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Century-scale stream network dynamics in the Russian Plain in response to climate and land use change

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Abstract

The spatial and temporal dynamics of stream net density (SND) within the Central and Southern parts of the Russian Plain during the last two centuries are studied by comparison of historical cartographic sources. A significant decrease of SND is observed in the forest–steppe and steppe zones. The maximum SND decrease is detected at the northern edge of the steppe zone, where SND values in the middle of the 20th century were only 50–60% of those at the beginning of the 19th century. Two stages of permanent stream disappearance were found within the study area: (1) The end of the 18th century to the first half of the 19th century, where the SND decrease was associated with a high frequency of droughts, that coincided with an expansion of the area of arable land, and (2) the last quarter of the 19th century, where the SND decrease can be explained by the extreme erosion rates resulting from the expansion of cultivation over steep slopes during the expansion of arable cultivation after the 1861 land reform. The roles of regional climate dynamics and land use change are confirmed by hydrological and meteorological data coupled with data on anthropogenic gully formation. Detailed studies of SND dynamics in a number of key basins provide a basis for understanding the mechanisms of SND reduction.

Keywords: Valley order; Stream net density; Erosion; Aggradation; Russian Plain

1. Introduction

A drainage network is composed of linked erosion forms of varying dimensions and age. It may change noticeably due to development of gullies, but here we emphasise the older component of the drainage network — the valley net, which in most cases is considered stable at century-to-millennial time scales within plain and lowland areas. In its lower reaches the valley network is occupied by perennial streams but first-order valleys often have only ephemeral or seasonal water flow and stay dry at other times. After its introduction by Horton (1945), the term "drainage density" has been used in the literature both in relation to the total valley network (e.g., Carlston, 1965) and to the stream network only (e.g., Gregory and Walling, 1968). To avoid misunderstanding, in this paper we use the terms "valley net density" (VND) and "stream net density" (SND), respectively.

Interest in the various aspects of drainage network composition reached a peak in the 1960–70s. Most research focussed on the geographical distribution of drainage density, its controlling factors and its relationship with water discharge. Thus, it was found that base flow is inversely related to VND (Carlston, 1965) but is directly related to SND (Gregory and Walling, 1968). Using examples from south-west England, Gregory (1966) showed that the network of present stream channels conforms more closely to Horton's first two laws than the valley network, the reason being that valley net includes elements of different ages and origin and some valleys were active under former hydrological conditions and are fossil in the present network. Gregory (1966) also suggested that the existence of dry valleys may in some situations reflect a reduction of discharge similar to that associated with the occurrence of underfit streams, and that the valley net is representative of the former stream

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network. As stressed by Carlston (1965), VND is a function of flood runoff.

Stream networks undergo cyclic changes over different time scales. The seasonal dynamics of stream length can be studied by direct observation. Gregory and Walling (1968) found that stream length varied by 5–10 times in two small catchments in south-west England and was highly correlated with water discharge. Calver (1990) described the annual migration of stream heads over several kilometers and short-lived expansion of the stream network associated with periods of high rainfall in several chalk catchments in southern England. The annual fluctuation of the groundwater table, which was almost opposite to that of the stream extension, together with geochemical data, show that the observed pattern of streamflow does not represent the incidence of the regional groundwater table but is rather linked to direct subsurface flow to channels over boulder clay cover promoted by artificial ditching.

Millennial-scale headwater migration may be investigated by interpretation of geological data available from subsurface surveys of dry valleys across the Russian Plain. Under humid conditions, stream heads in the southern forest zone at 55°N at low flow stage are located 1–3 km downstream from the valley head points. Within the dry stretches the valley bottom is typically flat or slightly concave, and a dry channel may not exist. Less than 0.5–1 m of thin-grained well-washed alluvial sandy gravels are found that seem to evidence perennial, or at least intermittent, stream extension up the valley in former times. The timing of this extension can be established using the age of buried stream gravels dated by ^{14}C from 4.3 to 4.7 kyr BP (Panin et al., 1999). In the semi-arid climate of the steppe zone, the dry upper reaches of the drainage net are much longer than in the forest zone. The term “balka” is used here to denote dry valleys. In a 8-km long balka in the southern Russian Plain at 49°N, channel sands were found under a 3-m loamy filling the base of which has been dated from 7.1 to 8.3 kyr BP (Panin et al., 1998). Both these examples illustrate that stream heads have been shifting along the valleys during the Holocene and in some periods could be located upstream from their present positions.

Headwater migration during recent centuries cannot be documented by direct observation and may not be preserved in the geological record, but if they are, problems of dating the associated sediments arise, because sediments from the last 200–400 years are too young for radiocarbon dating but too old for other radionuclide techniques, which used ^{137}Cs or ^{210}Pb$_{ex}$ as time markers. However this period is often covered by historical and cartographic sources that provide a valuable source of information. Examination of these sources has led many researchers in Russia to the conclusion that during the last 2–3 centuries, the headwaters have been moving downstream in most valleys in central and southern Russian Plain, so that in many small valleys in which there were formerly channels with perennial streams, only ephemeral flow is now observed. A typical example of this process is provided by the upper Don River basin (Fig. 1). This phenomenon referred to as “the problem of small river disappearance” has attracted the interest of many researchers since the end of the 19th century. Among the first was the well-known soil scientist and geomorphologist Vassily Dokuchaev, the author of the concept of soil zones. In his work of 1892 Dokuchaev drew attention to a clear trend observed in Russian steppes, where many rivers had completely disappeared during the previous few decades (Dokuchaev, 1892). Subsequently, several studies were undertaken for different river basins on the Russian Plain, which demonstrated a significant decrease of SND over the last centuries (Koval’chuk and Shtoiko, 1992; Boiko et al., 1993; Golosov and Ivanova, 1993 etc.).

The period following the end of the 18th century within the southern half of the Russian Plain was characterized by a rapid expansion of the area of cultivated land. Some researchers have therefore suggested that anthropogenic impact was a key influence on SND reduction. Deforestation of vast areas,

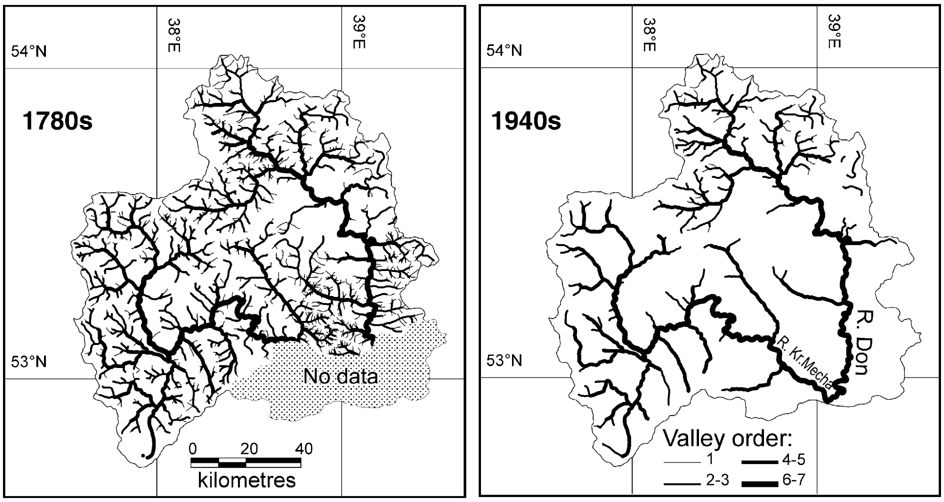

Fig. 1. Permanent streams occupying different-order valleys in the Upper Don River basin in the end of the 18th and in the middle of the 20th centuries (after Panin et al., 1997).

which resulted in decreasing ground water levels, is named as the main reason by one group of researchers (Dedkov et al., 1995; Dedkov and Mozzherin, 1996). Others have argued that SND reduction is a consequence of soil erosion within the river basin (Chernov, 1988; Ivanova, 1990). Also natural climate change is considered to be another reason for this phenomenon (Panin et al., 1997).

The objectives of this paper are to develop an improved understanding of this phenomenon by means of spatial and temporal analysis of stream head migration and changes in stream net density (SND) and evaluating the influence of different factors on the dynamics of SND change in different landscape zones of the southern half of the Russian Plain and some adjacent areas.

2. The study area

The southern half of the Russian Plain covers the southern part of the forest, forest–steppe and steppe landscape zones (Fig. 2). It is characterized by a temperate continental climate with a mean annual precipitation of 400–600 mm, one third of which falls during the cold season. Precipitation and moisture availability decrease in a south–south–eastern direction. In the central part of the Russian Plain, around Moscow city, annual precipitation is in the range 600–700 mm, with a mean July temperature of 18–20 °C. Annual precipitation near the northern coast of the Caspian Sea is less than 200 mm, with the July temperature increasing 23–24 °C.

The relief of the region is upland and lowland strongly dissected down to the bedrock and overlain by Pleistocene loess of varying thickness and in some places a thin layer of moraine. Soils change from podzol and grey forest soils in the south of the forest and the north of the forest–steppe zone to chestnut soils in the south of the steppe zone, with different types of chernozem in the middle. The major types of bedrock are limestone, dolomite, clay and sand of different ages.

The river regime is characterized by a high spring flood in April and May and low water conditions during the rest of the year. Systematic observations over a net of hydrological stations has shown that in recent years more than 60% of the river runoff is accounted for by the spring flood (Fig. 3A). The contribution of spring runoff to the annual river runoff increases from the forest to semi-desert zone. The input of flow from soil and underground runoff decreases in the same direction (Fig. 3B). The river network is characterized by a decrease in density from the north to the south-east.

The major rivers of the region are the Don and Volga Rivers. Their regime is now greatly modified by large reservoirs. Before the construction of the Tsimlyanskoye Reservoir some 60% of the Don River annual runoff passed during the two months of the spring flood (Fig. 4A). On the upper Volga River reservoir construction started in the late 1930s, but major changes in the flow regime of the middle and lower reaches occurred between the mid 1950s and the mid 1980s, when the whole Volga and its major tributary the Kama River were transformed into reservoir chains. Before the mid 1950s the flood on the middle Volga River began in April and continued into June on its falling stage (Fig. 4B).

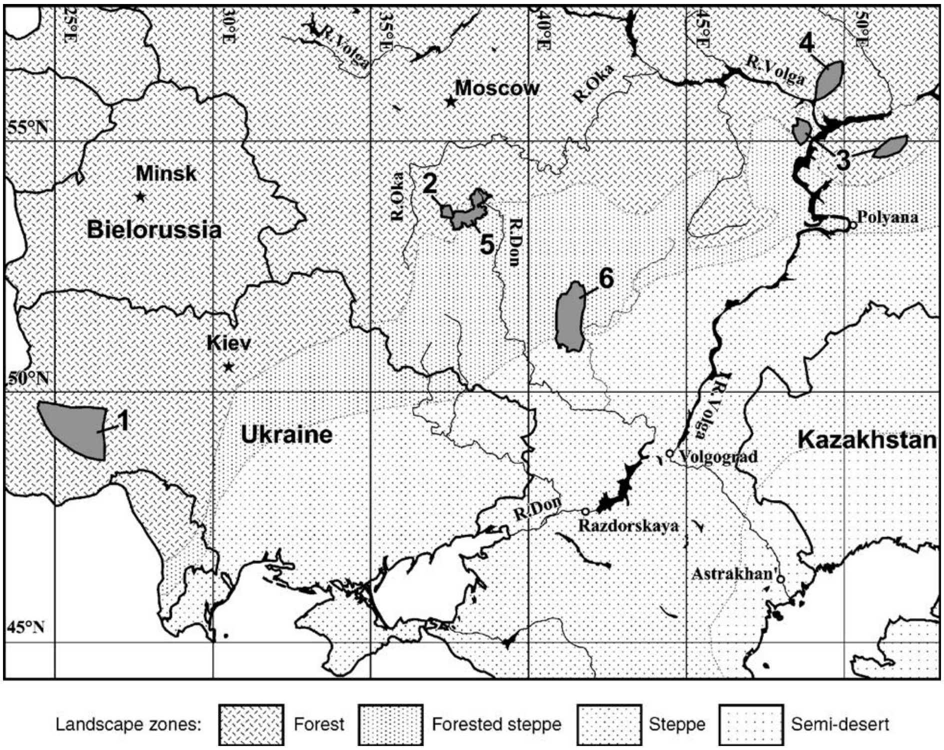

Fig. 2. The southern part of the Russian Plain and surrounding territories with key sites locations. Numbers correspond to Table 2.

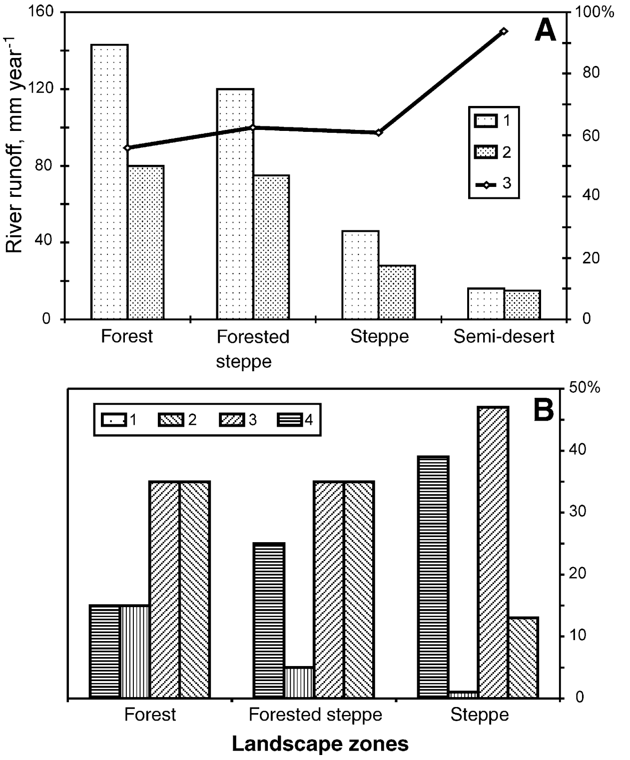

Fig. 3. Hydrological features of different landscape zones in the southern part of the Russian Plain (based on Koronkevich et al., 1994): the relationship between annual and spring flood river runoff (A) and components of annual river runoff (B). Legend: A1 — annual runoff; A2 — spring flood runoff; A3 — ratio of spring flood runoff to annual runoff (in %) for different landscape zones. B1 — surface runoff; B2 — soil runoff; B3 — runoff from short-lived streams; B4 — underground runoff.

This long flood duration is due to the large basin area and to extended snowmelt in the Ural Mountains. After July, the month average discharges are low and change relatively little. During this part of the year rivers are mostly fed by groundwater with only minimal contribution from rainfall. Rain-fed floods are most likely to occur at the end of autumn, producing a small increase of the average discharge in November (the Don River) or in October–November (the Volga River). The lowest discharges are observed between December and January on the Don and until March on the Volga River. During this time rivers are covered by ice.

Groundwater levels change during the year according to the ratio of precipitation and evaporation and demonstrate similar behaviour to surface runoff (Fig. 4C). The major peak in ground water level is observed during the spring snowmelt. After that the level gradually falls, due to groundwater outflow to the valley net and evaporation. The lowest levels in the warm period are observed during August and September. A second phase of increased groundwater levels is usually observed in late autumn. The period of stable snow cover in December–March is characterised by a lowering of ground water levels.

The southern part of the Russian Plain is a relatively young agricultural area, with the oldest areas of intensive cultivation located around Moscow. The areas south of Moscow were intensively cultivated after the end of the 17th century (Fig. 5), but most of the forest–steppe and steppe zone was intensively cultivated during the 19th and 20th centuries. The first surveyed maps of the Russian Empire were produced at the end of the 18th century.

A comparison of the SND for two time periods has been made for a large area of the Upper Oka River basin, most of the Don River basin and some basins in the Stavropol upland near the Caucasus Mountains. In addition several key basins were chosen for detailed study of the dynamics of river net change as well as to study sediment redistribution. The Plava River basin is located in the south of forest zone and belongs to the Oka River system (Fig. 2). It is an area that has been used for intensive agriculture for about 300–350 years. The Upper Don river basin is located largely within the forest–steppe zone, but the north of the basin is within the forest zone. The period of intensive agriculture in the study area extends over 250–300 years. The Savala River basin is situated in the northern part of the steppe zone, where the period of intensive cultivation extends over about 200 years. The territories of Southern Preduralie and Zauralie are located in steppe zone and here the period of intensive cultivation extends over 150 and 50 years, respectively. These were chosen for detailed comparisons of the effect of cultivation on the river network (Fig. 2).

3. Methods

Comparison of topographic maps produced at different times provided a basis for evaluating the SND dynamics of SND change. According to the rules issued for the mapping of water bodies, all watercourses should have been recorded according to their state during the low water phase of the warm period of the year, which usually occurs in August–September (Fig. 4). The position of the river sources at that time is the most stable from year to year and is thus representative for a period of time. Studies of archive data confirm that the rule referred to above was used since the first topographic survey of the Russian Empire at the end of the 18th century. It was affirmed in the “Governmental Instruction on Land Survey, 1797” which served as the rule book for field surveys and the subsequent compilation of maps (Vereschaka, 2002). As no change in mapping rules occurred, it is possible to suggest that all historical maps produced since the end of the 18th century are not influenced by systematic differences in river net representation. To avoid technical errors that are sometimes found on old maps, all valley thalwegs were digitised using the MapInfo GIS package from the 1:300 000 scale maps produced in the 1940–50s by the USSR Army by photographic reduction of the 1:100 000 map. All thalwegs were drawn through the middle of valley bottom, with no reference to river meandering and were indexed according to the Horton–Strahler order system. Each valley stretch

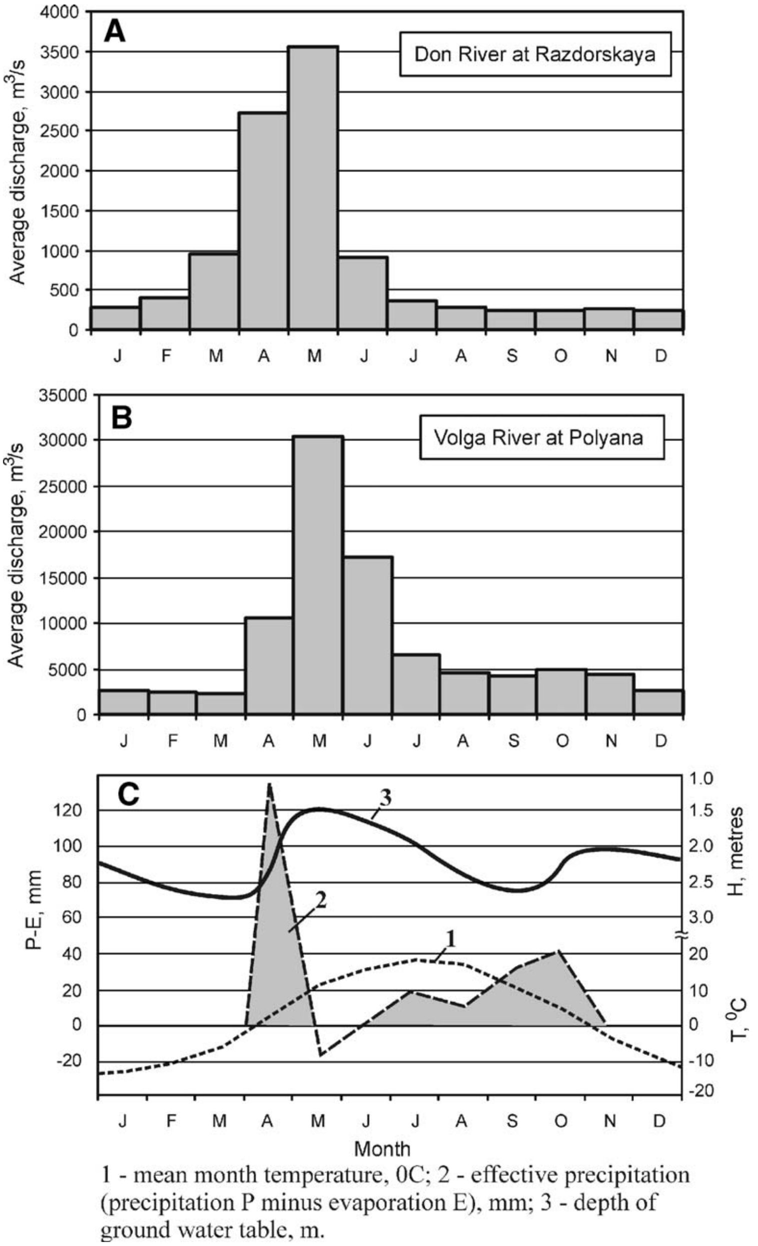

Fig. 4. The hydrological regime of the southern part of the Russian Plain. A, B — annual distribution of the Don and Volga River runoff (see location on Fig. 2). C — typical example of ground water regime in the middle Volga River basin (after Kovalevskiy, 1973).

was also given a code indicating the presence or absence of a stream on different historical maps. Identification of stream courses on old maps was undertaken using key elements of the hydrological net pattern (tributary confluences, river bends, etc.) and location of settlements. Basin boundaries were also digitized and stored in separate tables as polygons. Overlaying of the thalweg net over the basin contours makes it possible to calculate the total length of streams in a given basin and its change between different dates.

More detailed studies for several time periods were undertaken for several typical basins, located in different parts of study area. The following old maps were used for comparison: (1) 1 : 42 000–1 : 126 000 scale maps from the 1770s to the 1790s produced for the land reform of Catherine the Great; (2) “The Special Map of the Western Part of the Russian Empire”, 1 : 420 000 scale, engraved under the control of General F. Shubert in 1826–1839 (the so-called “Shubert Map”); (3) 1 : 126 000 scale maps made by the Military Topographic Corps in the middle of the 19th century; (4) 1 : 126 000 scale maps of the “Expedition for Investigation of the Sources of Main Rivers of European Russia” produced under the direction of A. Tillo (“Tillo maps”); (5) 1 : 300 000 (photographically reduced 1 : 100 000) scale maps produced in the 1940–50s by the USSR Armed Forces Staff; (6) 1 : 100 000–1 : 200 000 scale

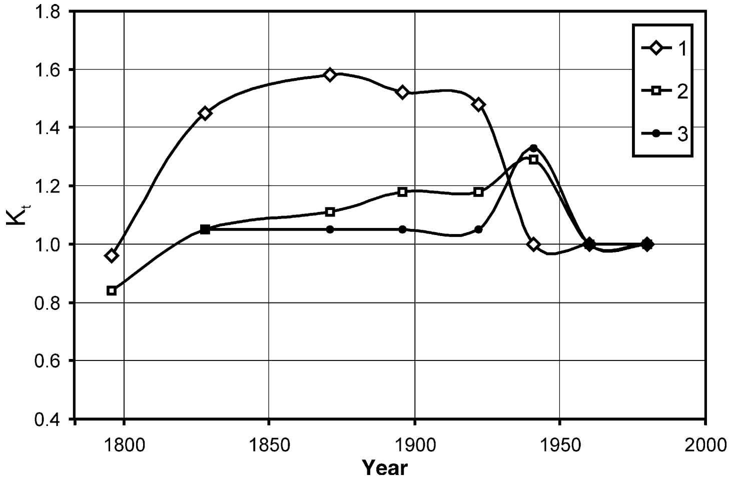

Fig. 5. Temporal changes of tillage area (K_t) averaged for different landscape zones in the Russian Plain (K_t equals to 1 for each zone in 1980). Legend: 1 — south of forest zone and north of forest–steppe zone; 2 — forest–steppe and north of steppe zones; 3 — south of steppe zone.

maps made by the Russian (USSR) State Cartographic Service in the 1970–90s.

4. Results

4.1. Spatial pattern of stream density change

Forty-four river basins each with areas between 1.5 and 60 10^3 km^2 each were chosen for evaluation of river net transformation during periods greater than a century (Fig. 6, Table 1). They cover all the major landscape zones of the Russian Plain: forest, forest–steppe and steppe. The total stream net was measured for each river basin using maps published in 1826–1839 and during the 1940–1950s. There are two reasons why particular maps were chosen for comparison. Firstly, both maps covered the whole study area while maps from other periods did not have such good coverage. Secondly, the selected time interval includes significant changes of the river net and is thus representative for our purposes.

Values of SND changes demonstrate clear spatial differences (Fig. 6, Table 1). In the forest zone SND changes are in the range ±10% and are considered to lie within the precision of the cartographic method used. A reduction of SND in the forest zone of more than 10% is found only in the Osiotr River basin which is located near the border with the forest–steppe zone. This basin is also characterized by steep cultivated slopes that suggest large inputs of sediment from the slopes to the river channels.

In the basins located at the border between the forest and forest–steppe zones, SND values have decreased by 20–40%. A similar decrease of SND is observed within the forest–steppe zone. Maximum values of permanent stream disappearance are observed in the northern part of steppe zone. Here typical values of SND reduction are 40–60%. Maximum values of 70% and more in some basins (the Lugan' and the Businovka) probably reflect lowering of the ground water table due to the development of coal mining. Further to the south, the values of SND decrease are not so high. In the Lower Don River region, the Kuban' Lowland and the Stavropol Upland it is similar to that for the forest–steppe zone.

4.2. The temporal dynamics of stream density change during the last two centuries

Temporal changes of SND were examined in several areas, using both our own data and that from published sources. Sets of historical maps sufficiently detailed to analyze the temporal dynamics of SND are in many cases only available for relatively small basins or for parts of large basins. To avoid local effects we tried to use areas as large as possible for averaging the detected changes. Basins that permit analysis of SND changes over time have been grouped in Table 2 into six key areas according to geographical location and the composition of the available sets of maps.

For four of the sites listed in Table 2 it is possible to look at the dynamics of SND change since the end of the 18th century. In the south of the forest zone the period of intensive cultivation exceeds four centuries. In the western part of this zone (Western Ukraine) SND decreased slowly until the middle of the 20th century (Fig. 7A, line 1), but in the Eastern part of the zone (North of the Tatarstan Republic) SND reduced appreciably during the first three quarters of the 19th century and then decreased more slowly until the middle of the 20th century (Fig. 7A, line 4). Some increase of the SND was observed in the second half of the 20th century (Fig. 7A, line 4). Some of the basins in the Upper Don River region selected for study are located on the border between the forest and forest–steppe zones, but most belong to the forest steppes (Fig. 2). The dynamics of SND change here are very similar to the Tatarstan key area (Fig. 7B, line 5). A more marked decrease of SND occurred in the Savala River basin situated on the border between forest–steppe and steppe zones (Figs. 2 and 7B, line 6). The river net was shrinking here until the beginning of the 20th century and then stabilized.

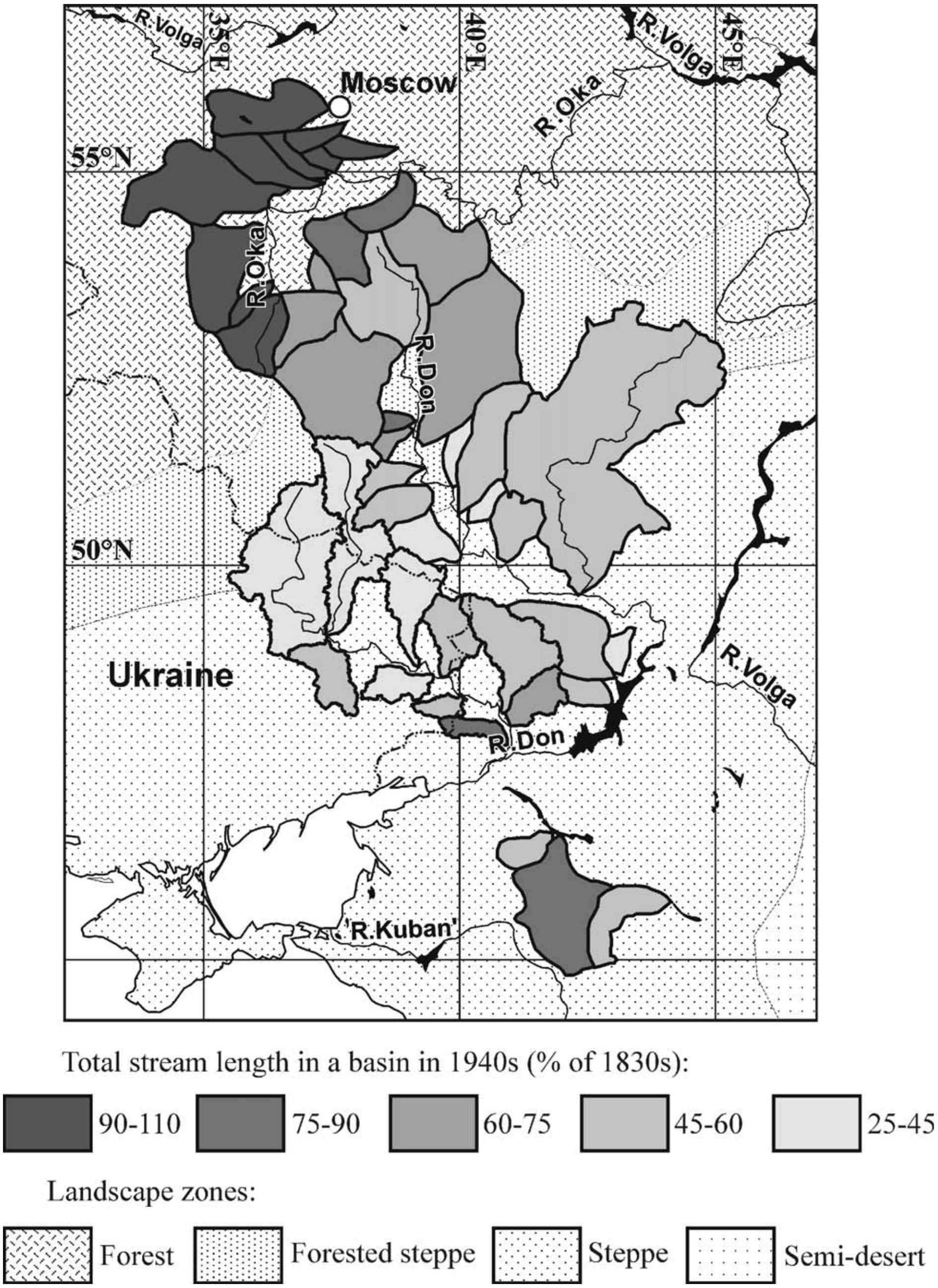

Fig. 6. Change of stream net density (SND) in the 1940s compared to 1830s.

In the Plava River basin the most significant changes in the channel network occurred at the end of the 19th and the beginning of the 20th centuries, while during most of the 20th century the channel network was either stable or some small increases of water course length were observed (Table 3). The latter may be explained by a reduction of arable land area and increase of subsurface runoff after the widespread adoption of winter tillage since the middle of the century (Golosov and Panin, 1995) as well as by fluctuations of precipitation. A high correlation was found between the rate of river network reduction and total valley length in different sub-basins during the period 1820s–1940s (Table 3).

Changes in permanent stream length occurred at different rates in valleys of different order. For example, in the part of the Upper Don River basin covered by the map for the end of the 18th century the total river length was 3687 km in the 1780s but only 1364 km in the 1940s (Fig. 1). Of the total 2323 km reduction of stream length, 972 km (42%) occurred in the 1st order valleys, 805 km (35%) in 2nd order, 477 km (20%) in 3rd and 69 km (3%) in 4th order valleys. In the valleys of 5th order, permanent streams were maintained throughout the whole period. In relative terms, the maximum loss of streams is associated with the 2nd and 3rd order valleys and equals 51% and 60% of the total valley length, respectively. All valleys of 4th order were

Table 1
Change of stream net density in a number of river basins within the Russian Plain during the 19th and 20th centuries

No.	River basin	Area (km^2)	Location			Stream net density SND[a] (km/km^2)		SND change (%)
			Latitude[b]	Longitude[b]	Landscape zone[c]	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	15 600	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	10 300	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	Zusha	7000	53.0	37.1	F–FS	0.227	0.161	−29.3
16	Upper Don	12 100	53.5	38.5	F–FS	0.232	0.120	−48.0
17	Voronezh	21 300	52.7	40.2	FS	0.204	0.123	−39.7
18	Sosna	17 000	52.4	37.6	FS	0.291	0.211	−27.5
19	Veduga	1520	51.8	38.8	FS	0.229	0.181	−20.9
20	Devitsa	1250	51.6	38.7	FS	0.173	0.110	−36.3
21	Bitiug	8900	51.5	40.7	FS	0.176	0.104	−41.0
22	Ikorets	1850	51.4	40	FS	0.184	0.075	−59.2
23	Potudan’	1880	51.0	38.7	FS	0.144	0.076	−47.0
24	Tikhaya Sosna	4180	50.7	38.7	FS	0.120	0.062	−48.0
25	Khoper	61 300	51.5	43	FS–S	0.163	0.096	−41.0
26	Oskol[d]	14 842	50.4	37.9	FS–S	0.148	0.064	−56.6
27	Severskiy Donets[d]	23 145	50	36.6	FS–S	0.174	0.071	−59.1
28	Osered’	2480	50.8	40.5	S	0.124	0.056	−55.1
29	Tolucheevka	5040	50.5	41.1	S	0.082	0.037	−54.3
30	Chernaya Kalitva	5560	50.4	39.3	S	0.098	0.037	−62.3
31	Aidar[d]	7383	49.5	39.1	S	0.099	0.043	−56.2
32	Derkul[d]	5418	49.1	39.9	S	0.083	0.044	−46.6
33	Chir	10 500	49	42	S	0.086	0.043	−50.0
34	Kalitva	10 454	48.9	41	S	0.103	0.053	−48.1
35	Buzinovka	1560	48.9	43.1	S	0.067	0.023	−73.6
36	Kazenny Torets[d]	5326	48.6	37.3	S	0.129	0.064	−50.2
37	Lugan’[d]	3473	48.5	38.8	S	0.099	0.030	−69.9
38	Bystraya	4228	48.4	41.5	S	0.073	0.051	−30.3
39	Tsimla	1540	48.4	42.5	S	0.088	0.034	−46.9
40	Likhaya[d]	1715	48.2	39.6	S	0.153	0.084	−44.9
41	Kundriuchya[d]	2349	47.9	40.3	S	0.125	0.100	−20.5
42	Sredny Egorlyk	2190	46.4	41.3	S	0.106	0.060	−43.4
43	Egorlyk	16 100	45.7	42	S	0.093	0.079	−15.6
44	Kalaus	9200	45.4	42.8	S	0.113	0.061	−46.2

[a] SND measured along valley axis, i.e.. reflects the length of valley stretches occupied by permanent streams with no respect to river sinuosity.
[b] Latitude and longitude refer to geographical centre of each basin.
[c] F — forest zone, FS — forest–steppes, S — steppe; F–FS and FS–S means that the basin is situated partly in neighbouring zones.
[d] River systems of the Severskiy Donets basin: period of change is between 1840s and 1950s.

occupied by permanent streams in the 1780s but these were found in only 82% of their total length in the 1980s. Equally, only 26% of the total length of the 1st order valleys was occupied by permanent streams in the 1780s and almost all of these had disappeared by the 1940s. In the 1980s, the total river length in the same area equaled 1490 km, demonstrating a 126 km growth, compared to the 1940s. The biggest contribution to this growth both in absolute (81 km) and relative (64%) terms was made by 3rd order valleys.

5. Discussion

5.1. Possible mechanisms of long-term stream head migration

Under natural conditions the main reason for stream head migration is the variation of groundwater levels because of climate fluctuations in different landscape zones. In fact we can see that groundwater levels decrease from the forest zone to the semi-desert zone within the Russian Plain.

Table 2
Published data on stream net length within the Russian Plain for several time periods

No.	River basins[a]	Zone	Total area (km^2)	Time series	Source
1	Left tributaries of the upper Dniester River, Western Podol'skaya Upland, Ukraine	F	13700	1772, 1855, 1925, 1955	Koval'chuk and Shtoiko, 1992
2	Upper Plava and Plavitsa (upper Oka River basin), the Tula Region	F	511	1830s, 1908, 1940s, 1980	Golosov and Panin, 1995
3	Ulema, Arya and Bol'shaya Sul'cha (middle Volga basin), South-Western Tatarstan Region	F–FS	3140	1870s, 1940s, 1960s, 1980s	Kourbanova and Boutakov, 1996
4	Kazanka (middle Volga basin), North-Western Tatarstan Region	F	2714	1800s, 1870s, 1940s, 1980s	Kourbanova and Boutakov, 1996; Boiko et al., 1993
5	Sitova Mecha, Krasivaya Mecha, Turdey, Nepriadva, Sukromna, Don basins (upper Don basin), Tula Region	F–FS	3130	1780s, 1830s, 1860s, 1895, 1940s, 1980	Panin et al., 1997
6	Savala (Khoper River basin), the Voronezh Region	FS	7680	1780s, 1830s, 1860s, 1900, 1940s, 1990	Panin and Golosov, 2001

[a] For location see Fig. 2.

Simultaneously, in the same direction, SND decreases, but the length of the dry valley net increases.

After the intensive cultivation of interfluve areas there is a major change in the relationship between surface and subsurface runoff, because of an increase in the former. This change is especially notable for the Russian Plain climatic condition, where the surface runoff coefficient strongly depends on the frozen soil depth before the snowmelt. Under natural conditions, vegetation prevents deep freezing of the soil, because of the deep turf, especially in the steppe zone. Also during summer rain-storms vegetation promotes infiltration. In addition soil erosion intensity increased dramatically after cultivation, causing additional inputs of sediment to the river channels which promoted their filling. This process is most intense in 1st and 2nd order valleys, because of the shorter distance between the cultivated slope and river channels. The latter is confirmed by the possibility of a reverse mechanism, which involves migration of the stream head after the regressive growth of bottom gullies in the river valleys. Such a phenomenon was observed, for example, by Kourbanova and Boutakov (1996) for the right hand tributaries of the Kazanka River in Tatarstan (forest zone). They reported that river length had increased from 492 to 595 km during one century.

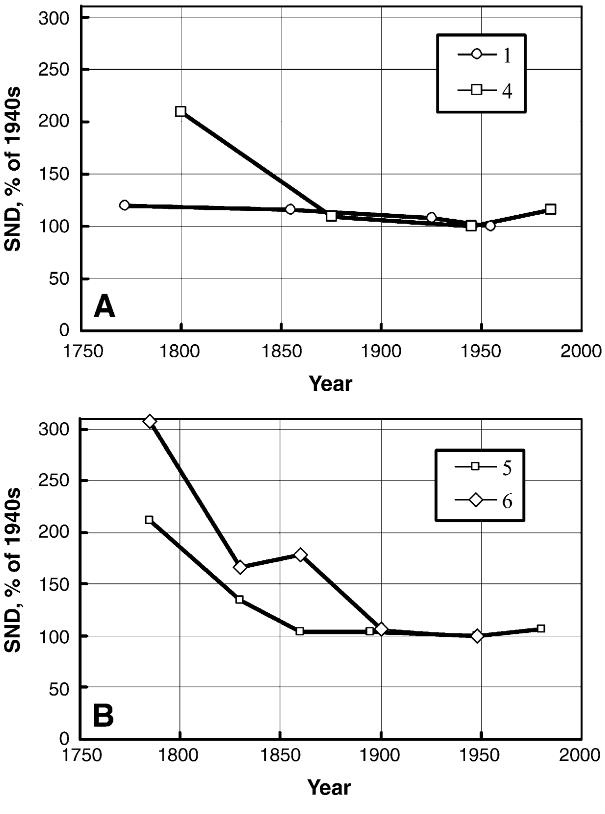

Fig. 7. Temporal changes in SND in several key basins. Basin numbers correspond to Table 2.

5.2. Climatic reasons for stream density decrease

A correlation between SND and moisture availability is illustrated for the Russian lain by the data of Nezhikhovsky (1971) who measured SND on 1 : 25 000 maps in key areas and estimated average SND value for different landscape zones (Fig. 8). A decrease of moisture availability leads to reduced SND, with the major contribution provided by small rivers with length L less than 10 km. The density of rivers with lengths of 10–100 km decreases more slowly, and the density of rivers more than 100-km long is not dependent on climate (Fig. 8). The values of SND obtained by Nezhikhovsky are considerably greater than those reported in this paper (cf. Table 1 and Fig. 8). This reflects the differences in measuring technique. The major difference is that in Nezhikhovsky's study river length is measured along the channel and thus includes the influence of the meandering pattern. In our study stream length is measured along the floodplain axis, so in this paper SND represents the length of valley stretches occupied by permanent streams with no account taken of stream meandering. The other reason is that Nezhikhovsky used 1 : 25 000 maps, while in our study the base scale is around

Table 3
Dynamic of stream and dry valley network density in the Plava River basin

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

1 : 100 000, so the smallest rivers ($L < 1$ km) may be partly missing from our estimates. One more point is that in our transect lowland basins dominate over strongly dissected upland basins, while stream density is strongly correlated with the density of the valley net. On a regional scale this correlation may be illustrated by the data of Nezhikhovsky: SND in the tundra is lower than in the drier climate of the forest zone (Fig. 8), the flat relief of the northern lowlands being the main reason.

As the modern SND correlates strongly with climate wetness, the higher SND values in the past may result from the more humid climatic conditions, compared to the present. Due to the relatively uniform topography, climate changes gradually on the Russian Plain, with moisture availability declining in a SSE direction, i.e., approximately with latitude (Fig. 9A). The SND values are quite variable, because of the influence of local conditions, so that adjacent basins may differ by two times and more. This results in only a general correlation of SND with climate humidity expressed as latitude. Such trends for two time periods are shown as best-fit 3-order polynomials (dashed lines on Fig. 9B). South from 50°N and north from 53°N the average SND changes slowly, while between 50°N and 53°N it changes by more than two times. Consequently considerable change of SND detected in this zone (Fig. 9C) may result from relatively small changes in moisture availability. The SND values from the first third of the 19th century correspond approximately to values for the middle 20th century, 1–2° to the north. Such a shift in latitude does not lead to winter temperature change, but is equivalent to a lowering of summer temperatures by 0.5–1 °C and an increase of annual precipitation by 25–50 mm (Fig. 9A). Since, at the end of the 18th century, SND was even greater (Fig. 7), the climate of this period may be assumed to be more humid.

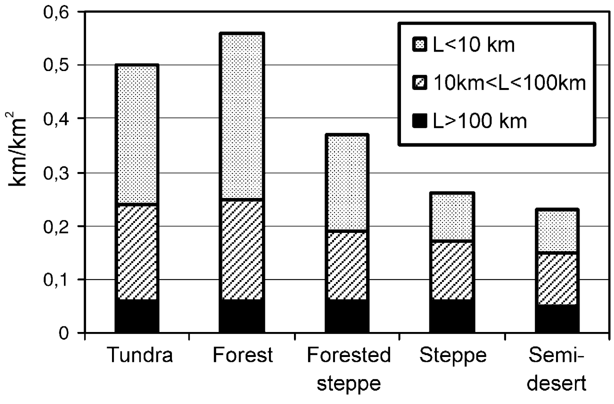

Fig. 8. Stream net density in different landscape zones of the Russian Plain (based on Nezhikhovsky, 1971). L — stream length.

The period from the end of the 18th to the first half of the 19th century is known as a time of wide-ranging climate change at the transition from the Little Ice Age to the modern warm period. Systematic meteorological measurements in the steppe regions of the Russian Plain began only in the 20th century, when the major reduction of river systems had already taken place. The role of climate in this process may therefore only be established indirectly. According to palynological data, annual precipitation in the steppe and forest–steppe regions of the Russian Plain was 25–50 mm higher, and winter and summer temperatures 1–1.5 °C lower, 200 years ago than at present (Klimanov, 1996). Turmanina (1980) studied changes in tree species composition in forest ecosystems of the Moscow region during the last thousand years. She found that in the late 16th to early 17th centuries fir replaced oak and lime as the dominant species in mixed forests, due to climate change and the onset of cooler and wetter conditions. Since the 18th century broad-leave species began to reappear, and since the middle of the 19th century this re-establishment was well developed. This may be interpreted in terms of restoration of warmer and drier climatic conditions. In another study Turmanina (1985) showed that steppe ecosystems in the southern Russian Plain were characterized by high productivity during the period from the 16th to the first half of the 19th centuries, and in the forested steppe zone invasion of oak and lime occurred from the north. Turmanina concludes that such changes in vegetation may be explained only by a sustained decrease of summer temperatures and an increase of moisture availability, in comparison to the preceding period and the present.

Valuable information on climate change can also be derived from historical sources, although its spatial coverage is usually limited to areas in the forest zone, which were

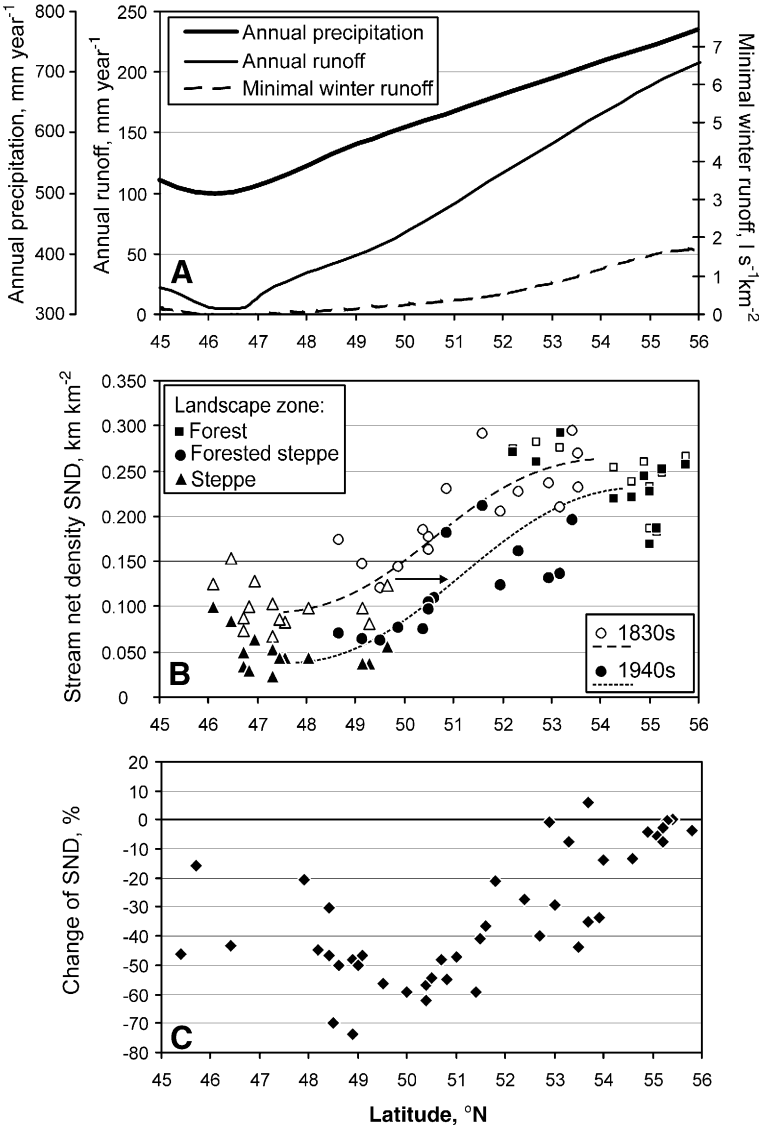

Fig. 9. Latitudinal change of selected climatic parameters (A — according to Tochenov, 1984) and stream net density (B, C) along the NNW–SSW transect across the Russian Plain (see Fig. 6 for location).

more densely populated in medieval times. In the central regions of the Russian Plain, a high frequency of extremely cold winters followed by summer droughts has been deduced by Lyakhov (1992) from historical sources for the first half of the 19th century (Fig. 10). Klige et al. (1993) statistically analysed weather data derived from written chronicles for the central (Moscow) and western (Kiev) regions of the Russian Plain since the 12th century. According to their reconstruction, the period 1750–1800 is characterized by a positive anomaly and the whole of the 19th century by a negative anomaly of winter precipitation, compared to the period of instrumental observations from 1900–1950. Annual precipitation demonstrates a decreasing tendency in both regions, from the middle/end of the 18th until the middle of the 19th century. The same trend is evident for annual runoff calculated from precipitation and temperature data (Fig. 11). This trend is most pronounced in the Kiev region, where a decrease in precipitation was accompanied by an increase in temperature. In the second half of the 19th century runoff values increased again, so

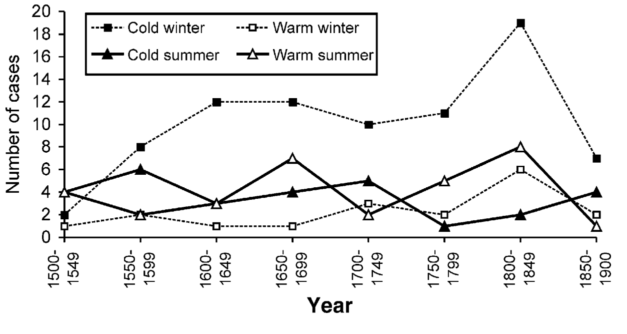

Fig. 10. Recurrence of extremely cold and warm seasons in the centre of the Russian Plain during 1500–1900 reconstructed from historical data (after Lyakhov, 1992). Each point represents a 50-year interval.

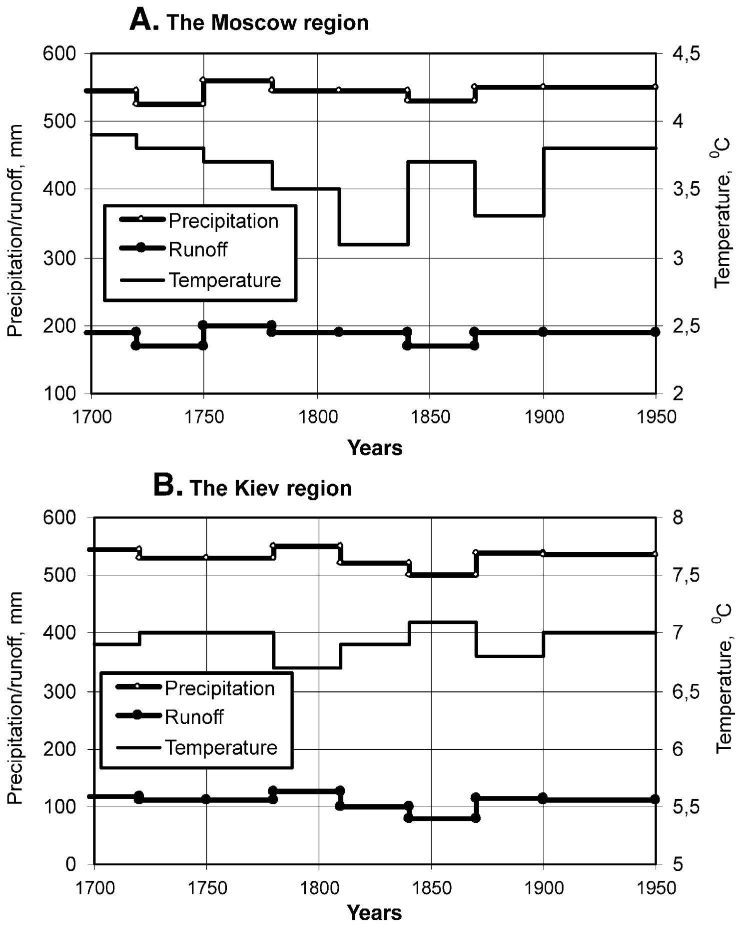

Fig. 11. Change of mean annual temperature, annual precipitation and runoff in the south periphery of the forest zone on the Russian Plain reconstructed from historical data (after Klige et al., 1993). Data from 1900–1950 were obtained by instrumental observations and are regarded as the climatic norm.

that in the middle of the 20th century they were the same as at the end of the 18th century in the Moscow region (Fig. 11A). This is consistent with the limited change of SND in river basins in the Moscow region (cf. no. 1–5 in Table 1). In the Kiev region runoff values in the first half of the 20th century were still 14% lower than those at the end of the 18th century (Fig. 11B). In the neighbouring region of Western Ukraine, values of SND in the middle of the 20th century are 19% lower than those for the end of the 18th century although no increase is evident since the middle of the 19th century (line 1 on Fig. 7).

Another method of runoff reconstruction is that used by Reshetnikov (1994). He established a least-squares empirical relationship between the annual runoff of the Volga River at Volgograd and values of spring flood height measured in Astrakhan’. Using this equation and earlier observation data on flood stages, Reschetnikov synthesised the record of annual runoff for the Volga River at Volgograd since 1792. As the runoff values are very variable from year to year, the use of cumulative coefficients $C_i = C_{i-1} + (Q_i - Q_\mathrm{m})/Q_\mathrm{m}$ is preferable, where Q_i is runoff in year i, Q_m is mean annual runoff during the study period. In this case $Q_\mathrm{m} = 255.3$ km^3 for the period 1792–1987. Rising and falling limbs of the C_i-curve correspond respectively to periods of prevailing high and low runoff, in comparison to the mean value. According to the form of the C_i curve the following periods were identified and the mean runoff was calculated for each. (Fig. 12A): high runoff — 1792–1813, 1844–1869 and since 1978, average runoff — 1870–1929, low runoff — 1814–1843, 1930–1977. At the boundary between the 18th and the 19th centuries, the Volga River had the highest runoff. Runoff then reduced considerably at the beginning of the 19th century, increased again in the middle of this century and then declined until the last quarter of the 20th century. This pattern resembles the runoff changes reconstructed from historical data with a shift of phase (cf. Figs. 11 and 12A).

Annual runoff in the Volga River basin depends primarily on the spring flood runoff. However, topographic maps show the situation in the low water period when rivers are supplied primarily by groundwater. It would therefore be more acceptable to use the minimum discharge during the ice-free September period (see Fig. 4), rather than the annual runoff, when investigating the relationship with SND. However, a relatively good correlation exists between annual and September runoff (Fig. 13A). This makes it possible to use the reconstructed annual runoff instead of the low water period runoff, beyond the period of observations. It is clear from Fig.

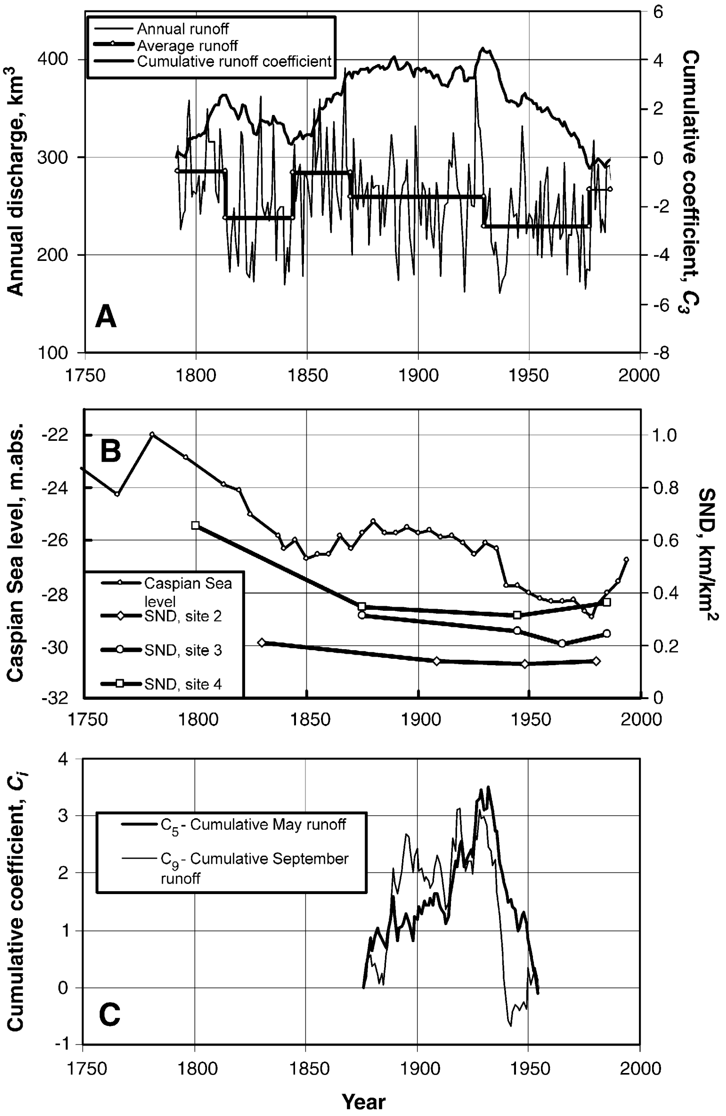

Fig. 12. Hydrological changes in the Volga River basin since the end of the 18th century. A — annual runoff at Volgograd (1792–1880 after Reshetnikov, 1994; since 1881 — observation data). Cumulative runoff coefficient $C_i = C_{i-1} + (Q_i - Q_m)/Q_m$ where Q_i is runoff in year i, Q_m is the average runoff during the study period. B — change of water storage represented by the Caspian Sea level (Varuschenko et al., 1987) and SND in the Volga River basin. Numbers of key sites correspond to Table 2, location shown on Fig. 2. C — trends in flood runoff (expressed as C_5) and base flow (expressed by C_9) changes at Polyana, the Volga River, since the beginning of observation till the reservoir construction on the middle Volga River. C_5, C_9 — cumulative coefficients calculated for the May and September runoff, respectively.

13A and B that the major decrease of SND corresponds to the period of low runoff in the Volga basin in the first half of the 19th century. However the low values of SND are taken from the maps produced in the 1850–60s when the average Volga River runoff had increased again up to the level at the beginning of the century (cf. the line of average runoff on Fig. 12A). The subsequent trend of runoff decrease until the last quarter of the 20th century was expressed as either stability or only a slight decrease of SND. An increase of runoff at the end of the 20th century corresponds to a slight increase in SND.

In the above discussion we assume that a direct correlation exists between SND and groundwater runoff from the basin. In turn, groundwater runoff is hypothesised to be proportional to groundwater storage — the mass of gravitational water stored in the surface layers of rocks and sediments that drain into the stream network. Accumulation of groundwater mass leads to an increase of SND and vice versa. Such a correlation is relatively distinct in the spatial context (see Fig. 8), and is thought to occur in the temporal dimensions as well. However, correlation of SND with changing climate cannot be simple, when various inertial effects are taken into account. If SND serves as an integral indicator of the long-term water balance of the territory, lake level changes being another such indicator, then a correlation should exist between the two. In our case such a correlation is expected between the Caspian Sea level and SND in the Volga River basin.

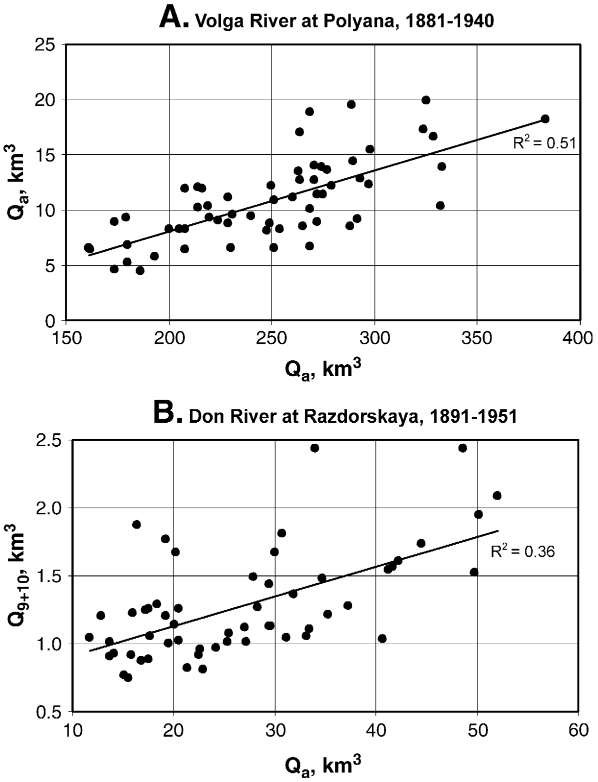

Fig. 13. Correlation between annual runoff (Q_a) and the low water period runoff (Q_i, i — the month number) for the Volga (A) and Don (B) Rivers. Based on the hydrological regime (cf. Fig. 4), runoff during the low water period of the year is regarded to be essentially base flow and is expressed as the September runoff (Q_9) or September+October runoff (Q_{9+10}). The data represent the interval since the beginning of observations until the construction of large reservoirs that considerably changed the runoff seasonal distribution (Rybinskoye Reservoir in the upper Volga River and Tsimlyanskoe Reserve in the middle Don River).

The major reduction of SND corresponds in time to the lowering of the Caspian level between the late 18th and the middle of the 19th centuries (Fig. 12B). The increase in the Volga River runoff in the 1850–60s had caused only a slight rise of the Caspian level. Probably the duration of runoff increase was not enough to cause a comprehensive increase of water mass. This may explain why the SND values in this period had not restored up to the level of the values of the beginning of the century, as did the average runoff. Between 1880 and 1978, two periods of gradual lowering of the Caspian level are detected, divided by a sharp drop in the early 1930s. The same trend is evident for SND in the Volga basin, but the sharp drop is not detected, even though the period 1929–1942 was characterised by very low runoff during the low water season (Fig. 12C). This is probably due to the inadequate frequency of the map sets used. The end of the 20th century is marked by both a rise in the Caspian level and an increase in SND in the Volga basin.

Hydrological reconstructions for the Don River were made by Bogucharskov (1990). He found a close relationship between the Don River annual runoff and the area of the maximum winter ice cover in the Baltic Sea. The reason for such correlation is that the Don River annual runoff depends primarily on the spring flood runoff. The more severe the winter in the north of Europe, the longer the duration of the cold season and the more frequent the cyclone invasions in the south of the Russian Plain, both favouring snow storage. Using this relationship and available data on the Baltic Sea winter conditions Bogucharskov synthesised the Don River annual runoff series since 1720. As the extreme values were considered unreliable, he did not represent the results as annual values, but identified periods characterised by low (<25 km^3), medium (25–30 km^3) and high (>30 km^3) annual runoff.

To make them comparable with the results of Bogucharskov, we divided the period of instrumental observations into characteristic intervals using the cumulative runoff coefficients and calculated mean annual discharge for each of these intervals. It was found that high runoff intervals were more frequent at the 18th to 19th century boundary than in the 20th century During the hundred years between 1750 and 1849, 57 years are attributed to the high runoff intervals, 19 years — to medium runoff and 24 years — to low runoff, but during the next hundred years (1850–1949) only 4 years constitute high runoff periods, but as many as 68 years make up medium and 28 small runoff periods. This corresponds to a considerable decrease of SND in the Don basin since the end of the 18th century until the middle (Fig. 7, site 5) and the end (Fig. 7, site 6) of the 19th century.

As in the case of the Volga River, annual runoff is used here as indicator of river runoff during the dry part of the year, when rivers are fed primarily by groundwater. The basis for this assumption is the correlation between annual runoff and the runoff of the driest months of the snow-free part of the year (Fig. 13B). However it should be noted that this correlation is less close than in the case of the Volga River. This is because the periodicity of the flood and low water runoff do not coincide. Between the start of instrumental measurements and the construction of the Tsimlyanskoe Reservoir, the Don River runoff changed four times: the large flood runoff intervals were 1881–1901 and 1915–1930, and the small flood runoff intervals were 1902–1914 and 1931–1951. However, there are only two characteristic intervals of low water runoff. These changes are not reflected in the stream net composition: SND in the middle of the 20th century was almost the same or even slightly lower than that around the beginning of the century (Fig. 7B), while the runoff in the dry season was relatively low during the period 1881–1914 and relatively high during 1915–1951.

It follows from the above that evidence exists that the climate of the central and southern regions of the Russian Plain was wetter at the boundary between the 18th and 19th centuries than today. High values of SND were therefore characteristic of this time and the subsequent decline may be explained by climatic control. An analogue of possible hydrogeological changes resulting from a significant increase of precipitation may be found in the consequences of irrigation activity in the Kashira district of the Voronezh region — a typical forest–steppe area. As reported by Akhtyrtsev et al. (1981), six years of irrigation had resulted in a significant rise of groundwater levels. Before the beginning of irrigation in 1973, a groundwater table depth of more than 5 m was characteristic of 25% of the area, 3–5 m of 57% and 2–3 m of 18%. In 1978 the area of groundwater deeper than 5 m reduced to 1%, and that of 3–5 m to 37%, but areas with groundwater 2–3 m deep constituted 31% and in 31% of the area the ground water depth was less than 2 m. The contemporary annual precipitation in the region is about 500 mm annually, some 350 mm coming as rain during the warm period. The irrigation norms were 600–2000 m^3 per hectare, which is equivalent to an increase of summer precipitation by 60–200 mm, or by 20–60% (a 10–40% increase of annual precipitation). This is significantly greater than the 25–50-mm increase in precipitation at the end of the 18th century reconstructed from pollen data (Klimanov, 1996) but still gives an indication of what would happen under an increase of climate wetness.

However, the "climate-alone" hypothesis of SND change does not explain all the available data. The unsolved question is why climate change during the 20th century is not reflected by SND. The high variability of SND changes in adjacent basins, especially in the southern regions (Table 1) is also beyond the climate-based explanation. There are also some cases where a reduction in SND occurred with no significant change of climate.

5.3. Transformation of the water balance and sediment budget due to land use change

The hydrological regime and sediment flux changes dramatically after cultivation of a basin. Surface runoff is extremely limited under grass or forest vegetation compared with agricultural land. Long-term monitoring at a key forest–steppe site in Central Russia showed that runoff during snowmelt from stubble is an order of magnitude higher than from undisturbed meadow. As a result, flood peaks increase 2–5 times compared to natural conditions (Koronkevich, 1990). In the southern part of the forest zone surface runoff can occur in the forest only on deeply frozen clay loam soils. The occurrence of this situation is relatively limited, so the mean annual water runoff coefficient for the forest zone is 0.18 (C_v=0.75) (Soubbotin and Dygalo, 1991). Cultivation of land exerts a major influence on the relationship between surface and subsurface flow. Annual surface runoff from a loam soil increases by four times in a cultivated catchment, according to data from long-term observations during snowmelt in paired catchments in the forest zone of Central Russia. Surface runoff from forest on sandy loam soils is absent, but the annual runoff coefficient is 0.41 (Soubbotin and Dygalo, 1991). During summer and autumn, surface runoff also increases within cultivated fields by at least twofold because of decreased infiltration (Nazarov, 1970).

In the forest–steppe and steppe zones, the area of arable land is as high as 80% in some basins. Under natural conditions, surface runoff, even during snowmelt is close to 0 (Koronkevich, 1990). The runoff coefficient for cultivated lands varies over a wide range (Table 4). However, it is possible to identify an increase in annual surface runoff by 6–7 times, compared with natural conditions. Since the middle of the 20th century, the low water river runoff in steppe and forest–steppe zones has increased by 10–30% because of the wide-spread adoption of winter tillage (Koronkevich, 1990). Winter tillage became widely used only in the second half of the 20th century. Hence the increase in surface runoff was even higher immediately following the beginning of widespread slope cultivation.

The intensity of sheet, rill and gully erosion from cultivated lands also exceeds erosion under natural conditions in the temperate zone by 2–4 times, depending on the relief, crop rotation and climate conditions. However sediment delivery to the river valley depends on a number of possible sinks, which retain part of the mobilised sediment. Very often the total mass of eroded soil is trapped in a closed slope basin (Norton, 1986). This is a very typical situation for vast areas of the Northern American Plains (Larson and Foster, 1990). In these cases the influence of cultivation on river channels is primarily restricted to changes in the hydrological regime and an increase in bed and bank erosion in the river channels (Priest et al., 1976; Prestegaard, 1988; Lohnes, 1997; Witter et al., 1997), which commonly result in enlarged channels (Knox, 1987). Cultivated slopes may also be separated from the river valley by a wide grassed strip or small dry valleys, which also detain a significant proportion of the eroded sediment (Golosov, 1998; Larue, 2002). In this case, an increase in sediment yield promotes an increase in floodplain sedimentation rates but it is not coupled with channel aggradation. River aggradation resulting from increased slope sediment flux is observed

Table 4
A comparison of surface runoff coefficients during snowmelt from fields under different land use (after Koronkevich, 1990)

Landscape zone	Fallow land			Winter corn	Perennial grasses	Pasture	Winter tillage
	Young	Middle	Old				
South of forest	1.15	1.0	0.8	1.15	1.1	–	0.75
Forested steppe	1.25	1.05	–	1.2	1.15	0.85	0.55
Steppe	–	1.15	–	1.3	1.25	0.7	0.3

The runoff coefficient from stubble is accepted as 1 for each landscape zone separately.

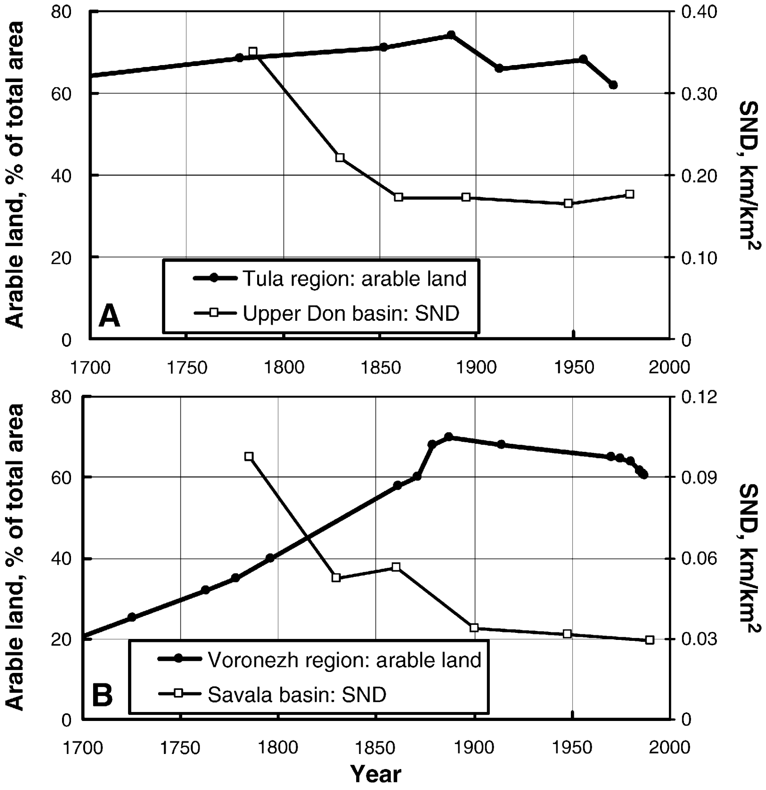

Fig. 14. Changes in SND and the area of arable land area. A — the upper Don River basin, B — the Savala River basin.

within intensively cultivated basins (tillage area in excess of 60%) with a sediment delivery ratio greater than 7–10% (Phillips, 1991).

Two types of temporal relationship may be found between the dynamics of the expansion of arable land and changes in SND. In the regions with a long agricultural history, such relationship is not clearly defined. For example, in the upper Don River basin the reduction in SND occurred in areas of arable land that had existed since at least the middle of the 18th century (Fig. 14A). However, in the north of the steppe zone the SND decrease coincided in time with the expansion of agricultural land (Fig. 14B). The SND decrease in the Savala River basin may be divided into two phases. The first phase coincided with the initial period of intensive cultivation and is likely to result from a combination of factors, including reduction of groundwater supply after the cultivation of virgin steppes and a drought period associated with the extremely cold winters observed in European Russia in the first half of the 19th century (Fig. 10). The second phase coincided with the achievement of the maximum area of arable land after the 1861 land reform (Fig. 14B). Additional decreases in SND could reflect excessive sedimentation in valley bottoms due to accelerated erosion in the fields.

This suggestion is confirmed by the results of a detailed study of sediment redistribution undertaken within the Popov Ovrag basin, which forms part of the upstream reaches of the Savala basin (Ivanova et al., 1998). Detailed maps were available for different periods for this particular basin that permit evaluation of the sediment budgets of the slopes (Table 5) and gully network development. The most significant increase in the area of arable land was observed at the end of the 19th century. Even the steep valley sides were cultivated during this period and this promoted the delivery of eroded sediment directly to the valley bottom through the rapidly expanding system of gullies. The last period of expansion of the area of arable land was associated with the cultivation of the very flat interfluve areas. As a result the channel was buried beneath eroded sediment, as confirmed by detailed drilling (Ivanova et al., 1998).

The Plava basin is located within an area where the period of intensive cultivation extends back 300–350 years. Comparison of the river net for three time periods shows, that a significant reduction in the river network was also observed at the end of the 19th century, when the increase in arable area was only about 9%. Very steep valley slopes were cultivated in this period. As a result,

Table 5
Changes in the slope sediment flux during the period 1790–1995 in the Popov Ovrag basin (after Ivanova et al., 1998)

Period	Area of arable lands (ha)	Total soil losses (t)	Annual soil losses (t)	Erosion rate (t ha^{-1} year^{-1})
1790–1825	100.4	7861	225	2.25
1825–1875	403.4	25 700	550	1.36
1875–1930	1097.8	149 600	2720	2.48
1930–1995	1681.6	111 150	1710	1.02

Table 6
The main stages of gully formation in the sod–podzol 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 (%/a)
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

gully erosion increase dramatically. This is confirmed by data, reported by Moryakova (1988) for this area, which indicate the maximum rate of gully growth in different periods (Table 6).

Some parts of the southern steppe zone of European Russia and adjacent areas were intensively cultivated only 100–50 years ago. A detailed study has been undertaken of two regions (the basin of the Samara River at Preduralie and an interfluve area between the Ural River and the Tobol River on the Zauralie plateau) with different periods of intensive cultivation, located in the south-east corner of the Russian Plain (Ivanova, 1990). Southern Preduralie was intensively cultivated at the end of the 19th and the beginning of the 20th centuries. The Southern Zauralie region was intensively cultivated only from 1954 to 1956. Based on a comparison of old maps made in 1855 and a recent map produced in 1954, the river net in Southern Preduralie decreased by 40%, whereas the stream net on the Zauralie plateau did not change and even increased its length in some basins (Table 7). A comparison of maps, produced at different times for the second half of the 20th century shows a marked reduction of the permanent streams on the Zauralie Plateau, although the number of permanent streams with a basin area less than 100 km also reduced in Southern Preduralie (Table 8). Different factors clearly influence the disappearance of water courses simultaneously. It is very likely that the marked reduction in the river network in Zauralie at that time was associated with the increase in the area of arable land from less than 10% at the beginning of the 1950s, which significantly changed the relationship between surface and groundwater runoff. The disappearance of streams in small basins in Southern Preduralie could reflect both the delivery of eroded sediment from cultivated slopes and a local decrease in precipitation. However, the latter is very unlikely, because there has been an increase of precipitation in the Southern part of the Russian Plain since the end of 1970s. Comparison of the longest series of hydrological observation for the two regions confirms that climatic variations exerted a similar influence on river runoff in both regions (Fig. 15).

Table 7
Changes of the stream net within the river basins of Southern Preduralie and Zauralie during the period 1855–1954

River basin	Stream net length (km)		Change of stream net (%)
	In 1855	In 1954	
Southern Preduralie (area of arable land> 60%)			
Buzuluk	821	427	−48
B. Pogromka	133	87	−35
Sorochka	167	100	−40
Soroka	129	44	−66
Kuvai	166	106	−36
M. Uran	420	298	−29
B. Uran	421	181	−57
Tok	1067	811	−24
Zauralie (area of arable land< 15%)			
Salmysh	984	975	−1
B. Yushatyr’	466	466	0
S. Kargalka	44	42	−4
Kasmarka	250	250	0
Ui	2180	2027	−7
Toguzak	354	400	+13
Souunduk	654	726	+11
Karaganka	315	306	−3
Zingeika	130	143	+10

Table 8
Change in the numbers of permanent streams in basins of different area for Zauralie and Southern Preduralie during the period 1954–1989 (after Golosov and Ivanova, 1995)

Basin area (km^2)	Number of permanent streams (%)		
	Beginning of 1950s	Beginning of 1970s	1989
<50	100/100*	71/92	43/60
50–100	100/100	100/76	14/47
100–300	100/100	57/100	21/88
300–1000	100/100	100/100	54/100
>1000	100/100	100/–	100/–

*Numerator — Zauralie, denominator — Preduralie.

5.4. Perspectives

The end of the 20th century was characterized by significant climatic changes. Increasing winter air temperatures and spring–summer precipitation were observed within European Russia (Bulygina et al., 2000). As a result the increase of low water river runoff is similar for a given

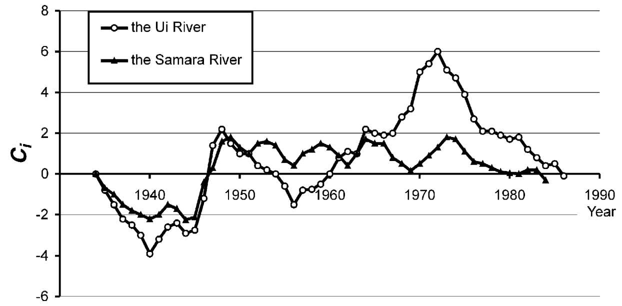

Fig. 15. Changes of river runoff during the period 1934–1985 expressed as cumulative runoff coefficients C_i: A — the Ui River, basin area 3600 km^2, Zaural’e; B — the Samara River, basin area 1340 km^2, Predural’e (after Ivanova, 1990).

area (Georgievsky et al., 1996). Monitoring of ground water levels at experimental water balance stations during recent decades showed an increase in level by 0.5–1.0 m since the 1970s (Shiklomanov and Georgievsky, 2002). The same trend since the end of 1960s is documented by hydrogeological surveys undertaken in different parts of the Volga River basin (Klige et al., 2000). The increase in the level of the Caspian Sea (Fig. 12B) is one more confirmation. A slight tendency for increased permanent flow is also observed in the river basins studied (Fig. 7). An increase of temperature and precipitation in central and southern European Russia is forecast for the first half of the 21st century (Shiklomanov and Georgievsky, 2002), and it is therefore possible that some increase of SND will occur. However the 1–3 m of erosion products accumulated in the valley bottoms during the agricultural period provide a major obstacle to the restoration of permanent flow in the dry valley bottoms.

6. Conclusion

Century-scale stream network dynamics have been evaluated in the southern forest, the forest–steppe and the steppe zones of the Russian Plain and related to a set of natural and anthropogenic factors. The maximum SND decrease is observed in the northern part of the steppe zone, where 50–60% of the watercourses disappeared during the one century. The most significant decrease of SND occurred during the 19th century, with the climate changes that occurred during the first half of century being the major cause. Extremely cold winters promoted high surface runoff during snowmelt and droughts in the following summers. Climate change during the transition from the Little Ice Age to the modern warm epoch coincided with a major increase in the area of arable land in the forest–steppe and partly steppe zone. The latter promoted an increase in the surface runoff coefficient. Further expansion of the area of arable land in the second half of the 19th century, with maximum cultivation after the 1861 land reform when even steep valley sides were ploughed, provides the main reason for the second stage of SND decrease, which is found in some basins. It has been suggested that small scale climatic variations exert a stronger influence on basins that are mainly cultivated, because of the higher magnitude of both surface runoff and sediment yield (Knox, 1977). However, this is not true in the case of the Russian Plain, because the former first and second order streams were completely aggraded by sediment and became very good sinks for sediment mobilised from the cultivated slopes. The recent increase in winter air temperatures and summer precipitation within the Russian Plain will promote the recovery of permanent streams, but it is a relatively slow process due to the 1–3 m of eroded sediment deposited in most of the valleys of order 1–3.

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