955-1974	Bottom	41	1.50
	1958-1974	Bottom	33	1.36
	1957-1984	Slope	59	0.36
		Bottom	123	1.16
	1984-1994	Slope	15	0.45
		Bottom	13	1.20
Zapadnoe Zakamie	1953-1965	Slope	11	2.90
		Bottom	20	4.25
	1953-1980	Slope	45	1.87
		Bottom	89	2.24
	1986-1987	Slope	6	0.50
		Bottom	5	1.20
	1995-1999	Slope	46	0.65
		Bottom	13	0.70
The Kazan City	1837-1928	Bottom	1	4.05
	1928-1932	Bottom	1	21.30
	1932-1938	Bottom	1	12.50

*Here slope gullies are those cutting slopes without any significant pre-existing negative landform, bottom gullies are those incised into bottoms of older negative landforms, in most cases – older stabilized gullies or dry valleys.

For some regions it has been possible to reconstruct rates of gully headcut retreat using airborne photos taken in various years: from the early 1950s for the Tatarstan Republic and from the late 1950s for the Udmurtiya Republic (Table 3.3, 3.4). In the latter case it is possible to investigate large number of gully heads over wider areas – tens and hundreds – making the results obtained statistically significant and avoiding possible bias of random signals from individual monitoring objects. For most of the studied areas decrease of gully headcut retreat rates has been detected. In 1950-1960s average rates were 2-3 times higher than in 1980-1990s (Fig. 3.2, 3.3).

Table 3.4. Long-term data on gully headcut retreat rate in various regions of the Volga River Basin.

Region	Period	Types of gullies	Average retreat rate (m/year)	Source of information
The Tatarstan Republic	1952-1956		2.40	Butakov & Jusupova, 1998
	1956-1959		2.15	
	1959-1966		1.45	
	1966-1975		1.25	
	1975-1982		1.05	
	1982-1990	Slope	0.49	
		Bottom	1.89	
	1990-1999	Slope	0.32	
		Bottom	1.63	
The Udmurtiya Region	1959-1970		2.40	Rysin, 1998, 2000
	1970-1980		1.90	
	1978-1989		1.24	
	1990-1999		1.16	
	1978-1997	Slope	1.26	
		Bottom	1.35	
The Ulyanovsk region	1865-1948		7.20	Armand, 1958; Mironova & Setunskaya, 1980
	1948-1966		2.30	
	1967-1974	Slope	0.47	
		Bottom	1.24	
The Penza Region	1960-1965		7.7	Nikulin, 1979
	1977-1979		3.0	
The Protva River Basin (the Oka River tributary)	1982-1990	Slope	1.36	Veretennikova, 1998
	1991-1999	Slope	0.95	
The Tula region	1831-1891	Slope	7.0	Zorina *et al.*, 1984
	1891-1980	Slope	2.2	

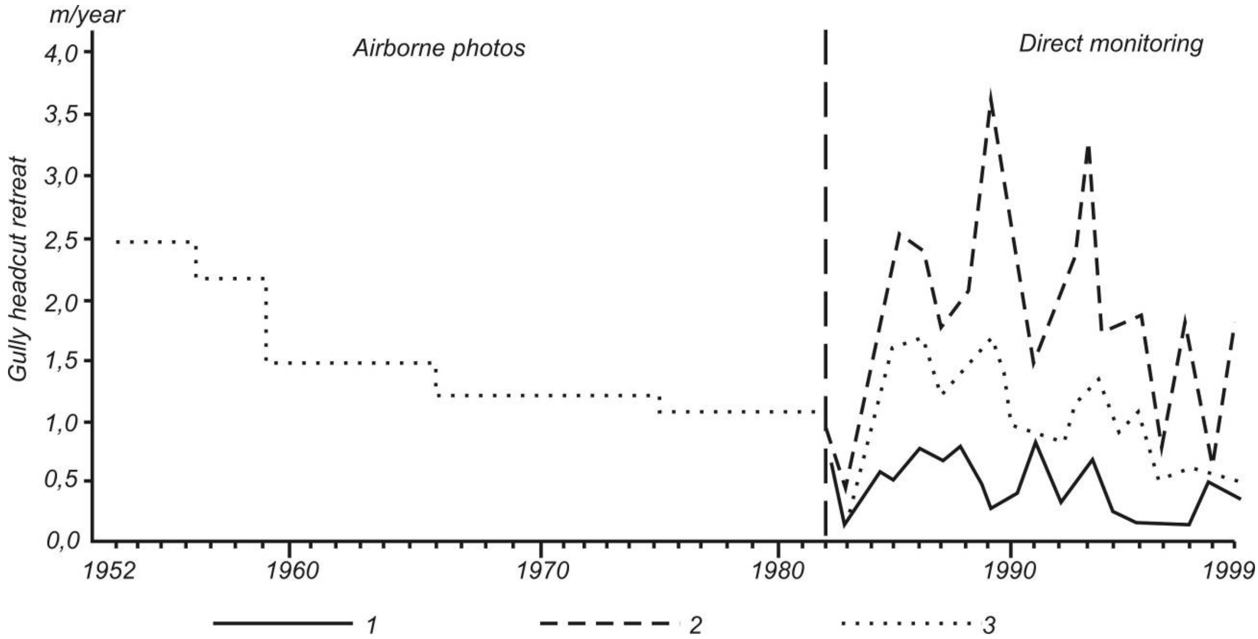

Figure 3.2. Rates of gully growth for the Tatarstan Republic.

Another situation has been discovered by Nazarov (1992) in his studies of gully erosion in foothills of the Ural Mountains within the Perm region. That territory is generally characterized by very low gully network density comparatively to more southern regions. However, average rates of gully headcut retreat in 1980s in that area were by 1.5-2.0 times higher than those in 1950s. Similar temporal pattern has been observed in a number of studied areas within the Udmurtiya Republic northern part (Rysin, 1998). In the Cheptsa River Basin together with decrease of growth rates of long-existing gullies a number of young active gullies have been formed recently.

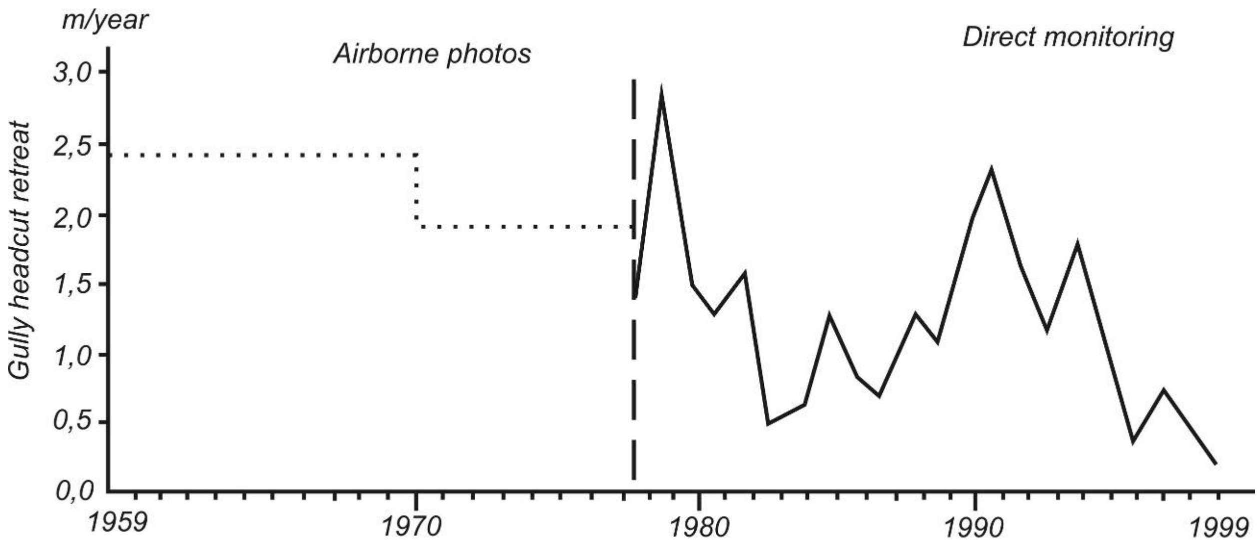

Figure 3.3. Rates of gully growth for the Udmurtiya Republic.

Table 3.5. Numbers of gullies with different maximum annual headcut retreat rates (in % to total number of gullies studied) grouped against land use types in areas of their locations.

Land use type	Number of gullies studied	Maximum annual headcut retreat rates, m/year				
		<5	5-15	15-40	40-80	80-100
Agriculture	169	50	25	15	8	2
Forest cutting	15	25	18	25	7	25
Road construction	17	15	25	30	25	5
Industrial and urban water dumping	19	20	20	25	10	25

Long-term average and maximum annual rates of gully linear growth vary in large range – from <1.0 m/year to >25.0 m/year. It does not prove possible to find any spatial regularity in distribution of gully growth rates, even by analyzing large distributed datasets with hundreds of gully heads considered (Gully erosion of eastern…, 1990). It proves that gully erosion rates are controlled by extremely complex combination of natural (geology, geomorphology, vegetation, climate) and anthropogenic factors. B.F. Kosov, nevertheless, argues that certain relationships between dominant land use type and rates of gully growth should be found (Table 3.5).

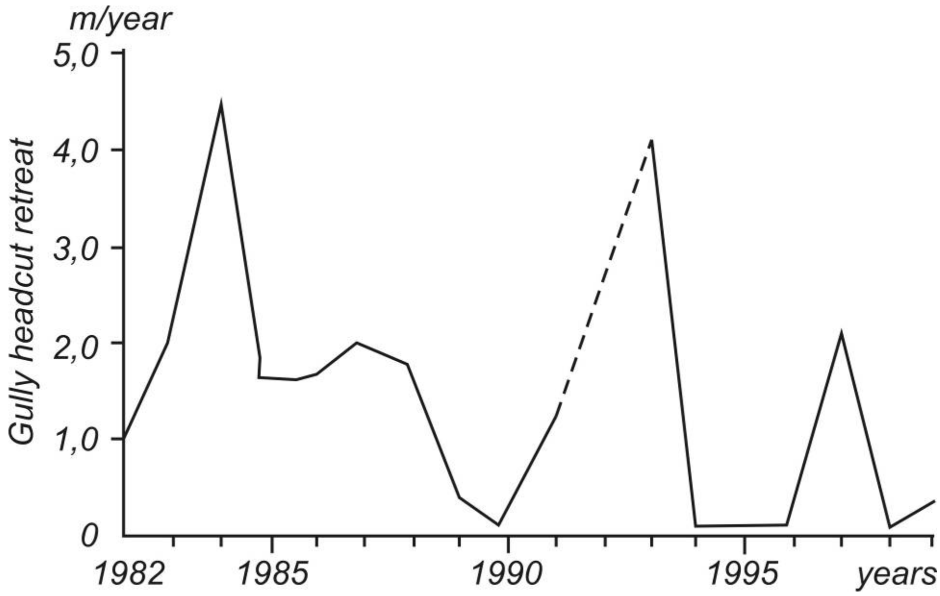

Figure 3.5. Rates of gully growth for the Protva Republic.

These are mainly arable lands where general decrease of gully erosion intensity is presently observed. It is believed that large percentage of gullies on arable land have already reached or just reaching the quasi-stable state, while peak of their activity was observed in late 19th and early 20th centuries (as was mentioned above in review of the temporal pattern of gully erosion in the Volga River Basin). It is especially evident for the most severely dissected areas of forest-steppe ands steppe zones.

The most detailed information on dynamics of gully growth can be obtained by regular (at least 1-2 observations per year) monitoring of selected gullies. In case of 2 observations per year it should be possible to discover contribution of snowmelt and rainfall runoff and associated seasonality of gully growth. Relatively long-term monitoring programs have been carried out in the Tatarstan (Fig. 3.3) and Udmurtiya (Fig. 3.4) Republics and in the Protva River Basin (Fig. 3.5). Shorter but also valuable experiments were established in the Ulyanovsk Region (Mironova & Setunskaya, 1980; Korotina, 1981), Perm region (Nazarov, 1992), Samara region (Milyukov & Kuznetsov, 1986), the Chuvashiya Republic (Sirotkina, 1966). All these datasets more or less certainly support the above trend of generally decreasing rates of gully erosion (Table 3.3, 3.4), though also providing some examples of formation of new active gullies.

The observed general tendency of decreasing rates of gully growth is superimposed on a background of rhythmic fluctuations of the process rates, as individual annual rates measured can differ from long-term average values by a factor of 10 and more (Fig. 3.3-3.5). Statistical analysis has made it possible to distinguish years with both positive and negative anomalies of gully growth rates. We have termed 'significant anomalies' those with individual annual headcut retreat rate differed from long term average by >2 times and 'insignificant anomalies' – those with difference in a range of 1.5-2.0 times (Table 3.6).

Table 3.6. Years with observed anomalies of gully headcut retreat rates in selected regions of the Volga River Basin.

Region	Positive anomalies		Negative anomalies	
	Significant	Insignificant	Insignificant	Significant
The Tatarstan Republic	1991, 1993	1986	1995-1997	1983, 1989
The Udmurtiya Repiblic	1979	1985, 1991, 1994		1983-1984, 1987
The Chuvashiya Republic		1964, 1969	1967	1996-1999
The Ulyanovsk Region		1964, 1969	1974	1972, 1975
The Protva River basin	1984, 1993, 1997			1990, 1994-1996, 1998

In eastern part of the Volga River Basin extremely high rates of gully headcut retreat were detected in 1979, 1991, 1993; insignificantly higher rates – in 1964, 1969, 1985-1986, 1994. In the Protva River basin (100 km south-west from the Moscow City) most of these anomalies appear to be shifted in time to 1-2 years. Insignificantly lower rates of gully growth were observed in 1967, 1974, 1995-1997; extremely low rates (in some cases no growth at all) – in 1972, 1975, 1983-1984, 1987, 1989, 1994, 1996, 1998-1999.

Those directly observed positive and negative variations of gully headcut retreat rates appear to be in notable relation with anomalies of suspended sediment yields in rivers of the Volga River Basin (Dedkov *et al.*, 1997), though it is not possible to talk about coinciding temporal patterns. Strongly fluctuating temporal pattern of gully development is usually regarded as reflection of strong control exerted by meteorological conditions of a particular year. The most important of those are water storage in snow by the beginning of snowmelt period, rate and duration of snowmelt (Gully erosion of eastern…, 1990), magnitude and frequency of summer rainstorms. However relationships between individual meteorological, geological and geomorphic factors have been found to be not very significant. It is therefore necessary to consider the entire complexity of factors, and also allow for stochastic (random to some extent) nature of gully development processes (Sidorchuk, 1999). For example, heavy summer rainstorms can cause catastrophic growth in some gullies and no growth at all in the neighboring ones because of their extremely patchy spatial distribution.

In conclusion, despite strong fluctuations of gully headcut retreat rates between individual years, evident tendency of their decrease is observed in most of the long-cultivated regions of the Volga River Basin. It should be borne in mind, however, that this tendency is the most applicable for gullies being developed on former arable land for relatively long periods of time (up to 200-300 years) and presently reaching quasi-stable state. There are, on the other hand, areas where new (and, therefore, very active) gullies are being formed at present, mainly as a result of negative effects of human activities and current land use changes. Stabilized large gullies can also develop active branches if there are catchment areas available.

In addition to internal gully system threshold of reaching the minimal headcut catchment area, other reasons for the observed tendency are:

1) Positive effects of soil conservation measures applied in 1950-1980s;
2) General decrease of arable areas in 1990-2000s;
3) Shift to more soil-protective crop rotations with high percentage of perennial grasses in 1990-2000s;
4) Decrease of surface runoff irregularity (lower extremes), snowmelt intensity and snowmelt runoff discharges in 1990-2000s.

Active gully development shifts from steppe and forest-steppe zones (where in most cases there are no sufficient slope catchments remaining available for new gullies) to forest zone where new development destroys vegetation on slopes previously unaffected by gully erosion. In areas of long-term gully development on arable land, some new gullies (and very active ones) can still be formed under other land use types. Especially active can be urban gullies, roadside gullies and gullies associated with dumping of industrial or urban wastewaters.

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SECTION 4

SMALL RIVERS OF THE VOLGA RIVER BASIN

4.1. General characteristics of small rivers of the Volga River Basin

Figure 4.1. The Volga River Basin hydrographic network structure.

In application to the Volga River Basin conditions the term ‘small rivers’ is used for rivers with length <200 km and drainage basin area approximately <7000 km^2. This is based on consideration of location of such river basins in more or less uniform landscape conditions (geology, geomorphology, climatic, soil and vegetation zones) and of their hydrological properties. Small rivers are the most numerous within the perennial watercourses network. Differing by their size (order) they comprise more or less dense hydrographic network with specific spatial pattern (see Section 1) that drains most of the larger river basin areas. Networks of ephemeral streams, gullies and hillslope runoff connect small rivers with interfluvial areas of surface runoff initiation. Thus, small rivers are more or less closely (depending on their actual size) linked to processes ongoing in catchment areas and, therefore, rapidly respond to any changes. This important relationship, role of small rivers in conducting fluvial sediment fluxes through to larger rivers as well as their large number and total drainage area determine their crucial role in environmental conditions of any larger fluvial system and in human activities.

There are more than 150000 small rivers in the Volga River Basin (Fig. 4.1) comprising about 99.9% of total number of perennial watercourses (Domanitskiy *et al.*, 1971). Half of that number are located in the Kama River Basin – the main left tributary of the Volga River (Chernyh, 1973). Total length of all small rivers in the basin makes up about 93% of the entire length of the Volga River Basin hydrographic network. Most of the total small rivers length is in turn represented by small streams <10 km long.

4.2. Anthropogenic decrease of small river network length in the Volga River Basin

Small rivers having relatively low discharges are the most vulnerable to natural and human-induced environmental changes. Large scale forest clearance and cultivation has profoundly changed natural state of all levels of fluvial systems in large areas of the Volga River Basin over the last few centuries. Human-accelerated soil and gully erosion are the most important additional contributors of sediment from small catchments into small rivers in comparison to undisturbed conditions. Deposition of large volumes of catchment-derived sediment (see Sections 2-3) in dry valleys (***balkas***), small streams and rivers causes degradation[1] of perennial watercourses. Some insight on scale of these processes is provided by data on total volumes of soil erosion in selected

[1] In general, ***small river degradation*** is understood in Russian fluvial geomorphology as a complex process of siltation and associated pollution of their channels and floodplains, subsequent decrease of length, discharges, quality of water and aquatic habitats as a result of human activities. Here and further in the text it is also used in more restricted sense for decrease of small river length, mainly as a result of human-induced aggradation of their headwaters.

parts of the Volga River Basin over the entire period of intensive cultivation, determined from the USLE-based modelling (Table 4.1).

Table 4.1. Total volumes of soil erosion in selected parts of the Volga River Basin over the entire period of intensive cultivation.

River basin	Area, km^2	Volume of soil erosion, km^3
Upper Volga	265200	5.9
Oka	245000	7.7
Sura	67500	2.2
Vetluga	39400	0.6
Vishera	31200	0.2
Belaya	142000	0.9
Vyatka	129000	4.3
Kama (without Vetluga, Vishera, Vyatka	204800	4.7
Lower Volga (downstream from confluence Kama and Volga	224000	3.3
Volga (entire basin)	1348100	29.8

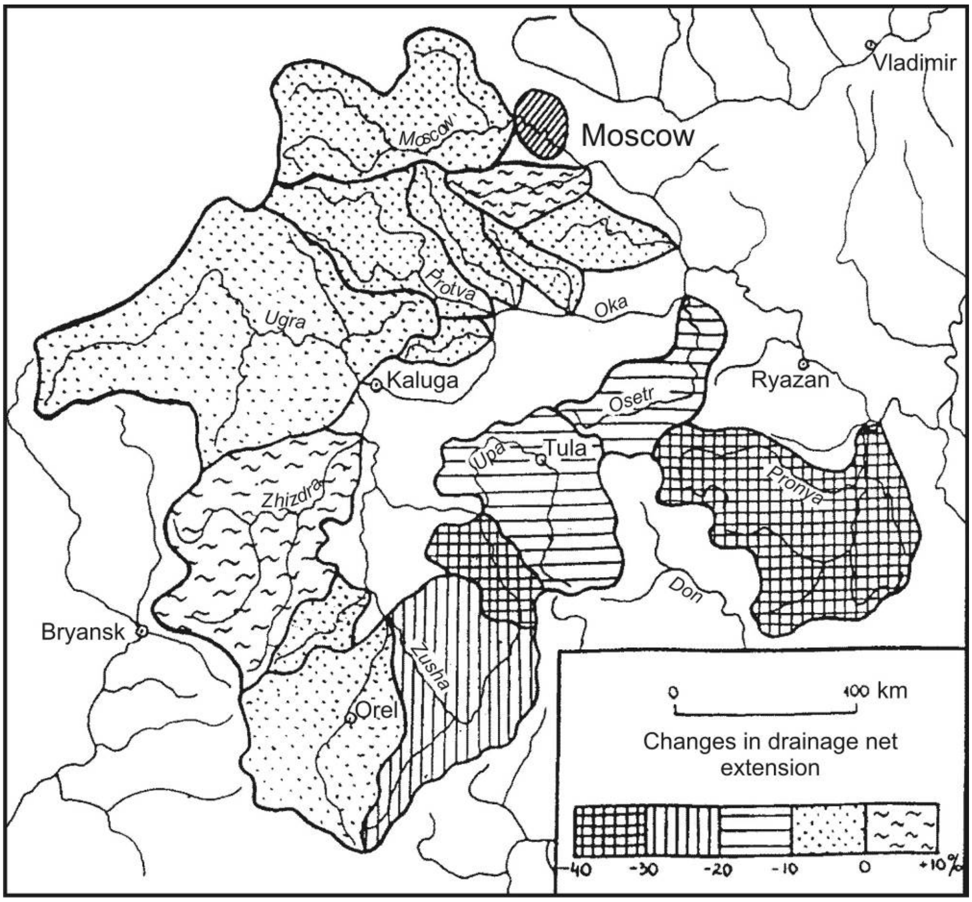

Figure 4.2. Small river network degradation in the Oka River Basin

Non-uniform spatial distribution of cultivation determines different degree of anthropogenic transformations of small rivers in various parts of the basin. As a broad picture, three main parts of the Volga River Basin can be determined in terms of different duration of agricultural land use. In the historical centre of the Russia (the Moscow Region and neighbouring regions) area of cultivated land was equal to the present already in 17th century, while its maximum was reached by the end of 18th century. Afterwards some gradual decline of cultivated areas has been taking place in the region. Further southward, in the Oka River basin headwaters (the Zusha, Zhizdra and Upa River Basins) and in some areas along the middle Volga River rapid expansion of cultivated land began in the end of 18th century and reached the maximum percentage in the end of 19th century. The lower part of the Volga River Basin experienced intensive expansion of arable land only in second half of 19th century, mainly after the 1861 landownership reform.

Dramatic increase of sediment yields from cultivated parts of basins resulted in gradual siltation of small watercourses, up to complete disappearance of some of those. Spatial distribution of small river network length reduction was evaluated on a basis of comparison of measurements of perennial watercourse network length taken from the 1:420000 scale map of 1820-1830 and the 1:300000 map of late 1940s – early 1950s (Golosov & Panin, 1998). Evaluation of length of perennial watercourses based on historical map analysis in the upper and middle parts of the Oka River Basin for the two periods of time (Table 4.2) showed that degradation is evident in absolute majority of the studied basins (Fig. 4.2). The only exception is the Zhizdra River Basin where certain increase of total length of perennial watercourses has been observed. It was associated with increasing length of the southern (forested and largely waterlogged) part of the basin. However, even in some parts of the same basin (the so-called Mechersko-Ulyanovskoe Opolie – the word ***opolie*** standing in Russian for relatively large patch of cultivated land surrounded by virgin lands) substantial decrease of many small rivers was detected. It is also important to bear in mind significant influence of natural factors such as local lithology and topography, groundwater regimes and soil cover on spatial distribution of river network length reduction. For example, length of small river network decreased by 42% on the Srednerusskaya Upland and by 31% in the Oksko-Donskaya Lowland (both are located in the forest-steppe zone), clearly showing importance of more contrasting topography in the first case for higher sediment delivery from arable slopes into adjacent valleys.

In the north-western part of forest zone density of small rivers has decreased insignificantly because of relatively smaller cultivated areas and longer period of agricultural development (not so abrupt changes). Maximum of small river degradation took place during the most intensive expansion of arable land in the end of 18th century. At present sediment budgets in most of small rivers of that part of the forest zone have become more or less stabilized.

Table 4.2. Changes of total length of river network in the upper and middle parts of the Oka River Basin (for a period from 1820-1830s to1940-1950s).

Basin	Area, km2	River network density, km km^{-2}		Changes of total length of river network, %		
		1820-1830 years	1940-1950 years	Total	Increase	Decrease
Moskva (upstream from Moscow)	8000	0.266	0.256	-3.8	2.8	6.6
Pakhra	2440	0.249	0.250	0.4	2.9	2.5
Severka	1490	0.185	0.184	-0.4	0	0.4
Osetr	3250	0.253	0219	-13.3	7.3	20.6
Lopasnya	1080	0.186	0.169	-7.6	0	7.6
Nara	1890	0.232	0.226	-2.6	1.2	3.8
Protva	4520	0.259	0.244	-5.8	3.8	9.5
Tarusa	915	0.312	0.295	-5.6	1.5	6.1
Ugra	15600	0.238	0.220	-4.1	9.4	13.5
Oka (upstream from Zusha mouth)	7280	0.273	0.271	-0.7	17.2	17.9
Nugr'	1550	0.282	0.260	-7.7	10.1	17.8
Zhizdra	2920	0.275	0.292	6.2	20.1	13.9
Pronya	10300	0.293	0.195	-33.4	4.7	38.1
Upa (upstream from Plava mouth)	6310	0.268	0.232	-13.7	11.6	25.3
Plava	1870	0.210	0.136	-35.1	5.9	41.1
Zusha	7000	0.227	0.161	-29.3	4.7	34.0

Small river degradation in the forest-steppe zone exceeds 30% (Fig. 4.2). Present channels of those rivers are in most cases composed of fine silty-clayey material, mainly delivered from catchment sediment sources. In many cases river channels still exist, but almost completely lost as a result of continuous aggradation of fine sediment. In such channels natural pool-riffle sequences are totally lost and channel depth during low-water periods is uniformly not more first tens of centimetres. Natural aquatic habitats are subsequently also severely deteriorated. Rivers at such environmental conditions cannot be used for practically any economical purposes except animal watering. Even worse is a situation with small rivers of the steppe zone. Small river degradation in the steppe reaches 30% for western and 50% for eastern part of the Volga River Basin. In forest-steppe and steppe zones siltation and resulting degradation of small rivers continues actively at present. In steppe zone it increases negative effects of general aridization and desertification of steppe landscapes.

There is however no necessarily direct relationship between rates of soil and gully erosion in a catchment and a river channel degradation, because catchment-derived sediment can partly be redeposited in some intermittent sinks within a catchment. On the other hand, degradation of small river headwaters in itself creates such additional sediment sink in a forming dry valley bottom that may act as buffer zone under favourable conditions. Therefore degradation of small river channels can be regarded as a self-inhibiting process with negative feedbacks providing that cultivated area and land use pattern in a catchment remain unchanged. That is clear from the above that design of effective soil and water conservation measures must be carried out basing on a catchment scale individual approach. Hard task of protection and restoration of small rivers of the Volga River Basin (and elsewhere) requires detailed assessment of catchment areas for determination of main sediment sources, pathways and sinks using GIS-based approach, the most advance techniques for quantification of process rates and remote sensing data for acquiring up-to-date information on land use changes.

4.3. Small river aggradation in the Volga River Basin

QUANTITATIVE ASSESSMENT OF ANTHROPOGENIC AGGRADATION OF SMALL RIVERS IN THE VOLGA RIVER BASIN

Small perennial watercourses are very sensitive to changes in climate and land use. Hydrological and sedimentation regimes of small rivers in the Volga River Basin are at present mainly controlled by changes in the forest cover and proportion of arable land in their catchments. Available data (Golosov & Panin, 1998) show that cultivation of up to 30% of a catchment area affects only the water runoff and sediment yield, without reducing the length of a river system due to aggradation. Data from 130 sites on 75 rivers with basin areas <100 km^2 located in the middle part of the Volga River Basin demonstrate that floodplain deposition rates depend on the area of arable land in the catchment. Total thickness of sediment layer deposited during the period of intensive agriculture is ~1 m for basins with forested areas <20%, and close to zero in the completely forested basins (Kurbanova & Petrenko, 1990).

Acceleration of overbank sedimentation on floodplains is in some cases evident even on large rivers. Archaeological data show that overbank sedimentation rates on the middle Oka River floodplain for the period 2500-200 years ago were ~0.6 mm/year, while over the last 200 years they increased to 6-6.5 mm/year (Glasko & Folomeev, 1981). Thickness of anthropogenic sedimentation in bottoms of a few small valleys (catchment areas 5-40 km^2) was estimated in different regions of the European Russia (the middle Oka River Basin, the lower Volga River Basin, the Samara River Basin). It ranges from 1.0 to 2.8 m, with range of aggradation rates of 3-38 mm/year for different durations of periods of intensive cultivation (50-350 years) (Golosov *et al.*, 1991).

If considering larger rivers, progressively smaller volumes of anthropogenic sediment can be detected with increase of a river length and drainage basin area. Thus, small river network acts indeed as a large-scale buffer protecting higher hierarchical levels of fluvial system from accelerated sediment and pollutant fluxes from the most human-affected small catchment areas. Long-term regular measurements of sediment yield in the Volga River delta show that not more than 6-7% of fine sediment derived from small headwater catchments is transported to the Caspian Sea, and the main part is being intercepted and accumulated in sediment sinks, mainly in upper parts of the fluvial system (Sidorchuk, 1995). This raises serious question of their future behavior. This problem is especially important as large numbers of various fine sediment-bound pollutants is also at present being accumulated in headwaters of the fluvial system, which environmental conditions have been shown above to be crucial for water and aquatic habitat quality throughout the entire fluvial system.

4.3.2. DEFINITION AND SPATIAL DISTRIBUTION OF TYPES OF SMALL RIVER AGGRADATION

Combination of field-based studies and map analysis has made it possible to pinpoint typical forms of small river aggradation (Litvin *et al*, 2003). Their spatial distribution allows the classification of the Volga River Basin on the basis of combination of natural and anthropogenic conditions. The following areas can be distinguished (Fig. 4.3):

1. Areas with predominantly meandering small rivers preserved in their natural, non-aggraded state with distinctive banks and relatively dry floodplain. These areas are not densely populated and have low percentage of cultivated area, being located in the forest zone. Mean channel gradients of 0.2-0.8‰ are sufficient to sustain transport of suspended sediment to the basin outlet.

2. Areas with both aggraded and non-aggraded rivers. Here an incipient aggradation in channels of small streams and rivers immediately adjacent to major cropland and farming areas occurs, while small streams and rivers of comparable sizes flowing through forests and wide floodplains remain in their natural state.

3. Areas in which small streams (of 1st Hortonian order) are mostly aggraded, while other small rivers largely remain in their natural state. These conditions occur in the south of the forest zone and in the forest-steppe zone, where arable land occupies <70% of total area. Most of the sediment from slopes reaches bottoms of small valleys up to 20 km long, where intensive aggradation takes place. This reduces deposition in the slightly larger rivers further down the fluvial system. Thus, small streams and their floodplains act as sediment-intercepting buffer zones between arable hillslopes and larger rivers.

4. Areas with evident aggradation in all small streams and. In steppe zone, under conditions of very intensive cultivation, large-scale water diversion, climate with regular droughts and sharp

flow peaks, sediment yield from slopes can reach both small and medium rivers. The result is that an ordinary channel spreads into a swampy network, in which overgrown with reeds old channel is marked only by firm dry banks.

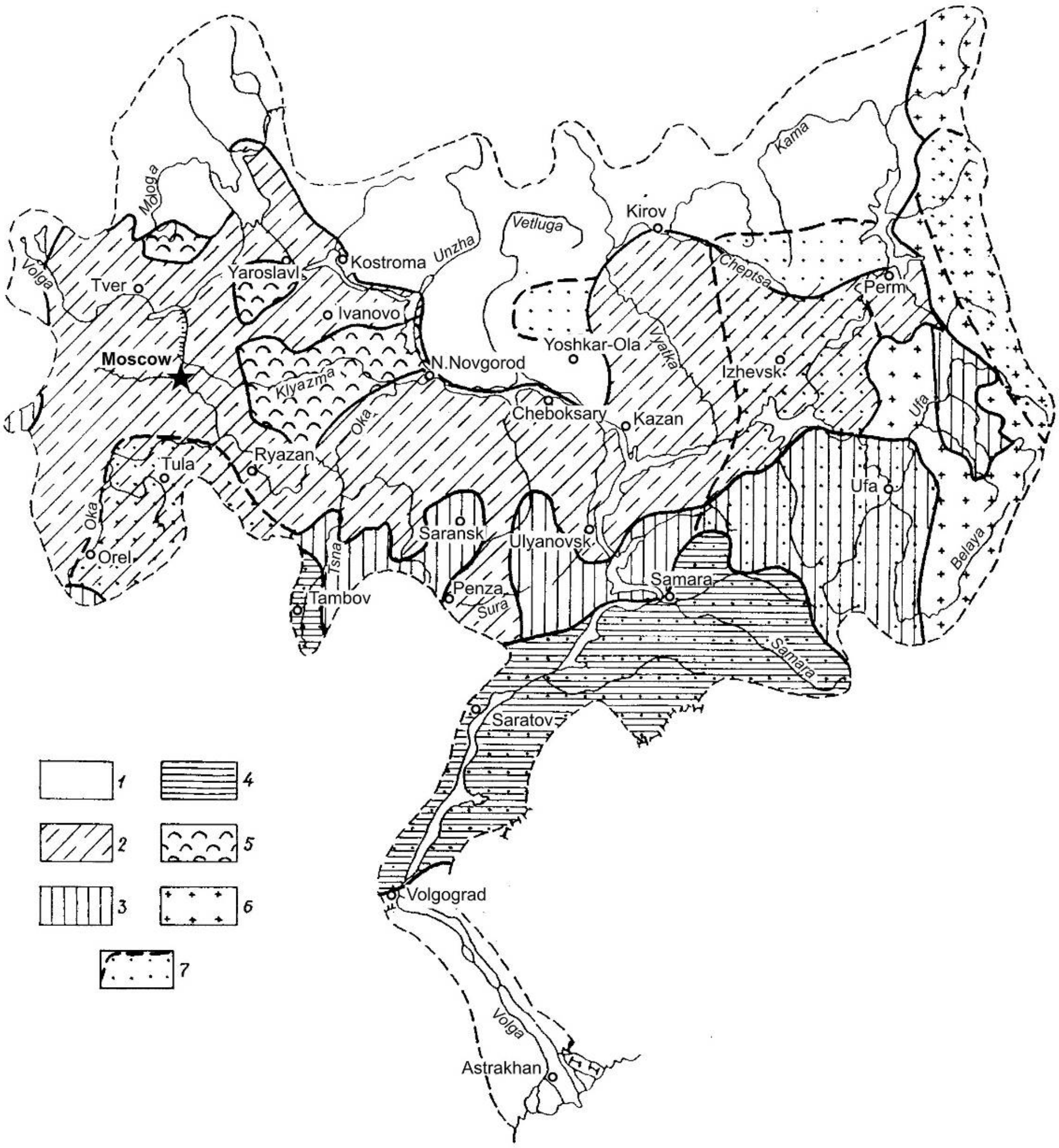

Figure 4.3. Spatial distribution of types of small river aggradation described in the text.

5. Areas in which rivers with waterlogged swampy floodplains predominate. Most of the small rivers flow in disproportional wide (to present river size) valleys mostly inherited from glacial outwash depressions, with very low gradients (0.05-0.15‰). Channel morphological pattern in swampy floodplains is highly erratic. Their width and depth change within very wide range of values (15-20 times). Sometimes distinctive channel disappears and water seeps unconfined through

the swampy and tussocky floodplain surface between separated small ponds. Naturally swampy floodplains are very vulnerable to human-induced aggradation.

6. Areas of high topography range (the Ural Mountains and piedmonts) with dominance of rivers with semi-mountainous and mountainous channels not vulnerable to anthropogenic aggradation because channel gradients are sufficient for a flow to transport much more fine sediment than is delivered from catchment areas.

7. Areas where small river channels have been profoundly affected by widespread construction of small reservoirs.

These areas broadly correspond to the natural landscape zones. Areas with no sedimentation coincide with taiga with their high runoff coefficient. Areas were both aggraded and non-aggraded rivers are found tend to be located to zones of mixed and deciduous forests. Areas with only upper reaches of the rivers affected by human-induced aggradation are mostly located within the forest-steppe zone. Complete aggradation of the entire small river network is typical for the steppe zone with low runoff coefficients. At the same time, however, boundaries of the areas defined above are more complicated than those of the landscape zones. This may be explained by both local specifics of anthropogenic and influence of azonal natural factors (mainly geological and geomorphological). The latter determine shapes of the longitudinal profiles of rivers, local variation of channel gradients and, therefore, downstream alternation of erosion and deposition along the channels.

Northern part of the Volga River Basin (the upper Volga and, to a lesser extent, left part of the middle Oka Basins) are dominated by non-aggraded rivers or aggradation evident in 1st order streams only. However, small river channels in those areas still experience considerable impact of other types of human activities. Their channels are often modified morphologically by such activities as canalization, construction of artificial levees, meander straightening. In the forest-steppe and steppe zones (right part of the Oka, middle and lower Volga Basins) the 1-2 order streams are often affected by construction of small reservoirs. The latter may have both positive and negative effects on environmental conditions of small rivers. During high floods earthen dams can be breached, causing local incision and subsequent deposition of large volumes of eroded sediment in channels and on floodplains further downstream.

Mountainous and semi-mountainous rivers of the Urals are not affected by human-induced aggradation. However, severe impact on fluvial environment on many rivers of the western Urals is exerted by exploration of gravel for constructional purposes (directly from river valleys) and other mineral resources. Effects of those on small rivers of the region is still largely unresearched. Developing programs for protection and restoration of small rivers in scale of the entire Volga River Basin, it will be absolutely necessary to pay special attention for collection and analysis of information regarding this problem.

Under conditions of progressive urbanization and deficit of recreational areas river valleys in the vicinity of large agglomerations experience ever increasing pressure of recreation activities of urban population. That adds specific component in overall anthropogenic modifications of small river environmental conditions. There are some other important factors that must be accounted for when considering causes and consequences of small river siltation and other negative changes of fluvial environment and associated aquatic ecosystems. In urban areas and nearby complex influence of a number of negative processes brings about degradational successions of biocenoses of small river valleys including forest, meadow and aquatic habitats. In each particular case general tendency of successive ecosystem changes can be modified by geomorphic factors and types of human impact. Similar successions also take place in rural areas, but under pressure of urbanization those are more prominent and dynamic. Among a large number of technogenic, economic and constructional impacts on rivers of urbanized areas probably the most dangerous are associated with construction of garages and car parkings in river valleys or on their slopes, causing pollution of waters, soils and sediments by oil products and other chemical substances toxic for all biota. Equally dangerous can be capital development in river valleys, which results in fragmentation of undisturbed habitats and further decrease areas available for recreational purposes.

4.4. Small river floodplains in the Volga River Basin

Main factor controlling conditions of small river floodplains is their inundation during flood periods. It controls overbank sedimentation, thus increasing fertility of floodplain meadow soils. On the other hand, in case of river water and/or sediment being chemically polluted, floodplain inundation will result in degradation of floodplain landscapes as a result of accumulation of pollutants. Duration and depth of floodplain inundation affects their possible use for agricultural purposes and determines risk for construction of social or industrial objects (Avilova et al, 1998).

Floodplain inundation regimes of small rivers of the Volga River Basin is a problem largely unattended by fluvial geomorpologists and hydrologists. Qualitative evaluation of floodplain inundation of small rivers in three parts of the basin (the upper Volga, Kama and lower Volga Basins) different in terms of hydrological conditions shows that its frequency, duration and depth can vary substantially not only within these large regions, but also along a single river. Largest duration and depth of inundation is observed in lower part of the Volga River Basin.

Obviously, largest influence on floodplain conditions is exerted by a river itself. Channel and floodplain together comprise a complex natural system of an active fluvial valley bottom. Consequently, all the present problems associated with small river channel environmental conditions discussed above are equally reflected in conditions of their floodplains. Aggradation of catchment-derived fine sediment affects both channel and floodplain, usually resulting in burying of previously formed floodplain soil under layer of laminated fresh sediment. Such geological structure is widespread among small river floodplains of the Volga River Basin. On the other hand, channel aggradation results in decrease of its flow-conducting capacity and, subsequently, in increased floodplain inundation. In opposite, channel incision in tailrace of a dam turns adjacent floodplain into non-inundated terrace. In both cases floodplain soil fertility and meadow productivity decreases – the latter either become waterlogged or change to dryer steppe-like vegetation. The most intensive ecological successions towards steppe vegetation are observed on floodplains of rivers in forest-steppe and steppe zones. Lower reaches of small rivers presently flowing into the Volga River reservoirs are characterized by complete transformation of floodplain landscapes. Floodplains have been either severely waterlogged or completely inundated.

Thickness of the anthropogenic sediment layer on floodplains of small rivers in south of the forest zone, in forest-steppe and steppe zones depends on land use duration, changes of cultivation practices and spatial pattern of arable land. In eastern part of the Volga River Basin modern rates of floodplain aggradation can reach 1 cm/year (Kurbanova & Petrenko, 1990). Average thickness of anthropogenic layer on floodplains increases from north-west (about 1.0 m) to south-east (about 1.60 cm) along with decreasing percentage of forested areas and the opposite of cultivated land. Accelerated floodplain aggradation and increasing elevation of floodplain surface brings about shift from floodplain to terrace environments.

Another important human impact on small river floodplains is caused by melioration. It seriously changes water regime of floodplain soils and, as a consequence, leads to substantial transformation of vegetation communities. Artificial grading of floodplain surfaces for installation of the "Frigate"-type artificial sprinkling machinery and tillage can lead to severe erosion of floodplain surfaces during high floods. In the Lower Volga Region (steppe and semi-desert natural zones) floodplains of many small rivers have lost their natural properties (especially fertile and well-structured soils) as a result of cultivation and subsequent surface erosion. Such eroded floodplain surfaces instead of being river-protecting buffer zone become an additional source of fine sediment and associated pollutants.

In areas of urban and industrial development floodplains of small rivers experience strong impacts of different types of constructional and engineering activities: construction of roads, above-ground and underground linear communications; earthworks for artificial cuts and fills for creating new constructional sites; development of new sites; etc. Nevertheless, profound impacts of urbanization on catchment areas has made undisturbed parts of small river valleys the only resorts and refuges for wildlife under such unfavorable conditions. Floodplains perform the important compensatory function relatively to river ecosystems as their catchment areas become more and more disturbed by human activities. This compensatory function is especially important in cases when river valleys maintain connections with some undisturbed territories outside the urban areas. In such cases river valleys become a kind of corridors for wildlife, helping to maintain unity of the biosphere on a regional scale. At the same time river valleys can decrease urbanization contrasts caused by specific spatial patterns of city planning – air pollution by exhaustion gases and dust, noise, etc. Complete devastation of small river network taking place in some agglomerations leads to complete ecological blockage of urban areas, disappearance of the majority of biological elements and loss of linkage between urban and undisturbed parts of river basins. Small rivers of undisturbed and urban areas represent natural buffers, acting as 'filters' preventing pollution of larger water bodies further down the fluvial system. This function is realized by substantial transformation of incoming material fluxes of various types (water, solids, solutes) within small river valleys, often associated with changes of their water qualities.

4.5. Case study. Regional-scale evaluation of small river bank erosion rates: the Udmurtiya Republic

Detail study of bank erosion was undertaken within the Udmurtiya Republic (UR), which is located at the north-eastern part of the Volga River Basin (Rysin & Petukhova, 2006). Since 1999, regular annual surveys of lateral channel shift have been carried out on some rivers of the UR in summer. For this purpose, about 300 fixed marks and control points have been installed on actively transforming sections (often on high floodplain levels). Repeated theodolittacheometrical surveys have been conducted on 30 sections annually. The river sections studied are rather diverse, with the intensity of channel processes differing greatly. This provided for classification of rivers into 3 groups according to their morphometry: 1 – very small; 2 – small; 3 – medium and large (Table 4.3).

Table 4.3. Morphometric characteristics of studied rivers.

Groups of rivers	1	2	3
Length, km	<25	25-100	>100
Channel width, m	5-10	15-50	>50
Meander radius, km	0.1-0.15	0.20-0.25	>0.7
Gradient, m km^{-1}	2-2.5	0.6-1.0	<0.2

Values of annual bank retreat vary considerably. During 2003 average bank downcutting rate in the UR was 0.47 m $year^{-1}$. Rates were on average greatest in 2001 (Table 4.4). The greatest average annual rates of lateral channel shift of 1.2 to 3.0 m $year^{-1}$ took place on rivers of the 3rd group, which are characterized by high discharges and flow velocity. The maximum annual rate of bank retreat occurred along river reaches where channel is at least 5-10 m wide. For the 2nd group of rivers, average rates of bank downcutting are between 0.4 and 0.7 m $year^{-1}$ with maximum rates of up to 2-3 m $year^{-1}$. For the streams of the 1st group, estimated values are lower: 0.1-0.3 m $year^{-1}$, though at certain points a shift of 1 m $year^{-1}$ and more has been observed.

The method of fixed marks and control points has its shortcoming: only certain points along actively retreating sections are studied and it is rather difficult to evaluate the whole process. More detailed investigation is possible by making systematic tacheometric surveys of entire channel sections. Conventional theodolits and, later, electronic tachometers have been used for carrying out geodetic surveys. The length of the survey sections ranged from 50-100 to 400-500 m.

Survey data processing has allowed us to create eroded bank plans. From these, not only average and maximum bank retreat rates, but also areas and volumes of erosion can be determined. To compare these, ratios of area and volume of eroded bank to the length of the certain section have been calculated and called the specific area and volumetric erosion rates. The greatest specific areas and volumetric rates of bank downcutting have also been observed on large rivers, varying from 0.4 to 0.8 $m^2 m^{-1}$ and from 2.0 to 17.2 $m^3 m^{-1}$ (Table 4.5).

Table 4.4. Average annual rates of bank retreat of rivers of the UR for the period of 2000-2003 years.

Number	Rivers	Control section (settlement)	Average annual rates of bank retreat, m $year^{-1}$					
			2000	2001	2002	2003	2004	2005
1	Loza	Kushya	-[1]	0.15	0.26	0.12	0.18	0.2
2	Loza	Sundur	0.0	0.23	0.10	0.63	0.22	0.23
3	Loza	Loza	0.14	0.09	0.38	0.36	0.1	0.1
4	Ita	Zura	-	0.27	0.41	0.23	0.17	0.24
5	Tcheptsa	Debesy	0.48	0.44	0.28	0.52	0.15	0.21
6	Lyp	Sosnovy bor	0.43	0.19	0.24	0.24	0.19	0.11
7	Tcheptsa	Barny	-	0.86	0.32	0.68	0.11	0.42
8	Tcheptsa	Kamenoe sadelye	-	1.80	-	1.2	0	1.06
9	Tcheptsa	Kozhilo	-	1.33	1.25	0.31	0.21	0.48
10	Varyzh	Keldikovo	-	0.42	0.32	0.29	0.1	0.21
11	Sepitch	Glazov	-	-	0.82	0.49	0.12	0
12	Ubyt	Tchura	-	0.34	0.13	0	0	0.1
13	Ubyt	Palagay	-	0.23	0.21	0.16	0.1	0.27
14	Tcheptsa	Yar	-	0.43	0.44	1.44	0.26	1.81
15	Tcheptsa	Dizmino	-	1.27	1.65	1.05	0.25	1.3
19	Lekma	Nizhny Ukan	-	0.16	0.07	0	0.14	0.17
20	Sada	Yur	-	0.17	0.10	0.05	0.06	0
21	Lema	Shamardan	-	0.10	0.05	0.08	0.1	0
22	Lekma	Potchinky	-	0.28	0.10	0.14	0.11	0.11
23	Kilmez	Goloviznin Yazok	-	2.24	1.43	0.56	0.2	0.43
24	Arlet	Tchibir-Zyunya	-	0.29	0.23	0.13	0.11	0.2
26	Uva	Uva-Tuklya	-	0.45	0.51	0.37	0.17	0.91
27	Nylga	Hilga	-	0.57	063	0.45	0.14	0.4
28	Vala	Makarovo	0.52	0.98	0.52	0.38	0.21	0.1
29	Bilibka	Shoner	0.10	0.34	0.10	0.16	0.14	0.1
30	Sharkan	Titovo	0.51	0.12	0.56	0.15	0.15	0.1
31	Siva	Gavrilovka	0.27	0.60	0.85	0.23	0.2	0.3
35	Golyanka	Goliany	0.38	0.20	0.25	0.3	0.32	0.4
36	Pozim	Kabanikha	0.44	0.05	0.12	0.28	0.1	0
37	Pozim	Pozim	-	0.10	0.10	0.27	0.14	0.1
38	Izh	Bolshaya Vehya	0.45	0.27	0.28	0.24	0.16	0.1
39	Ludzinka	Yusky	0.33	0.46	0.27	0.13	0.1	0.2
41	Agryzka	Bagrash-Bigra	-	-	0.92	3.15	0	0.35
42	Postolka	Postolsky	-	-	0.45	018	0.13	0.35
43	Bobinka	Abdes-Urdes	-	-	0.09	0.61	0.1	0.4
44	Piz	Novokreshenka	-	0.48	0.04	-	-	-
45	Kobylka	Klestovo	0.35	0.22	0.23	0.13	0.11	0.25
46	Kirikmas	Tavzyamal	-	0.55	0.18	0.72	0.1	0.32
47	Izh	Russkaya Sharshada	0.22	0.12	0.14	0.46	0.1	0.1
48	Varzinka	Yumyashur	-	0.15	0.11	0.2	0.27	0.27
49	Alnashka	Alnashy	-	0.19	0.21	0.15	0.17	0.1
50	Adamka	Grakhovo	0.20	0.25	0.40	0.15	0.19	0.35
51	Umyak	Pussky Kuyuk	0.52	0.45	0.18	0.15	0.1	0.3
52	Umyak	Bazhenikha	-	0.15	0.13	0.13	0.12	0.15
53	Vyatka	Krimskaya Sludka	3.25	3.97	4.53	3.0	1.23	5.9
54	Lumpun	Kharlamovskaya	-	-	-	0.16	0.1	0.1
55	Kilmez	Maliye Syumsy	-	-	-	0.65	0	1.0
Average total			0.48	0.54	0.50	0.47	0.14	0.38

[1] – indicate "not measured"

Table 4.5. Areas and volumes of bank retreat in rivers of the UR for the period of 2001-2002 year.

River	Control section (settlement)	Area (m^2) / specific area (m^2 m^{-1})		Volume (m^3) / specific volume (m^3 m^{-1})	
		2001	2002	2001	2002
Vyatka	Krimskaya Sludka	117.7/0.39	-	5107.7/17.2	-
Kilmez	GolovizninYazok	86.9/0.75	97.0/0.85	378.8/3.29	423.0/3.7
Tcheptsa	Lnozavod-1	170.0/0.41	43.5/021	884.0/2.2	226.2/1.10
Tcheptsa	Lnozavod-2	30.92/0.12	30.5/0.13	160.78/0.64	159.7/0.65
Tcheptsa	Adam-1	28.4/0.12	67.0/0.26	147.68/0.61	348.4/1.36
Tcheptsa	Adam12	-	170.0/0.41	-	885.4/4.29
Tcheptsa	Debecy-1	17.84/0.27	24.0/0.18	1340.23/1.0	175.2/1.29
Tcheptsa	Debesy-2	-	44.0/0.21	-	168.5/0.81
Tcheptsa	Varny	-	37.0/0.19	-	208.0/1.08
Siva	Metlyaky-1	-	116.0/0.47	-	464.0/1.9
Siva	Metlyaky-2	16.9/0.16	46.5/0.61	67.5/0.67	186.0/2.5
Kirikmas	Tavzyamal-1	-	38.5/0.16	-	200.2/0.82
Kirikmas	Tavzyamal-2	15.84/0.08	21.5/0.10	82.37/0.41	179.4/0.82
Uva	Uva	11.74/0.13	17.8/0.18	44.5/0.49	68.2/0.71
Kama,res.	Berkuty	25.76/0.42	29.0/0.51	762.49/12.7	858.9/15.3
Kama,res.	Galevo	-	27.0/0.22	-	810.0/5.53
Sharkanka	Titovo-1	-	24.0/0.27	-	68.3/0.78
Sharkanka	Titovo-2	-	16.5/0.24	-	42.02/0.60
Sharkanka	Shoner	-	10.0/0.17	-	32.5/0.54
Vala	B.Volkovo	38.55/0.19	-	115.05/0.58	-
Bidvayka	Zavyalovo	-	12.0/0.08	-	31.9/0.22

Table 4.6. Rates of systematic channel shifts in the Tcheptsa River basin during 1934-1987 year.

River basin	Number of sections	Maximum shift, m	Minimum shift, m	Average shift, m	Average rate of shift, m $year^{-1}$
Tcheptsa	47	105	9	55.3	1.02
Loza	5	98	35	63.3	1.17
Ita	4	60	30	48.7	0.90
Lekma	14	100	10	22.8	0.42
Ubit	18	30	10	16.1	0.30
Sada	5	30	12	19.0	0.35
Sepitch	50	160	10	40.6	0.75

Meandering channels actively develop in time and space, changing their planforms. The main causes of this are lateral channel deformations. Comparison of air photos taken in 1934 and 1987 (scale 1:10000) has allowed us to estimate the rates of lateral channel migration for the Tcheptsa River and its main tributaries (Table 4.6). For the main river, average channel lateral shift in 53 years has been estimated at 55.3 m (maximum – 105 m, minimum – <10 m), giving an average bank downcutting rate of 1.02 m yr^{-1}. On the tributaries of the Tcheptsa River, the channel deformation has been found to vary from 30 to 160 m, and the range of bank retreat rates are 0.30-0.90 m $year^{-1}$.

The data obtained for the last 4 years has allowed us to consider the dynamics of lateral channel shifts and make some conclusions about the influence of different factors. The major agent in the channel formation is water discharge. This is demonstrated by the higher correlation coefficients for the relationship between channel lateral shift and average annual water discharge (Table 4.7). Table 4.7 also shows that along with the discharge, other natural factors exert considerable influence in bank downcutting intensity. These are rock lithology, slope gradients, radius of meander curvature, soils and vegetation cover.

Intensity of erosion depends on such soil characteristics as resistance to erosion (bank strength) and permeability/infiltration capacity. Soil resistance to erosion has been determined using the approach proposed by Bastrakov (1983). It essentially involves measuring the impact of a single water jet with a knowing hydraulic power onto an undisturbed soil sample placed in a cylindrical steel container. Experiments were carried out on a specially designed apparatus in a laboratory.

Table 4.7. Coefficients of correlation between rate of bank retreat and different natural factors.

Groups of rivers	1	2	3
Water discharge	0.585	0.658	0.782
Stream gradient	0.577	0.451	0.758
Meander radius	0.687	0.381	0.812
Erosion stability	-0.622	-0.440	-0.690
Forest vegetation (% of basin area)	0.314	0.350	0.589

Obtained values of resistance to erosion (*R*) characterize the ability of soil to withstand erosion. The values of *R* vary greatly from 3.15 to 15.5 Newton (N). Erosion stability depends mainly on the soil texture. Average index of *R* for sandy soils is 3.7 N, loamy-sandy soils – 4.3 N, medium-loamy – 6.6 N and clayey-loamy – 10.0 N.

The relationship between erosion stability and bank retreat rates is separately determined for all 3 groups of streams by the calculation of the correlation coefficient. As expected, these are negatively correlated, i.e. the higher the erosion resistance, the lower is the lateral channel shift rate. This relationship is especially clear in the 1st and 3rd groups of rivers: r = -0.622 (1st

group) and r = -0.690 (3^{rd} group). For the most abundant 2^{nd} group or rivers this relationship is weaker (r = -0.440) because of the higher variability of both bank retreat rate and soil resistance to erosion (Table 4.7).

Channel gradient greatly influences the intensity of channel deformations and erosion. When the gradient is high, erosion and transportation capacity of flow increases. Calculated values of correlative ratio confirm this fact (Table 4.8). This linkage is especially clear for large rivers (r =0.758). The values of the 1^{st} and the 2^{nd} groups of rivers are lower (r =0.577 and r =0.451 respectively).

The value of the meander curvature radius also influences the rate of lateral erosion. The higher is the channel curvature, the higher is the flow velocity along the eroded concave bank of a meander. Circular currents directed from concave to convex meander bank are formed within the main flow, which intensify bank erosion significantly. This relationship is rather weak for the 2^{nd} group of rivers (r =0.381). The relationship is closer for the 1^{st} group of streams (r =0.687) and the best for the large rivers of the 3^{rd} group (r =0.812).

Another factor influencing the intensity of riverbank erosion is vegetation cover and in particular forest vegetation percentage (FVP). Values of FVP at control sections change from 10-20% in the southern part of the UR to 70% and more to the north. Calculated values of correlative ratio between the bank retreat rate and the FVP show that some relationship exists between them. However as the linkage is rather weak then FVP does not play the main role in river channel deformation.

The present condition of river channels is also strongly influenced by the extent of anthropogenic activity in river valleys. Its degree and extent is very diverse, especially for large rivers. Small rivers dominate in the region of the UR, and the extent of human impact on their valleys is relatively low. On the other hand, such rivers respond to natural and anthropogenic changes within their drainage basins more intensively and quickly.

Deforestation and intensive cultivation of the drainage basins result in delivering great amount of sediments to small river valleys and channels. It causes intensified deposition and siltation of channels. Ground dams are often constructed in small river valleys, in order to maintain water supply in summer months. During spring floods many such dams can be breached by intensive runoff, flow velocities increase greatly and erosion accelerates. For example, significant bank downcutting has been observed on the Agrizka River (the Izh River Basin) in 2003 as a result of earthen dam breach (Fig.4.8). The maximum value of the bank retreat was more than 8 m in this instance.

Table 4.8. Rates of bank retreat upstream and downstream from bridges (2003 year data).

River (settlement)	Average annual rate of bank retreat upstream from bridges, m $year^{-1}$	Average annual rate of bank retreat downstream from bridges, m $year^{-1}$
Ita (Zura)	0.10–0.15	0.25–0.40
Lyp (Sosnovy Bor)	0.01–0.10	0.50–0.90
Golianka (Golyany)	0.10–0.20	0.30–0.50
Ludzinka (Yusky)	0.05–0.10	0.30–0.40

Construction of some engineering structures, communication lines etc. on river banks and in channels also result in the process of channel regime changes. One of the oldest forms of local engineering effects to river channels is bridge construction. It usually causes flood capacity decrease, which results in the formation of hydraulic jump above the bridge (head wave is greatest at water conveying outlets of road embankments, crossing small rivers) and hydraulic fall below the bridge during floods. That increases specific water discharge and erosion intensity. Sharp changes of the channel morphology and intensification of lateral deformations can take place below the bridges. Some control sections give clear examples of the differences in channel deformation intensity upstream and downstream from bridges where bank retreat rates upstream of bridges are far lower (Table 4.8).

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SECTION 5

SEDIMENT REDISTRIBUTIUON WITHIN THE VOLGA RIVER BASIN

5.1. General large-scale analysis of recent fluvial sediment redistribution within the Volga River Basin

The present subsection of the Report is aimed to evaluate recent and modern fluvial sediment fluxes and storages within the Volga River Basin. The analysis was based on 3 main approaches (Sidorchuk, 1996). River sediment yield was evaluated using the available information on water and sediment discharge monitoring from network of gauging stations operated by the Russian Hydrometeorolgical Service. Some limited results of runoff and sediment transport instrumental monitoring from small valleys and slope catchments have also been used. Potential rates of soil erosion from catchment slopes under different land use conditions were determined using the USLE-based approach (see Section 2 for details). Data from some key locations where soil erosion rates were determined by the soil profile morphology method were used for verification of modeling results and correction of influence of some slope microforms (in particular, soil erosion and redeposition in linear depressions on arable slopes).

The following simplified equation has been used for representation of fluvial sediment budget in the Volga River Basin:

$$W_{es} - W_{ds} + W_{ed} + W_{eg} - W_{db} - W_{dss} - W_{dsr} - W_{dmr} - W_{dlr} = W_{olr} \qquad (5.1)$$

where W is a volume of sediment, first indexes e, d and b stand for erosion, deposition and output respectively. Second indexes stand for: s – slope; d – slope depression; g – gully; b – ***balka*** (small dry valley); ss – small stream valley; sr – small river valley; mr – medium river valley and lr – large river valley.

Shorter fluvial sediment budget equations can be written for different levels of fluvial system. For example, for a single slope it can be written as follows:

$$W_{es} - W_{ds} = W_{os} \tag{5.2}$$

Or for a ***balka***:

$$W_{es} - W_{as} + W_{ed} + W_{eg} - W_{db} = W_{ob} \tag{5.3}$$

The following approximations have been employed to evaluate the sediment budget components in the spatial scale of the entire Volga River Basin. For volume of sediment eroded from slopes W_{es}, as mentioned above, the USLE-based modeling was employed, with some key site data based on soil profile morphology method used for verification. Where data have been available, other independent techniques have been used to test the validity of results. For example, it has been found out that soil erosion rates calculated by the USLE-based model and obtained from soil profile morphology and ^{137}Cs radioactive tracer technique (see Section 2) had a coefficient of correlation about 0.8 (Yakimova, 1988). Good coincidence has been observed between erosion rate values calculated by the model and from soil profile properties on one side and reconstructed from rates of siltation of runoff-intercepting ponds built to prevent gully regressive growth on the other side (Azhigirov *et al.*, 1988).

Volume of within-slope sediment redeposition W_{ds} can be evaluated only indirectly basing on results of numerous field-based studies taking account for detailed land use pattern and, most importantly, presence of natural and artificial sediment-intercepting buffer lines or zones in agricultural slope landscapes (Ivanova, 1990). Such buffer zones are represented by concave slope breaks, lower field boundaries, plough terraces, runoff-intercepting ditches and ramparts, forest shelter belts planted along topographic contour lines, etc. According to data published by Golosov, such buffer zones intercept up to 50-90% of material mobilized upslope and cause its redeposition in associated within-slope sediment sinks. It must be admitted that present attempt of quantitative evaluation of within-slope sediment sinks for such large and diverse territory as the Volga River Basin should be regarded as the very first approach and tentative information only. Numerous detailed field-based studies, preferably including runoff and sediment transport monitoring on slopes with different topography, soils, land use patterns and practices will be required for developing more rigorous assessment of volume of within-slope sediment storage.

Volume of sediment eroded from bottoms of slope depressions W_{ed} has been determined from results obtained at a number of key field sites by soil profile morphology method. It has been established that there is a close relationship between truncation of soil humic horizon along a slope depression and length and gradient of a depression long profile (coefficients of correlation of 0.86 and 0.75 respectively.

Volume of gully erosion W_{eg} has been determined by classifying all gullies into 3 main groups (slope gullies, valley bank gullies and valley bottom gullies) and determining typical ranges of morphometric parameters for each of those from results of field or cartometric investigations. It is also important to determine correctly age of gully systems. For small catchments it can be determined by analyzing ages of soil and vegetation successions on gully banks, as proposed by Moryakova (Gully erosion, 1989). In the present large-scale study it has been assumed, according to hypothesis proposed by Kosov *et al*. (1982), that the absolute majority of gullies in European part of Russia have been formed during the period of intensive agriculture.

Volumes of sediment deposition in bottoms of ***balkas*** (W_{db}) and small stream valleys (W_{dss}) have been evaluated by summarizing results of numerous field-based studies where direct geological surveys were undertaken to obtain detailed picture of spatial distribution of human-induced sedimentation in bottoms of headwaters of fluvial system. Results form such key valleys can be interpolated to other valleys of similar size, geomorphology and geological structure, providing that land use patterns and histories are similar. In case if no key site data is available, it is possible to make some inference about aggradation of a valley bottom by comparing its long profile with the ideal graded shape. However, this approach gives very approximate results with errors possibly exceeding ±100%, while geological surveys provide information with ±5% precision.

Volumes of sediment deposited on floodplains and in channels of small, medium and large valleys (W_{dsr}, W_{dmr} and W_{dlr}, respectively) have been evaluated using data of the long-term monitoring of sediment transport by the Russian Hydrometeorolgical Service gauging station network. However, density of the network is not sufficient to evaluate sediment redeposition in bottoms of all river valleys, especially the smaller ones. In order to overcome this problem, sediment delivery ratios (*SDR*) have been determined for different parts of fluvial system (i.e. for rivers of different order, with different length and drainage basin area) from parts of the basin where direct monitoring data were found to be sufficient. It has been found out that for small rivers with drainage basin area F>100 km^2 in the Volga River Basin the following empirical relationship has been established (see also Section 4):

$$SDR = 0.25 \cdot F^{-0.2} \qquad (5.4)$$

It is obvious that volumes of sediment fluxes and sinks have continuously been varying with time due to both natural and anthropogenic environmental changes. However, for simplification within framework of this tentative study it has been assumed that all those have remained constant over the last 300 years (average duration of intensive cultivation for the entire Volga River Basin). The following SDR values (Table 5.1) have been obtained for different categories of rivers (distinguished by drainage basin areas):

Table 5.1. Average values of sediment delivery ratios SDR determined for rivers with different drainage basin areas within the Volga River Basin (σ – standard deviation, n – number of basins in the category from which the SDR values have been calculated).

	Range of drainage areas, km^2				
	100-1000	1000-10000	10000-50000	50000-100000	100000-1000000
SDR	0.08	0.05	0.04	-	0.02
Σ	0.07	0.07	0.05	-	0.02
N	33	96	28	-	7

Widely used quantitative characteristic of sediment redeposition that can be applied for any part of fluvial system providing that there is available data is the sediment delivery ration *SDR*, determined as a ration of sediment export from a catchment outlet to gross erosion within a catchment. For small rivers with drainage basin area F>200 km^2 in the Volga River Basin the following empirical relationship has been established:

$$SDR = 0.25 \cdot F^{0.2} \qquad (5.3)$$

Combining this equation with reconstructed volumes of soil erosion in small river basins over the period of intensive agriculture discussed above, it is possible to analyze magnitudes of catchment-derived sediment redeposition in valley bottoms of rivers with different lengths and drainage basin areas (Table 5.2). Average thickness of a layer deposited in small river channels and on floodplains in small rivers of different sizes over the period of intensive agriculture has been determined basing on data published by Nezhikhovskiy (1971) about areas of valley bottoms occupied by floodplain and channel in valleys of different Hortonian order. The most intensive anthropogenic aggradation has been taking place in rivers 10-25 km long. Anthropogenic sediment thickness decreases from west to east and from north to south (Table 4.3). Maximum thickness of aggradation is observed in the Oka (H=2.7-3.1 m), Vyatka and upper Kama (H=1.9-2.7 m) River Basins. Towards the north-west thickness of anthropogenic aggradation layer decreases to 1.1-2.4 m (the upper Volga River Basin), to the south-east – to 0.5-1.7 m (the middle and lower Volga Basins). However, it must be noted that the latter areas are characterized by much shorter periods of intensive cultivation, therefore rates of aggradation are higher in the forest-steppe and steppe zones than in the forest zone.

Substantially lower volumes of catchment-derived sediment reached small rivers with length of 25-20 and 50-100 km. Nevertheless, spatial variation of anthropogenic sedimentation in those resembles the one described above for shorter rivers. Maximum of anthropogenic sedimentation in rivers 25-50 km and 50-100 km long is found in the Oka, Sura and Vyatka River Basins (Table 5.2). Values of anthropogenic sediment thickness decrease both northward and southward.

It can be seen that most of the catchment-derived sediment over the last 300 years has been retained in small river valleys 10-25 km long, where the most intensive aggradation has been taking place (see also Section 4). Maximum thickness of aggradation is observed in the Oka (H=2.7-3.1 m), Vyatka and upper Kama (H=1.9-2.7 m) River Basins. Towards the north-west

Table 5.2. Redistribution of catchment-derived sediment in small rivers of the Volga River Basin (in upper row – volume of anthropogenic sediment in channels and on floodplains, km^3, in lower row – corresponding sediment layer thickness, m).

Drainage basin	F	W	K_T	W	River length, km			
					10-25	25-50	50-100	100-200
The Volga River upstream from the Oka River confluence	265200	120	0.90	8.4	3.20	0.20	0.15	0.10
					2.30	0.15	0.06	0.03
The Oka River	245000	180	0.85	11.0	4.20	0.25	0.15	0.15
					3.10	0.20	0.10	0.05
The Sura River	67500	240	0.65	3.1	1.15	0.07	0.045	0.035
					2.15	0.15	0.08	0.07
The Vetluga River	39400	90	0.85	0.9	0.35	0.02	0.015	0.01
					1.10	0.07	0.04	0.035
The Vishera River	31200	40	0.40	0.2	0.075	0.0045	0.003	0.0025
					0.35	0.025	0.015	0.009
The Belaya River	142000	90	0.35	1.3	0.50	0.03	0.02	0.015
					0.50	0.035	0.02	0.015
The Vyatka River	129000	250	0.65	6.1	2.30	0.15	0.09	0.075
					2.70	0.20	0.10	0.07
The Kama River (without the Vishera, Belaya and Vyatka River Basins)	204800	280	0.40	6.7	2.55	0.15	0.10	0.08
					1.85	0.10	0.07	0.045
The Volga River downstream from the Nizhniy Novgorod City	224000	130	0.55	4.7	1.80	0.10	0.07	0.055
					1.65	0.09	0.045	0.035

F is a drainage basin area (km^2); w – area-specific sediment yield from catchment slopes under present conditions (t/km^2/year); K_T – non-dimensional coefficient for transition to average sediment flux from slopes over the 300-year period, accounting for changes of climate, land use patterns, crop rotations and cultivation practices; W – total volume of anthropogenic sediment flux from slopes over the 300-year period (10^9 t).

It can be seen that most of the catchment-derived sediment over the last 300 years has been retained in small river valleys 10-25 km long, where the most intensive aggradation has been taking place (see also Section 4). Maximum thickness of aggradation is observed in the Oka (H=2.7-3.1 m), Vyatka and upper Kama (H=1.9-2.7 m) River Basins. Towards the north-west thickness of anthropogenic aggradation layer decreases to 1.1-2.4 m (the upper Volga River Basin), to the south-east – to 0.5-1.7 m (the middle and lower Volga Basins). Substantially lower volumes of catchment-derived sediment reached small rivers with length of 25-20 and 50-100 km. Nevertheless, spatial variation of anthropogenic sedimentation in those resembles the one described above for shorter rivers. Maximum of anthropogenic sedimentation in rivers 25-50 km and 50-100 km long is found in the Oka, Sura and Vyatka River Basins (Table 5.2). Values of anthropogenic sediment thickness decrease both northward and southward.

Progressively smaller volumes of anthropogenic sediment can be detected in valley bottoms with increase of a river length and drainage basin area. It can be concluded that small river network intercepts most of the human-accelerated sediment and pollutant fluxes from small catchment areas. Long-term regular measurements of sediment yield in the Volga River delta show that not more than 6-7% of fine sediment derived from small headwater catchments is transported to the Caspian Sea, and the main part is being intercepted and accumulated in sediment sinks, mainly in upper parts of the fluvial system (Sidorchuk, 1995). This raises serious question of their future behavior. This problem is especially important as large numbers of various fine sediment-bound pollutants is also at present being accumulated in headwaters of the fluvial system, which environmental conditions have been shown above to be crucial for water and aquatic habitat quality throughout the entire fluvial system.

5.2. Case study 1. Evaluating influence of different factors on sediment redistribution within the Oka River Basin

We have made an attempt to evaluate influence of different factors onto contribution of basin-derived sediment into the total river sediment yield for drainage basins located in the transition zone between forest and forest-steppe zones (the western part of the Volga River Basin) (Golosov, 2006). We believe that in that area the differences of conditions controlling a formation of basin-derived component of river sediment yield are clearly manifested. The Oka River Basin was selected as a study area. It is located on the border between forest and forest-steppe zones (Fig. 5.1).

Data from gauging stations with period of observation exceeding 10 years and without large reservoirs upstream were selected for analysis. The main hydrological characteristics and mean annual suspended sediment yields were determined for each of the studied drainage basins (Table 5.3). The bedload sediment yield was not taken into consideration because of lack of regular measurements at most of the gauging stations. Mean annual sediment yields from basin hillslopes were calculated for each study basin using data obtained from the Map of Erosion-Prone Lands of the European Russia. The map contains information about average rates of soil loss from the cultivated land calculated using a combination of the modified version of USLE (for evaluating rain-storm erosion) and State Hydrological Institute erosion model (for evaluating erosion during snowmelt) (Larionov, 1993). Mean annual sediment yield from hillslopes was calculated for each river basin using the following equation:

$$R_c = \Sigma r_{ci} S_i / S_b \tag{5.5}$$

where R_c is sediment yield from hillslopes, t km^{-2} year^{-1}; r_{ci} is average value of a soil loss rate range taken from the map, t km^{-2} year^{-1}; S_i is area, occupied by a given soil loss rate range on the map, km^2; S_b is drainage basin area, km^2.

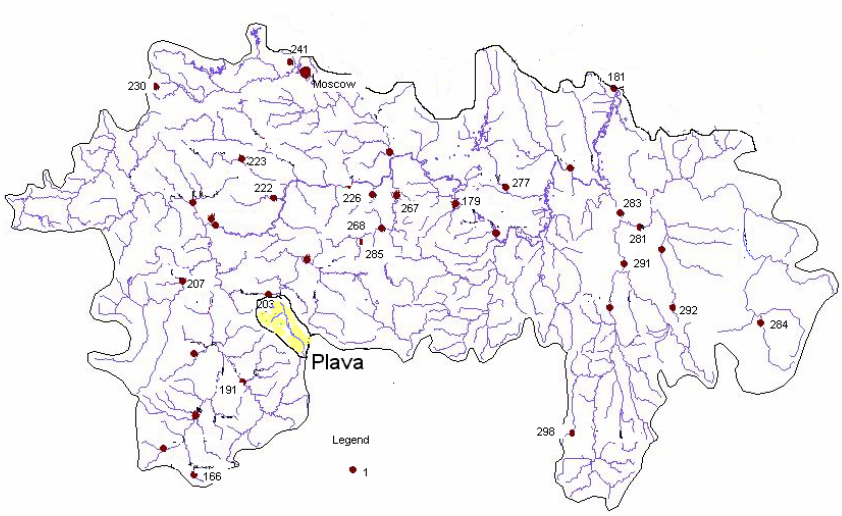

Figure 5.1. Location of the Oka River Basin, 1 – gauging stations.

Areas of the studied drainage basins and cultivated land within those are taken from the Hydrological Reference Books for excluding possible errors resulting from cartographic distortions. Mean gully density (number of gullies per km^2) was calculated from the Map of Gully Density (Kosov *et al.*, 1970) for each of the studied basins using a similar approach (Table 5.3).

Table 5.3. Some characteristics of the Oka Basin rivers.

River	Gauging station ID	Basin area, km^2	Mean annual sediment yield for basin, t km^{-2} year^{-1}		Relationship, M_p/M_c, %	Mean channel gradient, %	Forested area, %	Number of gullies , .unit per km^2	Cultivated area, %
			River, M_p	Slope, M_c					
Oka	166	513	55.0	464	11.9	1.2	7	59	75
Oka	179	54900	19.0	435	4.4	0.12	23	46	55
Oka	181	188000	7.5	317	2.4	-	35	42	59
Zusha	191	6000	53.0	454	11.7	0.32	7	68	67
Upa	203	8210	20.0	461	4.4	0.21	8	60	55
Zhizdra	207	6940	8.5	181	4.7	0.3	46	59	30
Tarusa	222	872	19.0	218	8.8	0.9	46	12	29
Protva	223	3640	7.5	273	2.7	0.28	49	12	27
Osetr	226	3020	17.0	340	5.0	0.43	14	47	64
Moksha	281	15800	13.0	305	4.3	0.18	16	35	60
Moksha	283	28600	9.9	261	3.8	0.18	25	66	50
Atmiss	284	2310	63.0	320	19.7	0.6	9	75	70
Lomovka	285	1110	40.0	266	15.0	1.50	17	37	40
Vad	291	527	25.0	248	10.1	1.80	24	37	45
Vad	292	1930	8.9	174	5.1	0.7	37	37	35
Chelnovaya	298	323	18.0	130	13.8	1.80	1	15	60
Vysha	301	2190	43.0	170	25.3	1.4	6	37	50
Buzha	277	1100	0.5	10	5.3	0.26	65	12	4
Kerd'	270	537	22.7	322	7.0	1.00	5	54	70
Pronya	267	3520	21.0	288	7.3	0.34	4	41	64
Pronya	268	2300	8.0	278	2.9	0.35	3	31	62
Pronya	285	1310	21.0	300	7.0	0.38	3	24	59
Medvedenka	250	40	61.0	737	8.3	0.6	45	12	51
Istra	241	1950	7.1	262	2.7	0.46	60	12	21
Moskva	230	500	7.0	305	2.3	0.33	46	12	25

Under natural conditions, sediment yield of rivers of forest and northern part of forest-steppe zones averages to 0.5-2.0 t km^{-2} depending on basin area (Dedkov & Mozzerin, 1984). It is believed that the relationship between river sediment yield M_p and sediment yield from hillslopes M_c roughly characterizes a sediment delivery ratio for each basin. Mean sediment delivery ratio for the entire dataset analyzed was estimated as 7%, with increasing trend from north-west to the south-east. The above value is in the good agreement with results of field observations and calculations of sediment redistribution within the Oka River Basin obtained by

Starostina (1972). If drainage basins with cultivated areas <25% are excluded from the calculation as weakly disturbed territories, the mean sediment yield for the rest of drainage basins is 16 t km^{-2} with increasing trend from forest zone to forest-steppe zone. The relationship between M_p and M_c for all the river basins analyzed within the Oka River Basin is relatively weak (r^2=0,36), because of differences in runoff formation conditions. But it becomes essentially stronger if the river basins analyzed are subdivided onto two groups according to the landscape zones (Fig. 5.2).

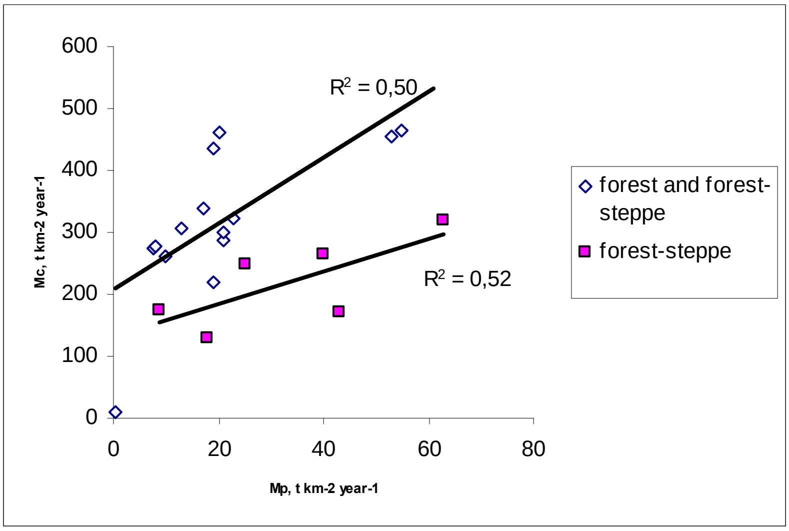

Figure 5.2. Correlation between river sediment yield (M_p) and cultivated slope sediment yield (M_c) for the rivers of the Oka River Basin of different landscape zones: 1 – rivers of forest and north of forest-steppe zones; 2 – rivers of forest-steppe zone.

Rivers of the south-eastern part of the study area, which are completely located within the forest-steppe zone, are characterized by higher input of hillslope-derived component into the total river sediment yield. It is mostly explained by a more intensive snowmelt runoff in that region, leading to delivery of relatively large amounts of sediment from hillslopes to river channels. As a result, the hillslope-derived component constitutes more than 80% of the total river sediment yield. On the other hand, essential part of hillslope-derived sediment is re-deposited within uncultivated hillslope toes and dry valley bottoms of the forest and northern part of the forest-steppe zones. Hence, even within the intensively cultivated areas contribution of basin-derived sediment into total river sediment yield is less than 60%.

There is no correlation observed between a number of gullies and river sediment yield for rivers of the Oka River basin (r^2=0.17). Most of the gullies are believed to have formed in 17-19 centuries, when the cultivated land expanded substantially because of the population growth. At present most of those are at the final stage of development with very low growth and sediment export rates (Butakov *et al.*, 2000). It can be therefore concluded that the gullies are not essential sources of sediment in the study area at present.

Good relationships between forested area within a basin and sediment delivery ratio are established (Fig. 5.3). There is a closer relationship for the small rivers that may be explained by a more sensitive reaction of a small drainage basin sediment yield on the conditions of a surface runoff formation within it.

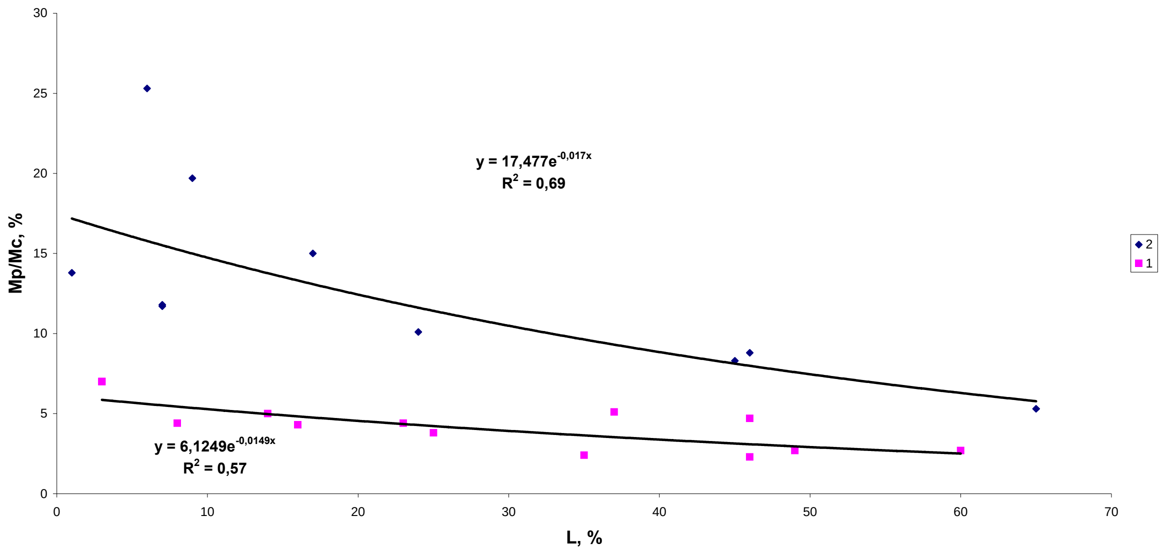

Figure 5.3. Relationship between sediment delivery ratio (*Mp/Mc*, %) and forested area within basin (*L*, %) for rivers of the Oka River Basin: 1 – large rivers; 2 – small rivers.

Total length of the network of perennial watercourses was measured for some river basins within the Oka River basin using maps published in 1826-1839 and in 1940-1950s. Values of stream net density (SND) changes demonstrate clear spatial differences (Table 5.4).

In the forest zone the SND changes are within the range of ±10%, which is considered to lie within the precision of the cartographic method used. In contrast, the drainage basins located at the border between the forest and forest-steppe zones are characterized by the SND values decrease to 20-40%. The more detailed assessment of the SND changes for the period 1820-1980 was made for the Plava River Basin, which drains a central part of the study area (Fig. 5.1). That basin is typical from the point of view of cultivated land dynamics for the transition zone between the forest and forest-steppe zones.

Table 5.4. Change of stream net density in a number of river basins over the Oka River Basin in the 19th and 20th centuries (Golosov & Panin, 2006).

No	River basin	Area (km^2)	Location			Stream net density SND[c] (km/km^2)		SND change (%)
			Latitude[a]	Longitude[a]	Landscape zone[b]	1830s	1940s	
1	Moskva	8000	55.8	36.3	F	0.266	0.256	-3.8
2	Pakhra	2440	55.4	37.2	F	0.249	0.250	0.4
3	Severka	1490	55.3	38	F	0.185	0.184	-0.4
4	Nara	1890	55.2	36.7	F	0.232	0.226	-2.6
5	Lopasnya	1080	55.2	37.3	F	0.186	0.169	-7.6
6	Protva	4520	55.1	36.3	F	0.259	0.244	-5.8
7	Ugra	15600	54.9	35	F	0.238	0.220	-4.1
8	Osiotr	3250	54.6	38.4	F	0.253	0.219	-13.3
9	Zhizdra	9290	53.7	35.4	F	0.275	0.292	6.2
10	Nugr'	1550	53.3	35.9	F	0.282	0.260	-7.7
11	Oka	7280	52.9	35.9	F	0.273	0.271	-0.7
12	Upa	6310	54.0	37.6	F-FS	0.268	0.232	-13.7
13	Pronya	10300	53.9	39.5	F-FS	0.293	0.195	-33.4
14	*Plava*	1870	53.7	37.4	F-FS	0.210	0.136	-35.1
15	Zhusha	7000	53.0	37.1	F-FS	0.227	0.161	-29.3

SND is stream network density.

Table 5.5. Dynamic of stream and dry valley network density in the Plava River Basin (Golosov & Panin, 2006)

River sub-basin	Area (km^2)	Density of dry valley network (km/km^2)		Stream network density in 1830s (km/km^2)	Density of stream network (% of 1830s)		
		1830s	1940s		1908	1940s	1980s
Kholokhol'nya	405	0.309	0.385	0.225	-	66	64
Malyn'	143	0.112	0.224	0.182	-	38	46
Lokna	182	0.225	0.280	0.198	-	72	53
Sorochka	117	0.077	0.239	0.265	-	39	39
Plavitsa	217	0.346	0.378	0.194	67	67	65
Plava upstream the Plavitsa R.	294	0.279	0.354	0.224	65	59	67
Total Plava Basin	1870	0.249	0.322	0.209	-	67	66

In the Plava River Basin the most essential changes of the perennial drainage network occurred from the end of 19^{th} to beginning of 20^{th} century, while during the most of 20^{th} century it was stable, or some small increase of watercourses length was observed (Table 5.5). The latter may be explained by some reduction of arable land area and increase of groundwater runoff after widespread introduction of winter tillage since the middle of 20^{th} century (Golosov & Panin, 1995), as well as by fluctuations of precipitation. High correlation was found between the rate of river network reduction and total valley length in different sub-basins during the period between 1820s and 1940s (Table 5.5). The latter is directly related to decreasing of the hillslope-derived sediment volume reaching the river channels after watercourses disappearance in the 1-3 Hortonian order valleys.

5.3. Case study 2. Sediment budget change in the Zusha River basin during the period of intensive agriculture

The Zusha River Basin (right tributary of the Oka River) is situated within the Srednerusskaya Upland with the altitudes in the range of 140-280 m. It is belong to the western part of the Volga river basin. Mean temperature of January is -9°C, of July is +19°C. The annual precipitation is 570-580 mm, and about 70% comes as rainfall. The catchment is covered by grey forest soils and chernozem on the loess substratum. The contemporary rate of sheet and rill erosion for agricultural lands was calculated by Belotserkovskiy *et al.* (1991) with 2 main Soil Loss models, which were verified for the Russian Plain conditions: There were the State Hydrological Institute Model, which was used for estimation of erosion during the spring snowmelt; and Universal Soil Loss Equation for the period of rainfall. The calculated soil loss rate varies from 3.0 to 10.0 t/ha per year within the basin. The volume of gully erosion (the volume of gullies more than 50 m long) for the period of intensive agriculture was calculated by Kosov *et al.* (1989), the mean value is 640 t/ha.

Retrospective calculations of erosion rates were conducted for several points in time using the method, described by Sidorchuk & Golosov (1993). The change of the main factors was taken into account (Table 5.6). The spring and summer precipitation for the central part of the Russian Plain during the last 500 years was reconstructed by Borisenkov *et al.* (1988). The history of land use and crop rotations was investigated by Krokhalev (1960). Information about changes of the area under cultivation, was taken from the compilation by Tsvetkov (1957) or obtained directly from the statistical yearbooks. The change of the relative intensity of gully erosion was calculated by the ages of 500 gullies, estimated by the soil profile depth measurements (Kosov *et al.*, 1989, Sidorchuk, 1995).

The precipitation amount varied within the range ±10%, and the level of protection of vegetation cover (in terms of *C*-factor of the USLE model) varied within the range ±20% (with the exception of natural vegetation cover). The main factor of temporal change of the slope erosion rate averaged for a subcatchment was the variation in arable land area. The same factor was of the main importance for the gully erosion rate, but significant time lag between commencement of cultivation of virgin lands and formation of developed gullies is apparent (Table 5.6).

Table 5.6. Temporal changes of the main erosion factors in the Zusha River Basin during the period of intensive agriculture.

Year	Annual Precipitation layer, mm	% of arable land	C factor of USLE	Relative rate of sheet and rill erosion	Relative rate of gully erosion
1550	520	0.0	0.005	0.0	0.05
1620	580	14.0	0.28	0.18	0.8
1700	640	42.0	0.28	0.62	0.8
1800	580	51.0	0.28	0.75	1.6
1900	580	62.0	0.43	1.38	2.4
1925	580	47.0	0.43	1.04	1.0
1938	580	71.0	0.43	1.57	1.0
1950	580	44.0	0.36	0.81	1.0
1990	580	54.0	0.36	1.0	1.0

Table 5.7. The main morphometrical, hydrological and erosion parameters of river network within the Zusha River.

N	L km	A_o km^2	q_w m^3/s km	E_s t/ha	E_g t/ha	A km^2	Q_o m^3/s	W m	D m	S	C g/m^3	SDR
1	19	163	0.46E-04	2.0	0.3	163	0.0	9.7	0.65	0.30E-02	529	0.22
2	16	175	0.58E-04	1.8	0.3	175	0.0	10.0	0.66	0.30E-02	525	0.25
3	31	267	0.46E-04	1.8	0.3	605	1.8	23.7	1.01	0.16E-02	437	0.32
4	26	174	0.36E-04	1.8	0.3	174	0.0	10.0	0.66	0.30E-02	525	0.25
5	10	86	0.46E-04	1.5	0.3	865	4.2	31.4	1.16	0.14E-02	412	0.37
6	7	51	0.39E-04	1.5	0.3	51	0.0	5.3	0.49	0.46E-02	600	0.34
7	14	120	0.46E-04	1.5	0.3	1036	4.9	34.3	1.21	0.13E-02	404	0.37
8	32	177	0.29E-04	1.8	0.3	177	0.0	10.1	0.66	0.30E-02	524	0.25
9	9	75	0.44E-04	1.8	0.3	75	0.0	6.5	0.53	0.40E-02	576	0.28
10	29	160	0.29E-04	1.5	0.3	412	1.3	19.8	0.92	0.19E-02	454	0.37
11	26	224	0.46E-04	3.0	1.6	1672	7.7	43.6	1.36	0.11E-02	384	0.32
12	16	104	0.35E-04	1.8	1.6	104	0.0	7.7	0.58	0.36E-02	556	0.27
13	14	88	0.34E-04	1.8	1.6	88	0.0	7.1	0.56	0.38E-02	566	0.27
14	19	124	0.35E-04	1.8	1.6	316	1.0	17.3	0.86	0.20E-02	468	0.36
15	22	100	0.24E-04	1.8	1.6	100	0.0	7.5	0.57	0.36E-02	558	0.27
16	5	33	0.35E-04	3.0	1.6	449	2.2	22.7	0.99	0.17E-02	442	0.39
17	18	155	0.46E-04	3.0	1.6	2276	11.3	51.9	1.48	0.96E-03	370	0.31
18	33	138	0.20E-04	1.8	0.3	138	0.0	8.4	0.60	0.32E-02	524	0.22
19	12	80	0.32E-04	1.8	0.3	80	0.0	6.3	0.53	0.39E-02	556	0.24
20	4	17	0.20E-04	1.8	0.3	235	1.0	15.3	0.81	0.21E-02	460	0.38
21	14	89	0.30E-04	1.8	0.3	89	0.0	6.7	0.54	0.38E-02	550	0.23
22	16	69	0.20E-04	1.8	0.3	393	1.5	19.4	0.91	0.18E-02	438	0.34
23	12	80	0.32E-04	1.8	0.3	80	0.0	6.3	0.53	0.39E-02	556	0.24
24	8	34	0.20E-04	1.8	0.3	507	2.2	22.7	0.99	0.16E-02	423	0.35
25	11	76	0.33E-04	1.8	0.3	76	0.0	6.2	0.52	0.40E-02	559	0.24
26	9	39	0.21E-04	2.0	0.3	622	2.8	25.3	1.04	0.15E-02	414	0.34
27	20	117	0.28E-04	2.0	0.3	117	0.0	7.7	0.58	0.34E-02	534	0.20
28	13	56	0.20E-04	2.0	0.3	795	3.5	28.6	1.10	0.14E-02	403	0.32
29	15	35	0.11E-04	2.0	1.6	35	0.0	4.2	0.43	0.52E-02	609	0.23
30	13	85	0.31E-04	1.8	1.6	85	0.0	6.5	0.54	0.38E-02	553	0.24
31	4	9	0.11E-04	1.8	1.6	129	0.6	11.3	0.70	0.26E-02	491	0.39
32	11	76	0.33E-04	1.8	1.6	76	0.0	6.2	0.52	0.40E-02	559	0.24
33	7	16	0.11E-04	1.5	1.6	221	1.0	14.9	0.80	0.22E-02	463	0.38
34	1	4	0.19E-04	2.0	1.6	1020	4.8	33.0	1.19	0.13E-02	391	0.32
35	12	80	0.32E-04	2.3	1.6	80	0.0	6.3	0.53	0.39E-02	557	0.19
36	6	26	0.21E-04	2.0	1.6	1126	5.2	34.6	1.21	0.12E-02	387	0.31
37	16	87	0.26E-04	1.3	1.6	87	0.0	6.6	0.54	0.38E-02	550	0.33
38	6	26	0.21E-04	2.0	1.6	1239	5.7	36.3	1.24	0.12E-02	383	0.31
39	11	76	0.33E-04	2.3	1.6	76	0.0	6.2	0.52	0.40E-02	560	0.19
40	4	17	0.20E-04	2.0	1.6	1332	6.2	37.8	1.27	0.11E-02	380	0.31
41	30	156	0.25E-04	1.8	1.6	156	0.0	8.9	0.62	0.31E-02	517	0.22
42	12	52	0.21E-04	2.0	1.6	1540	7.1	40.4	1.31	0.11E-02	375	0.30
43	14	120	0.39E-04	3.3	1.6	3936	17.5	64.2	1.64	0.79E-03	336	0.25
44	26	176	0.31E-04	2.3	1.6	176	0.0	9.3	0.64	0.30E-02	507	0.16
45	16	138	0.40E-04	3.3	1.6	4250	18.9	66.8	1.67	0.77E-03	333	0.24
46	11	76	0.32E-04	2.3	1.6	76	0.0	6.1	0.52	0.40E-02	556	0.18
47	3	26	0.40E-04	3.3	1.6	4352	19.9	68.1	1.69	0.76E-03	332	0.24
48	33	237	0.33E-04	2.5	1.6	237	0.0	10.8	0.69	0.27E-02	491	0.14
49	19	164	0.40E-04	3.3	1.6	4753	21.1	70.7	1.72	0.74E-03	329	0.23
50	11	76	0.32E-04	2.3	1.6	76	0.0	6.1	0.52	0.40E-02	556	0.18
51	4	32	0.37E-04	3.3	1.6	4861	22.2	72.0	1.74	0.73E-03	328	0.23
52	19	106	0.26E-04	2.3	1.6	106	0.0	7.2	0.56	0.35E-02	536	0.17
53	13	84	0.30E-04	2.3	1.6	84	0.0	6.4	0.53	0.38E-02	550	0.18
54	18	101	0.26E-04	2.3	1.6	291	0.9	15.6	0.82	0.21E-02	454	0.24
55	8	69	0.40E-04	3.5	1.6	5221	23.6	74.5	1.77	0.71E-03	326	0.22

56	42	229	0.25E-04	2.5	1.6	229	0.0	10.7	0.68	0.27E-02	493	0.14
57	17	115	0.31E-04	4.3	1.6	115	0.0	7.5	0.57	0.34E-02	534	0.09
58	23	125	0.25E-04	4.3	1.6	469	1.6	20.3	0.93	0.17E-02	430	0.16
59	55	280	0.23E-04	4.0	1.6	280	0.0	11.8	0.72	0.25E-02	483	0.09
60	8	44	0.25E-04	4.3	1.6	793	3.4	28.2	1.10	0.14E-02	401	0.15
61	17	90	0.24E-04	1.5	1.6	90	0.0	6.6	0.54	0.37E-02	545	0.26
62	15	96	0.29E-04	1.8	1.6	96	0.0	6.8	0.55	0.37E-02	541	0.22
63	12	64	0.24E-04	4.0	1.6	250	0.9	14.8	0.80	0.22E-02	460	0.26
64	27	147	0.25E-04	3.5	1.6	1190	4.8	34.1	1.20	0.12E-02	385	0.16
65	5	43	0.39E-04	3.0	1.6	6454	29.4	83.2	1.86	0.66E-03	318	0.20
66	18	100	0.26E-04	4.0	1.6	100	0.0	7.0	0.55	0.36E-02	542	0.10
67	10	86	0.39E-04	3.0	1.6	6640	30.1	84.3	1.88	0.65E-03	317	0.19

N – number of the channel reach; *L* – length of the reach; A_o – area of subcatchment, contributed to the reach; q_w – lateral discharge; E_s – slope erosion rate (minus sedimentation on the field); E_g – gully erosion rate; *A* – basin area, contributed to the end of the reach; Q_o – discharge at the upper link of the reach; *W* – channel width; *D* – channel depth; *S* – channel gradient; *C* – sediment concentration at the end of the reach (calculated); *SDR* – delivery ratio (calculated).

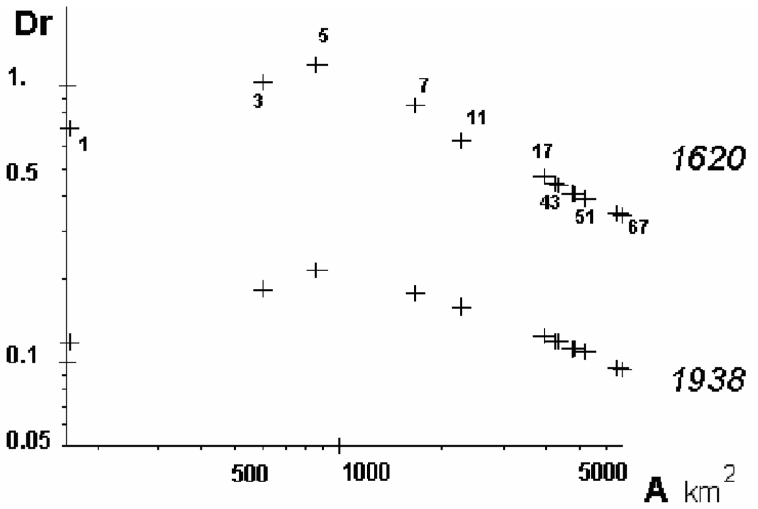

Figure 5.4. Change of sediment delivery ratio along the main channel of the Zusha River for conditions of low (1620) and high (1938) human impact (points labels are the *N* values in Table 5.7).

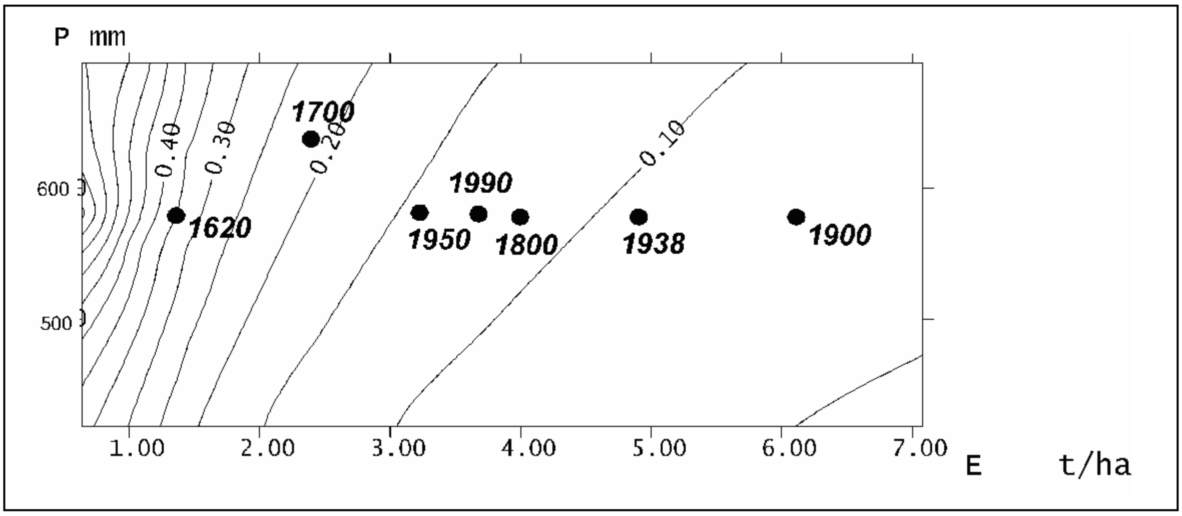

Figure 5.5. Temporal change of sediment delivery ratio of the Zusha River system during the period of intensive agriculture. Isolines shows *SDR* variance with climate (annual precipitation layer *P*) and degree of human impact (erosion rate *E*).

Structure of river network (more than 10 km long) and the main morphometrical and hydrological parameters were derived from the Russian Hydrometeorological Service data (Table 5.7). All these parameters correspond to the mean annual discharge, as the erosion at the basin takes place mainly during the summer rains. Suspended sediments are composed mainly of silt with mean V_f=0.002 m/s. The content of these particles in the bottom alluvium is P=10-20%. The coefficients in formula of Kamalova (1984) are k_b =2.5 (if C is in g m^{-3}), m=0.46, n=0.54. Recent rates of erosion were obtained from Belotserkovskiy *et al.* (1991) and Kosov *et al.* (1989).

The results can be analysed in the form of relations between delivery ratio and basin area along the main channel (Fig. 5.4). At 16th century, under natural condition with a very low level of slope and gully erosion *SDR* was higher than 1.0 for the entire basin (conditions of channel erosion). Under conditions of low level of human impact at the beginning of 17th century, when 14% of the river basin was tilled, the value of *SDR* became less than 1.0 for the main part of the basin (Fig. 5.4). Under conditions of high level of human impact in 1938, when the river basin was tilled over 71% of its territory, the value of *SDR* became less than 0.2 for the whole basin (Fig. 5.4). Only 8-9% of eroded sediment was delivered to the system outlet.

The total sediment output from the system decreases with an increase in arable land area and increases with precipitation growth (Fig. 5.5). The exponent '*b*' in relationship $SDR=a\ A^b$ (where A is a drainage basin area), which represents the rate of change of sedimentation along the channel, is constant for these numerical experiments (Fig. 5.4) and has a value of about -0.45 for the lower reach. Locations of the points, related to different years of agricultural history in the Zusha River Basin and to different levels of human impact and climatic conditions (Fig. 5.5), show the main sedimentological characteristic of the system i.e. sediment output from the system.

It can be concluded that fluvial system of the Zusha River Basin, which is typical for forest-steppe zone of the Volga River Basin, is very sensitive to the degree of human impact.

Human impact is at present the main factor controlling temporal change of sediment delivery ratios along the system, with the climatic factor being second in importance.

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SECTION 6

MEDIUM AND LARGE RIVERS OF THE VOLGA RIVER BASIN

6.1. Sediment yield and channel processes in rivers of the Volga River basin

This summary presents the results of investigations of sediment yield in rivers of the Volga River Basin (Chalov & Shankova, 2003). Most of the large and medium sized rivers and some longest from the category ‘small rivers’ (150-200 km long) were covered by this investigations, providing that there have been sediment yield-measuring gauging stations on those rivers. Beyond the scope of this investigation were completely regulated parts of the Volga Kama and a few other smaller rivers now turned into cascades of dams and reservoirs. Therefore, the maps presented below show only do not show the lower narrow part of the Volga River Basin, because it has no perennial tributaries and the main river itself has not been considered.

Suspended sediment yield has been estimated using empirically established relationships between water (Q) and suspended sediment (R_S) discharges measured at certified gauging stations of the Russian Hydrometeorological Service. Maximum number of gauging stations and amount of available data has been used for analysis. Importantly, this study also includes the first attempt to evaluate bedload sediment yield and its contribution into total sediment yield using the approach developed by N.I. Alekseevskiy (Alekseevskiy & Gaikovich, 1987; Alekseevskiy, 1998). It is based on relationships between morphometric parameters and rate of migration of alluvial bedforms and order of a river, established separately for different phases of hydrological regime (effectively, high-water and low-water periods).

Basing on the two approaches described, it has been possible to create a series of maps illustrating spatial pattern of river sediment yield within the Volga River Basin (Fig. 6.1-6.3). These include map of average annual suspended sediment concentration (*SSC*) (Fig. 6.1), map of average area-specific annual suspended sediment yield (*ASSY*) (Fig. 6.2) and map of percentage ratio ($W_B/W_T \times 100$) between annual bedload sediment yield (W_B) and total annual sediment yield ($W_T=W_B+W_S$) (Fig. 6.3).

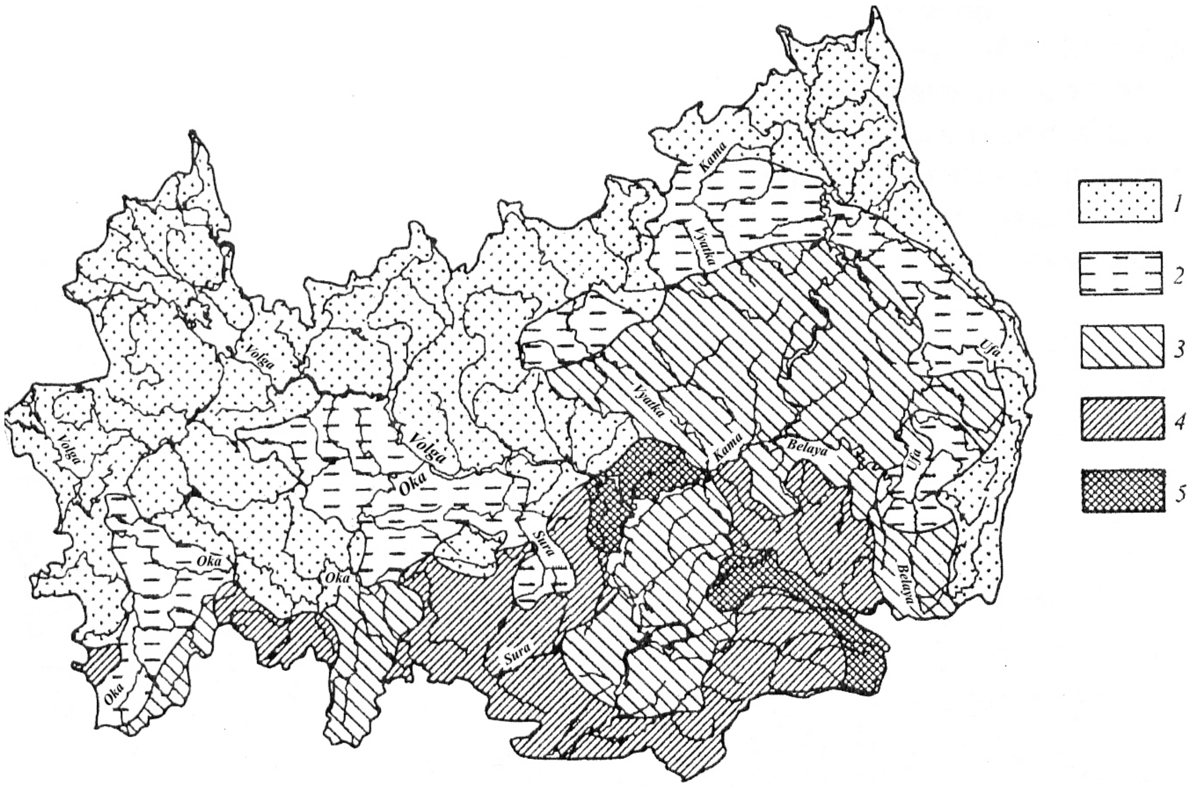

Figure 6.1. Average annual suspended sediment concentration in rivers of the Volga River Basin (without the lowest Volga reach). The *SSC* value intervals are: 1) <50 g/m^3; 2) 50-100 g/m^3; 3) 100-200 g/m^3; 4) 200-500 g/m^3; 5) >500 g/m^3.

The map of *SSC* shows 5 categories of areals (see Fig. 6.1 and its legend) according to changes of typical *SSC* values. Boundaries of areals were drawn taking into account spatial patterns of surface lithology and soil cover in the Volga River Basin. Lowest SSC (<50 g/m^3) characterizes rivers of the upper Volga Basin north from the north-western part of the Oka River Basin, left tributaries of the middle Volga River, rivers of the middle Vyatka River Basin and north part of the Kama River Basin. Areals of the lowest *SSC* form almost continuous belt across the northern part of the Volga River Basin with irregular southern boundary. Lowest *SSC* values are also observed on rivers of eastern part of the Kama River Basin flowing from the Ural Mountains and their foothills. In general, this zone is limited to forest zone with ***soddy podzolic soils*** and also to mountainous regions. From the south of the above zone there are few separated areals characterized by *SSC* values in a range of 50-100 g/m^3. Territories characterized by *SSC* values in a range of 100-200 g/m^3 are located in southern forest-steppe part of the Oka River Basin (the Srednerusskaya Upland), central and southern parts of the Kama River Basin (dissected upland areas of the Ufimskoe Plateau, Sarapulskaya, Bugulminsko-Belebeevskaya, Verhnekamskaya and Vyatskiy Uval Uplands). All these areas are characterized by high percentage of arable land (40-60% and higher) and high risk of soil erosion.

Steppe areas along the lower Volga River typically have higher *SSC* values in a range of 200-500 g/m^3 (Fig. 6.1). High suspended sediment yield can be explained by intensive cultivation of upland landscapes on easily erodible loessy loams where soil erosion is very intensive. Areals within even higher *SSC* values include the Mesha River Basin (interfluve between the Volga and Kama Rivers), small rivers of the Privolzskaya Upland and upper reaches of the Buzuluk, Samara, Tok, Sok and Bolshoy Kinel Rivers (Chalov & Shankova, 2003).

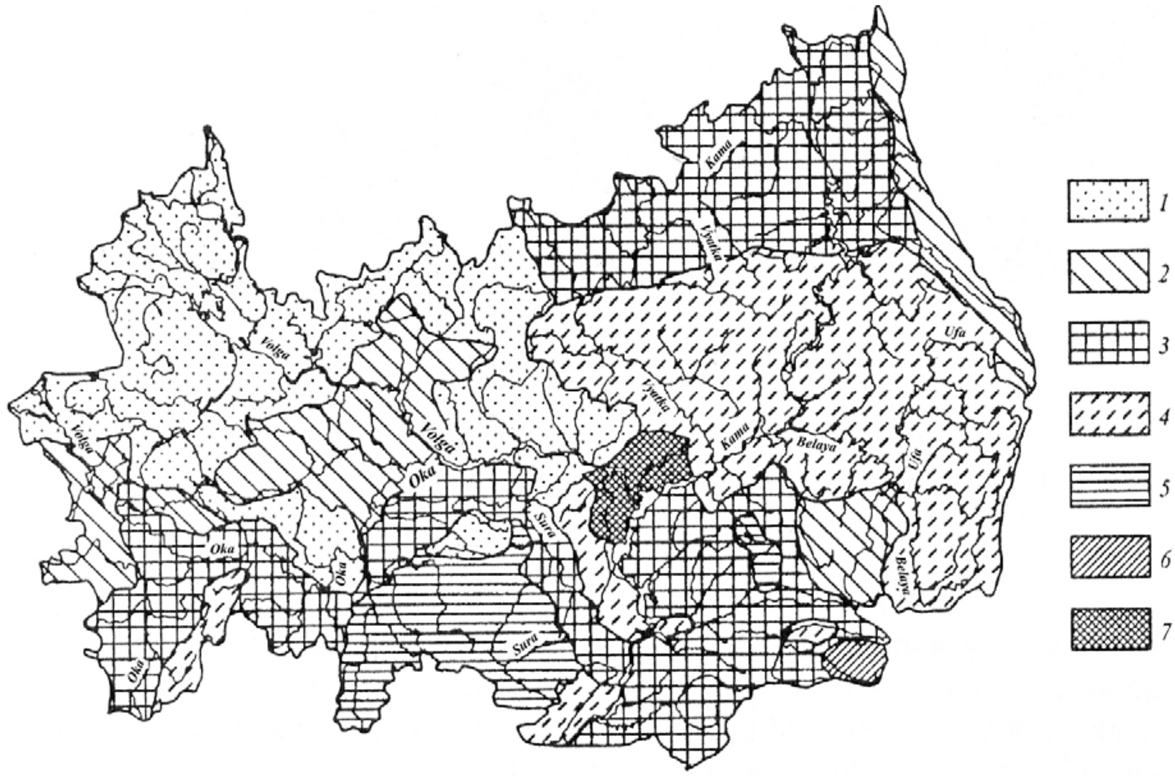

Figure 6.2. Average area-specific annual suspended sediment yield in rivers of the Volga River Basin (without the lowest Volga reach). The *ASSY* value intervals are: 1) <5 t/year/km^2; 2) 5-10 t/year/km^2; 3) 10-20 t/year/km^2; 4) 20-30 t/year/km^2; 5) 30-40 t/year/km^2; 6) 40-60 t/year/km^2; 7) >60 t/year/km^2.

On the map of average area-specific annual suspended sediment yield (*ASSY*) 7 categories of areas has been distinguished according to values of this parameter (see Fig. 6.2 and its legend). Spatial distribution of the *ASSY* values generally resemble that of the *SSC*, though the pattern is somewhat more mosaic. There is general tendency of increase of the *ASSY* values from north to south. It is the most evident within the Kama River Basin, which has quasi-longitudinal elongation through a number of landscape zones from taiga to dry steppes. In the Oka River Basin that tendency is rather unclear, obviously because it is located entirely in southern part of the forest zone being elongated in quasi-latitudinal direction. Most of rivers of the upper Volga Basin are characterized by lowest values of *ASSY*.

Variety of conditions influencing sediment mobilization and routing in western part of the Volga River Basin (mainly in the Oka River Basin) is reflected in changes of the *ASSY* values along the larger rivers (Fig. 6.2). Along the Oka River the *ASSY* values decrease downstream as it receives tributaries (the Zhizdra and Ugra Rivers, rivers of the Mecherskaya Lowland) having low suspended sediment concentrations. Along the Moksha River the *ASSY* values also initially decrease downstream (towards the central part of the Oksko-Mokshinskaya Lowland), but then grow back further downstream (the river crosses the Oksko-Tsninskiy Upland). Along the Klyazma River the *ASSY* values initially increase downstream as the river flows through the Vladimirskoe ***Opolye*** with high soil erosion rates, but then begin to fall once the river leaves the actively eroded areas.

In the Kama River Basin highest values of the *ASSY* (30-40 t/year/km^2) are found in central and lower parts, including upper and lower parts of the Vyatka River Basin and most of the Belaya River Basin. Lowest values (<10 t/year/km^2) correspond to mountainous areas and central parts of the Bugulmisko-Belebeevskaya Upland. Intermittent *ASSY* values are observed in northern part of the Kama River Basin under taiga forests and slopes of the Bugulmisko-Belebeevskaya Upland towards the Kuibyshevskoe Reservoir on the Volga River.

In lower part of the Volga River Basin left tributaries flow through the lowland areas, while right tributaries descend from short steep slopes of the Privolzhskaya Upland. Consequently, the latter are characterized by higher *ASSY* values (20-30 t/year/km^2), as the

Tereshka River and middle reach of the Sviyaga River. On the left side of the basin, however, there is also localized area of very high *ASSY* values (40-60 t/year/km^2), most likely associated with local geomorphological factors (more dissected topography). This area of high *ASSY* values coincides with zone of maximum *SSC* values (upper reaches of the Samara, Bolshaya Kinel and Sok Rivers). Absolutely maximal values of *ASSY* (>60 t/year/km^2) characterize upper reach of the Sviyaga River and the entire Mesha River, also in accordance with maximum values of *SSC*.

In conclusion, the lowest (<5 t/year/km^2) values of *ASSY* are typical for rivers of the upper part of the Volga River Basin and central part of the Oka River Basin. In eastern part of the Volga River Basin (mainly in the Kama River Basin) such low values of *ASSY* have not been observed at all. Maximum values of *ASSY* (>40 t/year/km^2) have been observed in steppes of lower part of the Volga River Basin (Chalov & Shankova, 2003).

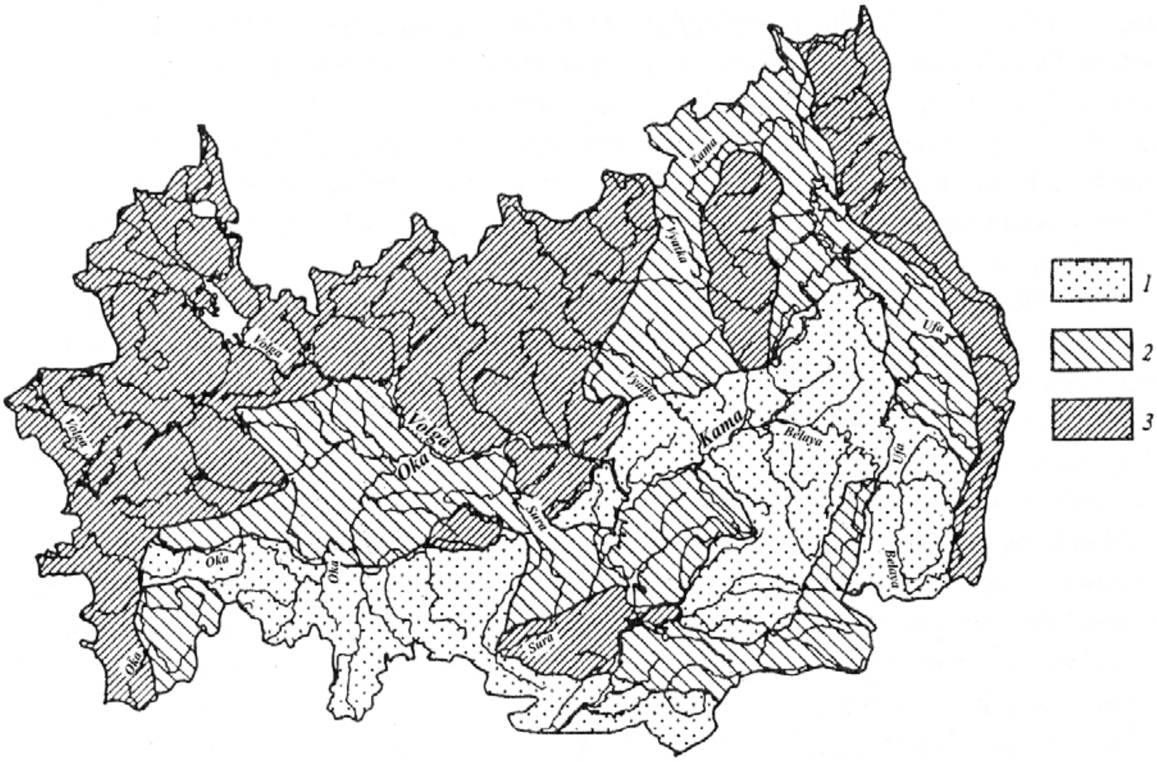

Figure 6.3. Contribution of bedload annual sediment yield into total annual sediment yield in rivers of the Volga River Basin (without the lowest Volga reach). The (W_B/W_T×100) value intervals are: 1) <25%; 2) 25-50%; 3) >50%.

The map of ratio of annual bedload sediment yield to total annual sediment yield for rivers of the Volga River Basin shows that distinctive differences in this parameter important for river channel deformation processes do occur within the studied area. Areals on the map have been distinguished according to 3 categories of ratio ($W_B/W_T\times100$) typical for the studied river basins (see Fig. 6.3 and its legend). Their distribution is generally opposite to that of the suspended sediment yield characteristics (see Fig. 6.1-6.2). Maximum contribution of bedload sediment (80-90%) is observed in rivers of the upper Volga Basin (the Kema, Andoga, Suda and Chagodoscha Rivers) and mountainous part of the Kama River Basin (the Kolva, Vishera, Sylva, Ay, Chusovaya and upper Belaya Rivers). In the former case it is associated with low topography gradients (no fine sediment delivery from catchment slopes) and dominance of glaciofluvial sands in the region. In the latter case exceptionally high contribution of bedload into total sediment yield can be explained by dominance of coarse sediment from mountain slopes and small tributary streams in river sediment supply.

Providing all other conditions are uniform, contribution of bedload sediment growth from south to north or from west to east, reaching maximum values in rivers of the Ural Mountains and foothills, sandy glaciofluvial lowlands of north-western part of the basin and the Verhnekamskaya Upland (Fig. 3). Lowest value of the ($W_B/W_T\times100$) ratio characterize rivers of steppe and forest-steppe zones flowing through both lowlands and uplands of southern part of the Volga River Basin.

On most of the studied medium and large rivers bedload sediment yield growth downstream and, together with suspended sediment yield forming negative sediment budget indicative of gradual long-term incision tendency. This is however not the case for the aggrading small rivers, as well as for zones of flow backing and regressive deposition upstream from reservoirs. Minimum values of bedload sediment contribution (<25%) are typical for southern part of the basin, where practically all the flow transportation capacity is spent on transport of catchment-derived fine sediment mobilized by soil erosion on cultivated slopes. In northern part of the basin situation is exactly the opposite, as most of the flow transportation capacity is spent on bedload particle dragging. Obviously, rates of long-term channel incision decrease in the same direction-from north to south (Chalov & Shankova, 2003).

In addition to more or less regular changes of bedload sediment yield along a river associated with downstream increase of its discharge, local conditions may have an important effect. The most obvious is increased (by 2.5-4.0 times) bedload sediment yield in rivers flowing through sandy lowlands (the Zhizdra River, the Klyazma River near the Kovrov City) comparatively to rivers of the same size flowing through largely cultivated uplands covered by loessy loams with widespread soil erosion (the Upa, Zusha and upper Oka Rivers).

Comparing the information presented above with distribution of different morphodynamic types of channels (channel patterns) on rivers of the Volga River Basin, it has been possible to establish clear causal linkages between morphological manifestations of channel processes and the controlling factors. Morphodynamic classification of river channels proposed by Chalov has been used as a basis for determination of spatial distribution of types of channel processes on rivers of the Volga Basin (Chalov, 1997). For lowland rivers it first distinguishes two main classes of river channels according to dominance of confined or unconfined geomorphic conditions of their development: incised (mostly confined) and wide-floodplain (mostly unconfined) channels. Within each of these classes, morphodynamic types (channel patterns) are determined, as in most of the existing classifications of channel processes: relatively straight single-thread channels; meandering channels; and multi-thread channels. Each of the main morphodynamic types can in turn be subdivided into more detailed subtypes, if necessary, on a basis of some selected criteria. For example, meandering channels can be further subdivided into ***forced*** and ***adjusted meanders*** (partly controlled by bedrock valley slope), ***segmented meanders***, ***Ω-shaped meanders***, ***sinusoidal meanders*** (different planform and curvature radius) and ***breached meanders*** (meanders with chute cutoffs). Multi-thread channels can be subdivided into braiding, anabranching and anastomosing channels. It has to be noted that the latter is practically absent as independent morphodynamic channel type in rivers of the Volga Basin. Only single braids are commonly observed on absolute majority of the rivers, without formation of more or less prolonged channel sections characterized by braided pattern. On some rivers of the basin, however, combination of meandering and anastomosing channel patterns is observed (Chalov & Shankova, 2003).

It has been established that within the Volga River Basin incised channels occupy about 21% of total length of the studied rivers. Incised meanders account for 14%, while relatively straight single-thread incised channel represents the remaining 6%. Incised multi-thread channels are very rare and represented by some rivers in the Ural Mountains foothills. In eastern part of the basin incised meandering channel on some rivers occupies relatively long reaches without alternation with any other channel patterns (the Moloma, Vyatka, Belaya, Chusovaya, Sylva and Ufa Rivers). Percentage of incised channel length occupied by relatively straight incised channel pattern is higher on rivers where contribution of bedload sediment is relatively low (up to 40% length for $W_B/W_T \times 100 < 25\%$), while for higher contribution of bedload sediment it is commonly lower than 25%.

Wide-floodplain channels occupy 77% of total length of the studied rivers. Wide-floodplain relatively straight single-thread channels occupy 27% of total length of rivers in the Volga River Basin. The most widespread are meandering channels (46%), of which 11% is represented by ***forced*** and ***adjusted meanders***. These are most common channel patterns in regions characterized by alternation of unconfined and partly confined geomorphic conditions of river channel development (the Ural Mountains and foothills, the Srednerusskaya, Valdayskaya, Privolzhskaya Uplands, etc.), where ***forced*** and ***adjusted meanders*** occupy prominently long river reaches in relatively narrow valleys. The most widespread of the meandering channel subtypes are ***segmented*** and ***Ω-shaped meanders*** (15% and 12% respectively). ***Sinusoidal*** and ***overturned*** (highly tortuous meanders of irregularly elongated planform) ***meanders*** (1%) are mainly observed on the lower Volga River left tributaries (the Bolshoy Irgiz, Chapaevka, Buzuluk, Sok and Bolshoy Cheremshan Rivers). These are usually alternated with ***Ω-shaped meanders*** and relatively straight channel sections. ***Sinusoidal*** and ***overturned meanders*** (in low percentage) also alternate with relatively straight channel sections on two of the middle Volga

River left tributaries – the Kerzhenets and Ust Rivers. ***Breached meanders*** and combination of meandering and anabranching channel patterns occupy about 7% of the studied river length.

Prominent alternation of ***segmented*** and ***Ω-shaped meanders*** is typical for rivers of the Kama River Basin eastern part (the Kama and Vyatka Rivers upper reaches, the Cheptsa River and its tributaries). On rivers of western part of the Volga River Basin (W_B/W_T×100>50%) ***segmented*** and ***breached meanders*** alternate with relatively straight single-thread channel and combination of meandering and anabranching channel patterns (Chalov & Shankova, 2003).

Spatial distribution of different channel patterns within the basin depends on both geomorphic conditions and specifics of channel-forming discharge passage, total sediment yield and contribution of bedload component in it. The former determine differentiation of mountainous and lowland rivers as well as of incised and wide-floodplain channel classes. The latter mainly control differentiation of channel patterns of wide-floodplain channels. For example, relatively straight single-thread channels are the most widespread (38% of all wide-floodplain river channels) in southern part of the Volga River Basin where contribution of the bedload component into total sediment yield is below 25%. Increased contribution of bedload in the total sediment yield (25-50%) is favorable for meandering channels (81% of all wide-floodplain river channels in such regions), of which ***Ω-shaped meanders*** occupy 35%, ***segmented meanders*** – 33%, breached meanders – 10%. The latter commonly form on rivers where one of the channel-forming effective discharge intervals occurs when floodplain surface is inundated. In northern part of the Volga River Basin (W_B/W_T×100>50%) percentage of river length occupied by meandering channels decreases to 64%. On rivers of that territory single braids and combination of meandering and anabranching channel patterns are also observed, in contrast to other parts of the basin.

Long-term monitoring (form 1940) has shown that small and medium rivers of eastern parts of the Volga River Basin experience evident tendency of meander breaching (mainly by chute cutoffs), formation of anabranching channel with chutes and general decrease of the meandering channel pattern length (Butakov *et al.*, 2000). Such an increase of anabranching has been observed on the Vyatka River along its entire course, indicated by total number and area of islands. Formation of new islands and sections characterized by anabranching channel pattern on rivers with low contribution of bedload component (<25%) into total sediment yield can be explained by large additional volume of sediment input into rivers produced by soil and gully erosion on cultivated catchment areas.

It can be concluded from the above that changing contributions of bedload and suspended components into total sediment yield have clear reflections in spatial distribution of river channel morphodynamic types (channel patterns). Influence of a number of other independent factors can bias this relationship, but the general tendency is evident. For example, important modification of spatial distribution of river channel patterns can be determined by conditions of the effective channel-forming discharge (Q_{ef}) passage. For example, ***breached meanders*** (chute cutoffs) can form only on rivers where there is one of the Q_{ef} intervals passing when floodplain is inundated. However, low recurrence probability of that upper Q_{ef} interval on most of rivers in the Volga River Basin renders ***breached meanders*** relatively rare channel pattern for the studied rivers. The same upper Q_{ef} interval and another one, correspondent to bankfull discharge determine development of multi-thread channel and its combination with meandering pattern. In opposite, ***Ω-shaped meanders*** are typical for rivers of territories characterized by dominance of the lower Q_{ef} interval (water level below bankfull). Presence of multi-thread channel pattern on rivers with sediment yield dominated by suspended component may indicate that fine sediment play major role in composition of channel bedforms. That, in turn, determines generally low stability and high migration rates of such channels with bed sediment composition dominated by fine fractions. Some influence on channel patterns is also exerted by floodplain lithological composition, floodplain vegetation (meadow, shrubs or forest) and some other factors (Chalov & Shankova, 2003).

6.2. Impact of sand extraction for constructional purposes from the Oka River channel on its vertical deformations

The Oka River channel section near the Ryazan City has been recently affected by large-scale sand extraction for constructional purposes. According to available information, at least 30×10^6 m^3 of sand has been extracted from that part of the Oka River channel since 1973. Nevertheless, due to dominance of mobile medium-grained sand fraction in the river bedload material, decrease of water levels due to incision over that period has not exceeded 0.4 m and is notable only directly near sites where channel quarries are located. No significant regressive or transgressive propagation of incision has been detected (Berkovich, 2001).

Table 6.1. Changes of the Oka River channel long profile within its section between the Kaluga and Serpukhov Cities as a result of large-scale sand extraction during the 1970-1980s (if not stated specifically in the notes).

No.	Distance from the Serpukhov City up the Oka River channel, km	Channel gradient, ‰		Range of incision, cm	Notes
		1987	1991		
1	107.1-101.5	0.084	0.096	18	
2	101.5-92.3	0.055	0.060	26	
3	92.3-85.4	0.036	0.078	43	
4	85.4-73.6	0.105	0.142	62	
5	73.6-64.4	0.104	0.029	49	Active extraction during 1989-1990
6	64.4-54.4	0.012	0.022	36	
7	54.4-45.2	0.020	0.014	36	Active extraction during 1989-1988
8	45.2-39.2	0.103	0.076	15	
9	39.2-34.6	0.096	0.123	21	Riffle zone
10	34.6-28.3	0.071	0.064	23	
11	28.3-21.0	0.053	0.035	20	
12	21.0-13.4	0.091	0.125	34	
13	13.4-11.9	0.027	0.047	41	Active extraction during 1989-1990
14	11.9-6.4	0.176	0.120	26	
15	6.4-0	0.081	0.080	9	Riffle zone with river training works

Nevertheless, in channel sections where sand quarries are numerous and distributed more or less uniformly along the Oka River channel, regressive and transgressive incision waves from each of the quarries overlay with those from the adjacent ones, causing significant local transformations of the channel long profile. For example, a few large sand quarries (Alexinskie, Lanshinskie, etc.) are located along the more than 100 km long Oka River channel section between the Kaluga and Serpukhov Cities. Changes of the channel long profile over the 1987-1991 year period as a result of human-induced incision along that section are presented in Table 6.1.

It can be seen from the Table 6.1 data that notable decrease of channel gradient is observed at channel sections where sand extraction was carried out in 1970-1980s. Immediately upstream from quarries gradients commonly decrease as a result of the ongoing channel incision. Riffle zones in such channel sections are characterized by highest gradients. This situation is even more evident for the Oka River section upstream from the Kashira City, where another group of large channel sand quarries is situated. Average channel gradient at that section is about 0.14‰.

Table 6.2. Distribution of channel dredging works along the studied part of the Oka River channel and volumes of bedload alluvium extraction for constructional purposes.

Section	Distance from the mouth, km	Average fairway depth, m	Volume of dredging works, 10^3 m^3/km/year	Volume of alluvium extraction from quarries, 10^3 m^3
Kaluga-Aleksin	1100-1035	1.5	4.5	8140
Aleksin-Tarusa	1035-998	2.1	6.0	9760
Tarusa-Serpukhov	998-970	1.5	24.0	6900
Serpukhov-Puchino	970-955	2.2	16.0	3700
Puchino-Kashira	955-920	2.2	50.0	-
Kashira-Ozery	920-890	4.5	6.5	18630
Ozery-Kolomna	890-850	3.0	4.7	7600
Kolomna-Beloomut	850-800	2.0	-	16000
Beloomut-Kuzminsk	800-753	-	10.0	-
Kuzminsk-Ryazan	753-696	3.6	4.7	6620
Ryazan-Polovskoe	696-645	3.1	25.0	19640

Changing distribution of channel dredging works along the river can also be indirect evidence of vertical channel deformations as a result of bed-forming alluvium artificial extraction. For example, on the Oka River channel section between the Aleksin and Serpukhov Cities with typical depth of 1.2 m at fairway annual volume of dredging works was 840×10^3 m^3/year in 1971-1975. By 1981-1985 it increased to 1360×10^3 m^3/year. In many cases largest volumes of dragging works were undertaken at riffle zones located at some distance upstream from large quarries or immediately nearby of those (Table 6.2). The latter is the most typical for the Oka River channel sections with purely sandy bedload alluvium composition (near the Ryazan City).

Decrease of necessary volumes of dredging works, especially at riffles, at or nearby large channel quarries can be explained by channel incision and is especially evident on rivers with sand-gravel (such as the Oka River) and gravel bedload composition, characterized by relatively high degree of natural stability. Gravel alluvial armoring forms on a channel bed at riffles when regressive erosion from quarries begins to propagate upstream. Such a riffle soon becomes local basis of erosion for the upper channel section. The more incision occurs near quarries, the lower is water level in such riffles between them, requiring more and more dredging works to sustain a navigable fairway conditions.

6.3. Sedimentation in the Volga River reservoirs and its main sources

Main characteristics of the Volga River reservoirs are given in Table 6.3. The major results of sedimentation rates in the Volga river reservoirs are presented in Table 6.5. In column 4 we included only sediments, which had entered the reservoirs on the section of river between two dams plus sediments from tributaries, and minus sediments, which had entered the low pool from the upper pool. Accurate data about river sediment discharge for the Saratov and the Volgograd reservoirs are absent.

The river sediment discharge is the main component (29% and 39% from total sedimentation) only for the Ivankovo and the Uglich reservoirs. Abrasion processes are the principal source of sediment for reservoirs of low and middle reaches of Volga river (Table 6.5). Intensity of sedimentation increase along the cascade length from 0.17-0.25 cm per year for forest zone reservoirs till 0.60 cm per year for steppe zone reservoirs (Zakonov, 1989).

Erosion rates are high enough on the arable lands inside Ivankovo reservoir catchment (Table 6.6). Maximum values of soil loss are observed in the Vazuza river basin, which drains

Smolensk-Moscow upland. But now sediments from the Vazuza river can not reach the Ivankovo reservoir because of the construction of dam of the Vazuza reservoir, used for supplying of Moscow with drinking water.

Table 6.3. Main characteristics of the Volga River reservoirs.

No	Reservoir	Natural zone	Year of construction	Volume (10^6 m^3)	Length, km)	Depth (m)
1	Ivankovo	forest	1937	1120	113	3.4
2	Uglich	forest	1939	1245	120	5.0
3	Rybinsk	forest	1940	25420	250	5.6
4	Gorki	forest-steppe	1955	8700	434	5.5
5	Cheboksary	forest-steppe	1981	14200	340	6.2
6	Kuibyshev	forest-steppe	1955	58000	510	9.0
7	Saratov	steppe	1968	13000	340	6.7
8	Volgograd	steppe	1960	31450	524	10.1

Table 6.4. Erosion rates from cultivated lands for some typical river basins of the Volga River reservoirs.

River basin	Reservoir	Area of cultivated land (%)	Erosion rate (t/ha/year)	Specific sediment yield (t/km^2/year)
Vazuza	Ivankovo	60	10.2	610
Tvertsa	Ivankovo	33	4.8	160
Medveditsa	Uglich	45	4.3	190
Dubna	Uglich	28	9.8	270
Mologa	Rybinsk	13	5.1	66
Suda	Rybinsk	10	4.0	40
Unzha	Gorki	15	4.0	84
Kostroma	Gorki	38	5.6	210
Vetluga	Cheboksary	22	4.3	95
Zusha	Cheboksary	67	6.7	454
Upa	Cheboksary	55	8.4	460
Cheptsa	Kuibyshev	60	11.2	730
Civil	Kuibyshev	62	8.4	520
B.Cheremshan	Kuibyshev	45	3.0	133
Syzranka	Saratov	72	5.3	385
Tereshka	Saratov	83	4.3	355
Chardym	Volgograd	83	3.0	246
Eruslan	Volgograd	88	1.5	129

Erosion rates on the slope of the Uglich reservoir basin are almost equal with erosion rates in the Ivankovo reservoir basin (Table 6.4, 6.5). Maximum soil loss is observed in the Dubna river basin (Table 6.4). But specific sediment discharge is lower here due to small area of arable lands. The small coefficient of delivery ratio is typical for this section of the Volga River. It is connected with large distance between cultivated lands and river channels.

Table 6.5. Some sources of sediment and rate of sedimentation in the Volga river reservoirs.

Reservoir	Basin area (10^3 km^2)	Annual erosion volume, 10^3 t		W2/W1 (%)	Input in reservoir	
		Slope W_1	River W_2		River sediment	Bank abrasion
Ivankovo	40.57	12495	195	1.6	29	66
Uglich	60.043	4109	78	1.9	39	58
Rybinsk	146.0	8080	541	6.7	18	80
Gorki	229.0	15355	453	3.0	18	82
Kuibyshev	1210.0	186355	6295	3.4	14	85

Table 6.6. Relationship between specific sediment discharge and rate of sedimentation.

No	Reservoir	Specific sediment yield (t/km)	Rate of sedimentation (10^3 t/km/year)	Phosphorus concentration* (mg/l)
1	Ivankovo	3.08	2.09	<1
2	Uglich	2.11	2.55	2.5
3	Rybinsk	0.94	0.95	1.5
4	Gorki	1.85	2.35	1.2
5	Cheboksary	3.13	-	-
6	Kuibyshev	3.05	6.97	2.7
7	Saratov	2.51	-	3.0
8	Volgograd	2.68	-	3.0

*According to Litvin & Kiryukhina (in press).

Different situation is observed in the Rybinsk reservoir basin. As a rule steep slopes of river valleys are cultivated here first of all. This facilitates delivery large quantities of sediments to the bottom of river valleys. But total area of arable lands is extremely small. So total amount of sediment is relatively moderate.

Growth of soil erosion intensity is observed in the Gorki reservoir basin. Specific sediment yield is slightly higher here then in the Upper Volga basin (Table 6.6).

Vast basin of the Cheboksary reservoir is characterized by large differences of soil loss rates, which are connected with different landscapes and with changes of area of cultivated lands. Large part of the basin is situated in the forest-steppe zone with high percent of arable lands. High level of erosion rates led to small river aggradation, especially in the Upper Oka river basin (Golosov & Ivanova, 1993). As the result zone of accumulation had increased within small river basins. This process decreased the delivery of soil particles in large river channels and reservoirs.

High percentage of arable lands is more typical for middle and low reaches of Volga river basin. From the other hand heavy rains occur here more often. Both these circumstances result in the growth of sedimentation rates in the reservoir (Table 6.5).

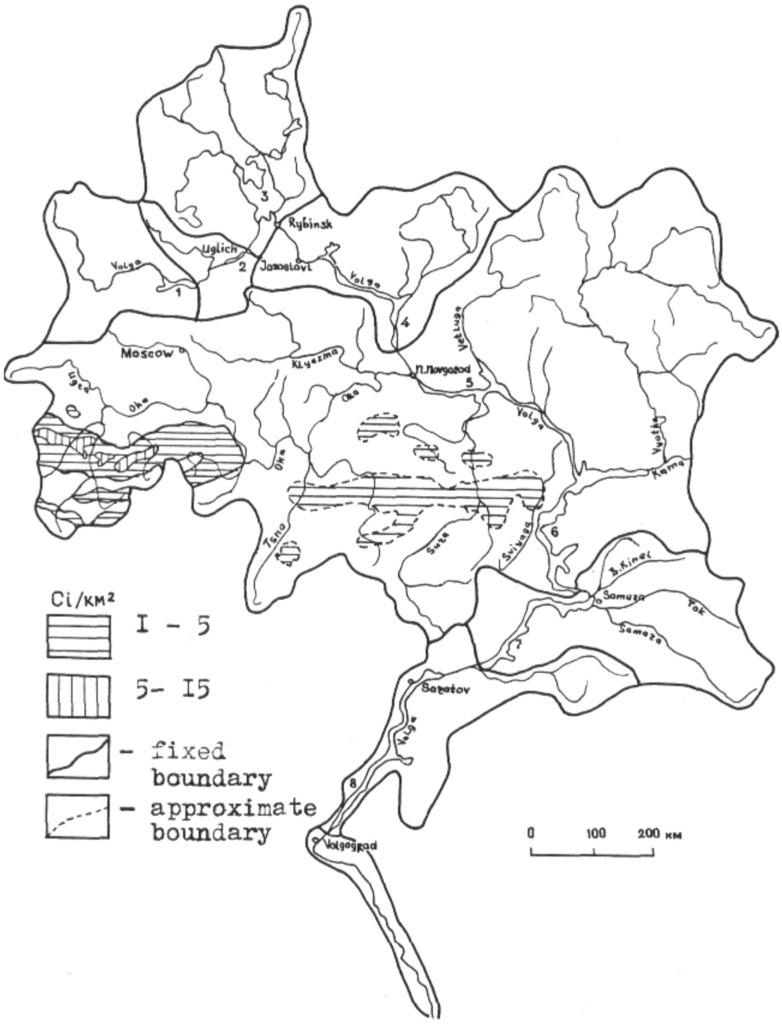

Figure 6.4. A generalized map of fallout inputs of the Chernobyl-derived caesium-137 in the Volga River Basin.

Especially dangerous situation is connected with growth of use of fertilizers and ^{137}Cs delivery in river channel. Maximum of cesium-137 precipitation is observed in the Oka River Basin, especially in the Zhizdra and the Upa Rivers Basins (Fig. 6.4). Our field observation in these regions shown that about 30 percent of ^{137}Cs can be transported downstream in association with suspended sediment, which was eroded from the surface of drainage basin. As the result, the input of ^{137}Cs in sedimentation zone of reservoirs may be extremely high since suspended sediment can transport very easy on the long distance. So total radioactive emanation of sediments can exceed permissible levels, especially in the Cheboksary and the Kuibyshev reservoirs.

Two main factors affect the pollution of the Volga reservoirs with fertilizers: specific sediment yield of reservoir basins and quantity of the fertilizer per area unit For example, the concentration of phosphorus in reservoir water increase from the Upper Volga reach to the Lower Volga reach (Table 6.6). The Uglich reservoir is the exception of this rule. This fact can be explained by very high level of fertilization in the Moscow region farms.

The results presented above indicate that sedimentation rates in the Volga River reservoirs are not very high due to relatively low erosion rates, as well as high levels of redeposition of sediment within river basins. Maximum values of sedimentation rates are observed in the Kuibyshev reservoir.

The soil erosion map of the Volga basin can help to define areas with maximum soil-loss, where water and soil conservation works should be implemented first of all. It is especially urgent for territories with high levels of pollution with ^{137}Cs. The influence of fertilizers on the water quality is higher for reservoirs of the Lower Volga River.

Because in the last years the loss of fertility of chernozem in the steppe and forest-steppe zones of the Volga river basin is observed, it is possible to expect wider use of fertilizers in these areas. This can provoke higher levels of water pollution in the Lower Volga reservoirs if the adequate water and soil conservation works are not designed and implemented.

6.4. The Lower Volga River hydrological regime and channel-forming bedload sediment

The Lower Volga River hydrological regime

The Volga River drains a large portion of the Eastern European (Russian) Plain territory. It is a typical lowland river with average channel gradient of 0.006%. The Volga River main tributaries are: Selizharovka, Tvertsa, Mologa and Sheksna at the upper reach; Oka, Unzha, Vetluga and Kama at the middle reach; Samara, Bolshoy Irgiz and Eruslan at the lower reach. There are no tributaries downstream the Volgograd city. Near that city the large left branch named Akhtuba separates from the main Volga River channel and flows farther towards the sea as a separated watercourse. Central part of the Lower Volga River valley from 15 to 30 km wide between the main Volga River channel and the Akhtuba branch dissected by numerous secondary branches is called the Volga-Akhtuba floodplain (The Lower Volga…, in press).

Most of the Volga River basin is located within the forest vegetation zone. It is the area where most of the Volga River discharge forms under conditions of precipitation exceeding evapotranspiration. The river is characterized by relatively high discharge, which gradually increases downstream as it receives more tributaries. Downstream the Volgograd city within the steppe vegetation zone the Lower Volga River loses part of its discharge to evaporation. Total river discharge at the Volgograd city is 259 $км^3$ a^{-1}, at its mouth – 253 $км^3$ a^{-1}.

Large cascade of reservoirs and hydroelectric power plants was constructed in the beginning of the second part of XXth century both on the Volga River itself and on its largest tributaries. It exerted very significant influence on the Volga River hydrological regime. Especially substantial effect had a construction in 1959 of the Volzhskaya hydroelectric power plant and the Volgograd reservoir – lowest in the cascade. Farther downstream relatively natural river conditions have remained preserved. Taking into account differences of the valley and channel morphology and characteristics of hydrological regime, the Lower Volga River downstream the Volgograd city can be divided into the Volga-Akhtuba reach and the Volga delta (The Lower Volga…, in press).

Within the Volga-Akhtuba section of the Volga River valley the river divides into two main branches – the main channel itself and the Akhtuba branch. Both flow down the wide Volga-Akhtuba valley, having multiple connections by the system of numerous transversal branches. Total discharge of the Volga River at that section has three main components: the main channel discharge, the Akhtuba branch discharge and the Volga-Akhtuba floodplain surface flow with secondary branches discharge (Table 6.7).

Table 6.7. Measured water discharges during the different phases of the Volga River hydrological regime downstream the Volgograd city (example of the year 1995).

Phase of hydrological regime	Date	Water discharge, Q ($m^3 s^{-1}$)		
		Main channel	Floodplain	Akhtuba branch
Spring high-water period	20.05	21800	95.1	799
Summer low-water period	20.07	11500	21.8	288
Autumn low-water period	20.09	4280	-	3.5

The Volga River average annual discharge downstream the Volgograd city varied from 9720 $m^3 s^{-1}$ (years 1929, 1947) to 5120 $m^3 s^{-1}$ (year 1937) during the period of 1929-1999. The long-term average annual discharge is measured as about 7500 $m^3 s^{-1}$. In addition to climatic factors, the long-term discharge variation has been substantially affected by a construction of the cascade of 13 large dams and reservoirs within the Volga River basin, including the Volzhskaya hydroelectric power plant on the Lower Volga. As a result of the flow regulating influence of dams, general decrease of water discharges released downstream from dams took place. For example, the average annual discharge near the Dubovka settlement prior to the Volzhskaya hydroelectric power plant construction was 8380 $m^3 s^{-1}$, whereas afterwards it decreased to 7240 $m^3 s^{-1}$ (The Lower Volga…, in press).

Seasonal pattern of the Volga River discharge has always been characterized by high-water and low-water phases. Highest discharges have been observed during the spring high-water period (April-June). Under conditions relatively close to natural, the Lower Volga River reach downstream the Volgograd city received up to 52% of the total annual discharge over the spring high-water period. The spring flood period lasted for 74 days on average. The summer-autumn low-water period (July-November) was characterized by significantly decreased water discharges. During this period, the Volga-Akhtuba section of the Lower Volga valley received 32-35% of the total annual discharge. Contribution of the winter flow usually did not exceed 13% of the total annual Volga River discharge.

After the Volzhskaya hydroelectric power plant construction the seasonal pattern of the river discharge downstream was altered substantially. Under present regime of the water release from the reservoir, the spring high-water period begins earlier, but its duration decreased to 51 days. In addition, both rising and falling limbs of the spring flood hydrograph became steeper. Time of the usual peak discharge passage shifted from first decade of June to the last decade of May. The most significant was a change of the maximum discharge values. Extreme values decreased from 51900 $м^3$ s^{-1} (year 1926) to 34100 $м^3$ s^{-1} (year 1979) (Fig. 6.5). During the 1959-1999 period average value of the maximum annual flood discharge was approximately 26800 $м^3$ s^{-1}.

Flow-regulating effect of the hydroelectric power plant dam and associated decrease of the flood peak discharges resulted in lowering of the maximum observed water levels. Different investigations provide values of this lowering within the range of 1.0-1.5 m (Brylev et al., 2001). In the channel section immediately downstream the Volzhskaya hydroelectric power plant dam lowering of the water levels was also caused by the intensive bed erosion after the dam construction. It was mainly associated with release of almost clear (without any sediment load) water from the reservoir. Active bed erosion is also promoted by unsteady flow conditions at the dam tailrace. During a release wave passage water level variation immediately downstream the dam can reach 2.5 m day^{-1}. Flow velocity near the channel bed exceeds 1.0 m s^{-1} at a release wave peak. Such a velocity is sufficient for intensive transport of bed sediment dominated by sand with median diameter of 0.3-0.4 mm. By 1998, intensive incision caused the water level lowering to 1.3-1.4 m (for discharge about 10000 $m^3 s^{-1}$).

There is no single relationship between water discharges and levels within the Volga-Akhtuba section of the Volga River valley. The diagrams of *Q=f(H)* relationships for different gauging stations show prominent hysteretic loops. Such a shape of relationship is associated with existence of well-developed network of channel and floodplain branches, which is filled by water on rising limb of the flood hydrograph and gradually releases it when the water levels fall (The Lower Volga…, in press).

The reservoir construction also influenced the Volga River flow during winter. Since 1961, contribution of the winter period discharge into the total annual discharge has grown to 26%. At the same time, minimum instantaneous discharge decreased to 550 $m^3 s^{-1}$ (year 1968).

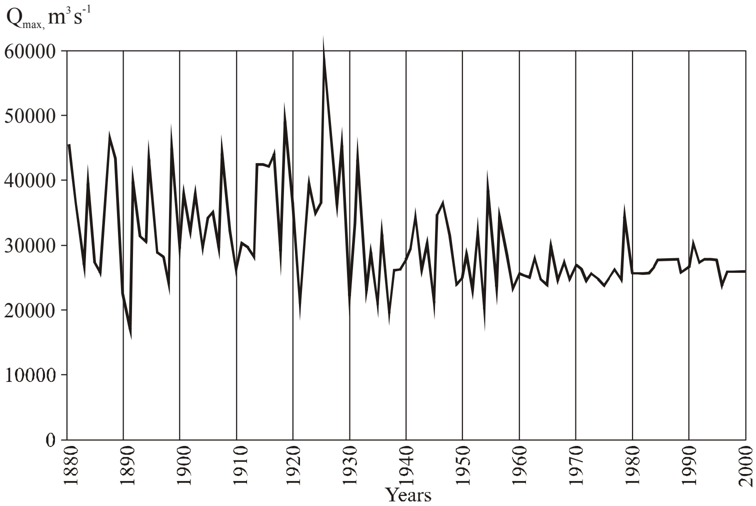

Figure 6.5. Maximum discharges of the Volga River at the Volgograd city gauging station (Brylev *et al.*, 2001).

Flow-regulating effect of the Volzhskaya hydroelectric power plant dam also caused transformation of the channel-forming discharge curve shape, as described by Makkaveev and . Chalov (1986). The Volga River channel-forming discharge curve near the Volgograd city has three main peaks. The upper peak is associated with channel-forming discharge interval observed when floodplain is inundated completely. The middle peak relates to the bankfull discharge. The lower one occurs when water begins to cover low bars. Since 1960, the upper maximum has been approximately equal to 24500 $m^3\ s^{-1}$ with 3.2% probability, whereas prior to the dam construction it was associated with discharge of about 36000 $m^3\ s^{-1}$ with 2.4% probability. The lower maximum has also lowered from 8800 $m^3\ s^{-1}$ (with 27.0% probability) to 5900 $m^3\ s^{-1}$, but its probability has risen to 52.0%.

Sediment interception (partial for suspended and practically complete for bedload) by the Volgograd reservoir has led to significant decrease of sediment yield in the Volga River lower reach. During the 1934-1953 period average annual suspended sediment yield measured at the Dubovka gauging station was 18.5 million t (Baidin *et al.*, 1956). After the reservoir construction it has decreased more than twice (The Volga…, 2001). Along the lowest valley section towards the delta apex certain increase of the suspended sediment yield (to 7.3 million t) is observed. Average water turbidity has also been substantially altered. It lowered to present averages of about 32 $g\ m^{-3}$.

Average annual discharge of the Akhtuba branch before 1955 was 211 $m^3\ s^{-1}$ near the Dosang settlement. After the flow regulation by the reservoir and dam the amount of water diverted into the Akhtuba branch has decreased. Its average annual discharge lowered almost twice – to 101 $m^3\ s^{-1}$ (at the Akhtubinsk city). The Akhtuba channel near the Akhtubinsk city often dries significantly during the summer-autumn low-water periods. Complete drying up was observed in 1973. Downstream from the Akhtubinsk city average annual discharge increases to some extent due to additional flow from the Volga main channel through secondary transversal floodplain branches. Near the Verkhnee Lebyazhee settlement it was measured as 131 $m^3\ s^{-1}$. During the spring flood maximum observed instantaneous discharges do not exceed 900 $m^3\ s^{-1}$ on average (maximum discharge measured over the period of flow regulation was 1760 $m^3\ s^{-1}$), which represents approximately 3% of the total Volga River discharge. In recent years, decrease of the total Volga River discharge percentage passing through the Akhtuba branch during spring floods is observed, whereas this value for the flow over the Volga-Akhtuba floodplain grows. It has been suggested that such a flow redistribution is caused by general shallowing of the Akhtuba channel (The Lower Volga…, in press).

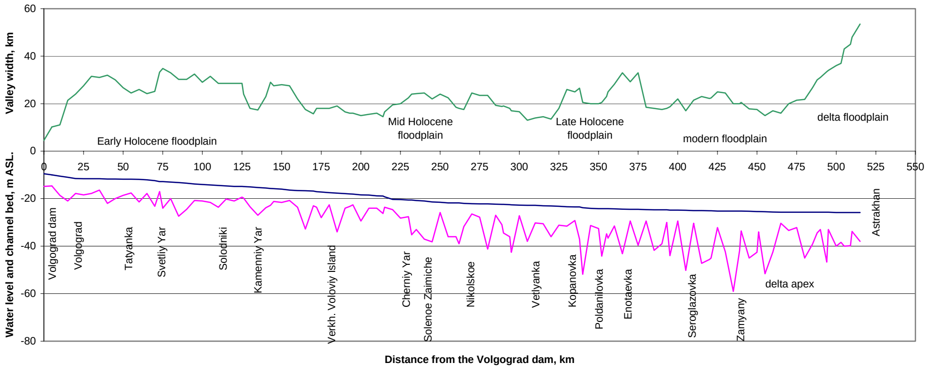

Figure 6.6. Variation of the Volga-Akhtuba valley width, water surface levels and channel bed elevation from Volgograd dam to the Astrakhan city.

Average annual sediment yield of the Akhtuba branch during the 1950-1960 period was equal to approximately 0.15 million t, as measured at the Verkhnee Lebyazhee gauging station at the Akhtuba downstream end. Since the 1960, it has decreased to approximately 0.13 million t. Average water turbidity in the Akhtuba branch is about 30 g m^{-3}, which is almost equal to that of the Volga River main channel (Main …,1980; The Volga…., 2001) .

The Lower Volga River channel bed sediment

Channel bed sediments of the Volga-Akhtuba floodplain and Volga delta branches have not been yet subject to sufficiently detailed studies, though some investigations did take place. Formation of the bed sediment layer results partly from settling of dome suspended sediement, but mainly from accumulation of sediment transported by saltation or dragging. Grain size composition of the Volga River channel bed sediment downstream the Volzhskaya hydroelectric power plant dam is dominated by sands with average median diameter varying from 0.15 to 0.50 mm. Finer sediments (silty sands, silts, clays) are accumulated during floods on inundated parts of the Volga-Akhtuba floodplain and Volga delta surfaces as overbank deposits.

Field investigations of the Lower Volga River channel section from the Volgograd city to the Astrakhan water divider was carried out in 1997-2002. It involved taking bed sediment samples and continuous mapping of bed morphology by the side-scan sonar device. It has shown that medium-grained sands (Md=0.25-0.50 mm) represent the most widespread sediment type within the studied channel section. Fine sands (Md=0.10-0.25 mm) and coarse silts (Md=0.05-0.10 mm) were found to be less widespread. Increased grain size of the channel bed sediment near settlements Cherniy Yar, Solenoe Zaimiche and Nikolskoe is believed to be associated with formation of poorly sorted sediments as a result of erosion of the valley side bedrock exposures located nearby.

Different types of the channel bed topography related to dune development are formed in the Volga River channel from sandy sediments. Morphometrical characteristics of dunes vary along the river course depending on hydrological and morphological conditions of the flow-sediment interaction, morphodynamic channel type and bed sediment thickness. For example, in high-sinuosity meanders (the Tsagan-Amanskiy, Shaposhnikovskiy and Zamyanovskiy main channel sections) and in relatively straight channel sections with active braid bar formation (such as the Dembinskiy-Kapitanskiy main channel section) the entire main channel bed width is occupied by relatively small 1.5-2.5 m high and 25-40 m long. In meander apexes and downstream limbs, as well as in widened sections of a relatively straight channel, sandy bedload sediment compose larger dune bedforms with length up to 130-160 m and relative height up to 3 m.

Exposures of marine clays or floodplain loams on the channel bed without superficial sediment cover are often observed along eroded bedrock slopes in straight channel sections (Kopanovka, Seroglazka and Rechnoy) or in meanders with actively eroded floodplain banks (*yar* Chilimniy, Tsaganskiy, Kopanovskiy, Kuznetsovskiy, Danilovskiy, Parashkin, Arbuzniy and Shambayskiy). Their eroded surface possesses a very characteristic striate microtopography formed by longitudinal rills and ridges. Clay exposures represent relatively elevated zones of the channel bed (to 2-4 m) forming local obstacles for sandy dune migration. The “sand-clay” boundary on the channel bed is always very sharp, without any transitional zone, except for channel sections with actively accreting point bars, where clayey bed surface is overlain by underwater ends of sandy spits. Medium or small ripples are formed from fine-grained sands at the channel bed sections where clays or loams are covered by thin (less than 1 m) bedload sediment layer. In such cases, the bedrock surface microtopography appears through the sandy bed microforms.

The Volga River floodplain alluvium is most widely distributed between the Volga main channel and Akhtuba branch. It is represented mainly by clays. Usually, central parts of floodplain segments are dominated by clays, whereas zones adjacent to channels are covered by loamy sands. Thickness of floodplain deposits do not usually exceed 2-3 m. However, on levees along channels it can reach 5-7 m, in central parts of floodplain – 10 m. Palaeochannel infill sediments are represented by high-porosity oozes, clays, loams and loamy sands with thickness varying from 8-10 to 20 m.

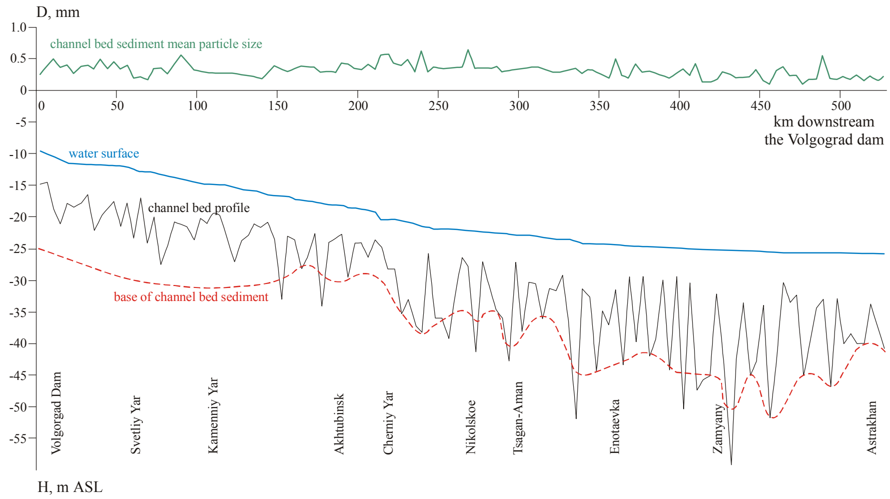

Figure 6.7. Downstream variation of mean particle size and thickness of modern channel bed sediment, water surface level and channel bed elevation of the Lower Volga River from the Volgograd dam to the Astrakhan city.

Continuous seismoacoustic profiling carried out in the Volga River main channel from the Akhtubinsk to Astrakhan city, in the Volga delta branches Buzan, Bakhtemir, Bushma, Krivaya Bolda and in some other branches has allowed to trace variations of the marine deposit roof elevation along the studied channels and determine precisely a real thickness of the modern channel bed sediment layer. Results of the seismoacoustic diagram interpretation and analysis has shown that bed sediment thickness in the Volga River main channel between the Volgograd city and the Verkhnee Lebyazhee settlement does not exceed 6-8 m on average. Along the eroded bedrock escarpments of the right valley side, where roof of marine clays lies close to the surface, the bed sediment layer thickness does not exceed 1-2 m. Some sections of the Volga River main channel bed are almost devoid of bedload sediment, and up to 1/3 of the bed surface area at such sections is represented by exposures of bedrock clay (*yar* Cherniy, Nikolskiy, Vetlyanskiy, Pechinistiy, Kopanovskiy, Seroglazovskiy, Zamyanovskiy) or floodplain loams – *pechina* – (yar Soleniy, Gerasimovckiy, Bolhunskiy, Chilimniy, Tsaganskiy, Nizhnekopanovskiy, Kuznetsovskiy, Danilovskiy, Enotaevskiy, Parashkin, Arbuzniy, Shambaiskiy) (Fig. 6.7).

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Conclusion

First investigations of different aspects of sediment redistribution within the Volga River Basin were undertaken in the middle of 19^{th} century. At present it is extremely difficult to summarize thoroughly in relatively short report even the main results obtained during more than 150 years of scientific research and applied investigations. We therefore have made an attempt to present the most detailed information about the main landscape characteristics of the Volga River Basin and some latest results concerning sediment transport from interfluve hillslopes to the Volga River mouth.

Despite the long history of investigations of different processes responsible for sediment transfer within the fluvial system of the Volga River, some of research areas still require serious attention. For example, we need to know in more details dynamic of deposition rates on river floodplains in different parts of the basin and we already have methodology to study this problem. There is still not enough information about contribution of extreme erosion events in sediment redistribution for different landscape zones. Quantitative assessment of erosion rates, especially during warm period of year, should be seriously improved for elaboration of effective soil conservation measures. To evaluate the fate of different pollutants, which are transported through the fluvial system with sediment, is one of the most important tasks. Quantitative assessment of trap effectiveness of small ponds and reservoirs should be improved for understanding of their role in sediment redistribution processes. Changes of erosion and deposition rates associated with climate changes are also very essential issue of future studies. List of problems requiring more research attention can be continued further. Hence it is possible to conclude that sediment problem for the Volga River Basin is one of the key environmental problems, which influence social and economic development of Russia.