FLUVIAL RESPONSE TO THE LATE VALDAI/HOLOCENE ENVIRONMENTAL CHANGE ON THE EAST EUROPEAN PLAIN.

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Abstract
The relicts of large meandering paleochannels are found throughout the territory of the periglacial zone of the Last (Valdai = Weichselian) Glaciation on the Russian Plain on the lower levels of river terraces and on the floodplains. Channel widths of so-called macromeanders can be 15 times larger than the recent meanders on the same rivers. Paleolandscape and paleohydrological reconstructions show that such periglacial river channels were formed under the conditions of high spring water flow up to eight times greater than modern discharges, when the flow coefficient was close to 0.9 – 1.0 due to the existence of permafrost. Also, summers were dry and streams lacked ground water supply. Permafrost degradation increased soil permeability in the spring and increased ground water flow during summer, causing a decrease of annual flow 12,000 – 14,000 years B.P. in the southern periglacial zone, and up to 8,500 years B.P. in the northern periglacial zone. In the taiga zone an annual flow in the recent river basins is about 80 – 85% of that found in the periglacial zone in the east and 30 – 60% of that in the west. In the east of the broad–leaved forest zone it is about 40 – 50% of that of the periglacial zone, and 20 – 25% in the western part of the broad–leaved forest zone. In the eastern steppe and forest steppe the modern annual flow is about 40 – 60% of that of the periglacial zone and about 10% in the western part of steppe and forest steppe zones. As a result, large periglacial channels were abandoned and transformed into floodplain lakes and bogs. The Holocene channels have much smaller channel widths and meander lengths, formed under conditions of lower annual flows and much steadier flow regime.

Keywords
Periglacial landscapes; paleochannels; paleohydrology; change of hydrological regime; Late Weichselian/Holocene; Russian Plain.

Introduction

The East European or Russian Plain occupies a vast territory (4,600,000 km^2) from the shore of the Arctic Ocean in the North to the Caucasus, Crimea and Carpathians Mountains in the South. It extends to the Urals in the East and the Baltic Sea coast to the northwest. Geologically the territory generally corresponds to the Russian platform, and is characterised by gently undulating fluvial relief with the mean altitude of 170 m above sea level (Alayev *et al*., 1990). A number of highlands within the Russian Plain have elevations of 250-473 m. The northernmost Russian Plain is occupied by a cover of tundra and forest tundra over continuous and discontinuous permafrost conditions. The forest zone occupies about 50% of the area, and is represented by northern, middle and southern taiga (dark coniferous forest), mixed and broad-leaved forests. Further to the south are the forest steppe and steppe zones. Semidesert and desert zones occupy the southeastern part of the Plain (Vegetation…, 1980).

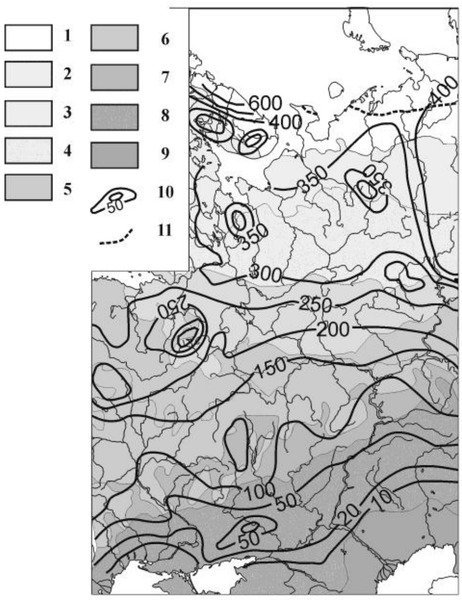

Fig.1. Modern landscapes of the Russian Plain: 1 – tundra and forest – tundra; 2 – northern taiga; 3 – middle taiga; 4 – southern taiga; 5 - mixed coniferous and broad – leaved forest; 6 - broad – leaved forest; 7 – forest – steppe; 8 – steppe; 9 – semidesert; 10 – runoff-depth contours (mm); 11 – the southern boundary of the continuous permafrost.

The territory is characterized by temperate climate influenced by Westerlies, so that the continentality increases toward the east. South of 48-50ºN eastern winds from the arid continental interior of Asia are predominant. Mean annual precipitation varies mostly within 500 – 700 mm in the north and approximately 500 - 600 mm in the central and north - western part of the Plain, and sharply decreases to 200-250 mm in the southeast on the Plain. The annual runoff is determined by the amount of precipitation, and by the annual runoff coefficient. The latter is greatest in the northeastern part of the Plain within the modern permafrost zone (0.8-0.9). It gradually decreases toward the south to 0.1 in the semidesert zone. As a result runoff decreases from the north to the south of the Plain from 350-400 mm to 20-50 mm, being governed mostly by the runoff coefficient (Fig. 1).

During the last glaciation, the northwestern part of the Russian Plain was covered by the Valdai (Weichselian) ice-sheet. During the last glacial maximum a vast periglacial zone occupied most of the ice-free area of the Russian Plain (Grichuk, 1989). The northern part of the Plain was covered by periglacial forest steppe with tundra elements, and the central and southern parts by the periglacial steppe. Dry steppe and semidesert zones formed a narrow belt along the coast of the Caspian Sea. Most of the Plain was then within the zone of low temperature continuous permafrost which reached its maximum extent 20-15 K B.P. (Velichko *et al.*, 1982).

Significant fluvial changes at the Late Glacial/ Holocene transition are well known in western and central Europe. For example, marked channel evolution was shown in England by Rose *et al*. (1980), in France by Carcaud *et al.* (1991), and in the Netherlands by Bohncke and Vandenberghe (1991). The transformation of large periglacial rivers into much smaller Holocene streams was intensively investigated in Poland (Starkel, 1977, 1995; Kozarski, Rotnicki, 1977; Schumanski, 1983; Rotnicki, 1991; Starkel *et al.*, 1996). Similar fluvial changes were discovered in the southern part of West Siberia, in northern Kazakhstan (Volkov, 1960, 1963) and on the plains of the Altai (Makkaveev *et al*., 1969). The morphology of large paleochannels on the Russian Plain and their paleohydrological importance are documented only in few papers (for example, Lyutsau, 1968; Makkaveev *et al*., 1969), and their broad distribution over the Plain was discovered only in the last decade (Panin *et al*., 1992, 1999; Sidorchuk *et al*., 1999).

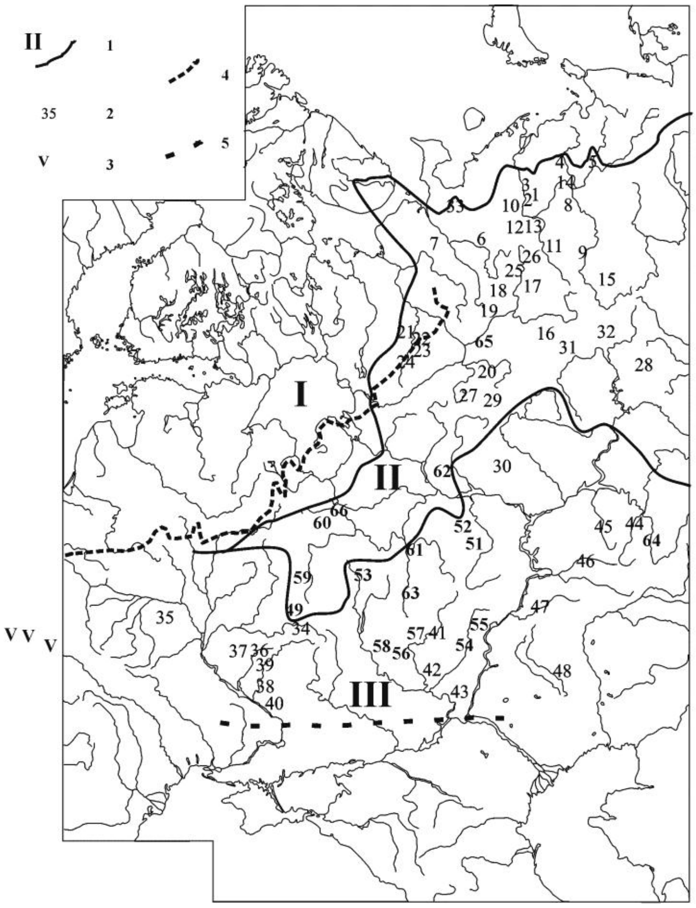

Fig. 2. Distribution of macromeanders on the Russian Plain. 1 – index and boundary of macromeander type region; 2 – index of key study area basin in table 1; 3 – macromeanders in the Vistula River basin (after Starkel, 1995); 4 – edge of the Valdai ice-sheet; 5 – southern boundary of permafrost at the maximum of Valdai glaciation (after Velichko *et al*., 1982)

Periglacial paleochannels on the Russian Plain

The relicts of large paleochannels are found on the lower levels of river terraces and on the floodplains across the territory of the former periglacial zone. The majority of the paleochannels have a meandering pattern and have channel widths as great as 15 times larger than the Late Holocene meanders on the same rivers. The Russian Plain may be divided into three main regions based on the distribution and type of macromeanders (Fig. 2).

I. *The region devoid of macromeanders* generally corresponds to the territory occupied by the Last Glaciation, or regions close to the ice-sheet margin. The reasons for the absence of macromeanders vary across the region. Its northwestern part is composed of nearly barren igneous and metamorphic rocks. Therefore most of the river valleys there were stable during the Late Glacial and the Holocene. River basins in the tundra of the northeastern part of the Plain are still within the permafrost zone, so that the hydrological conditions there did not change significantly during the last 18,000 years.

II. *The region with macromeanders situated on low terraces of modern river valleys*. In this region modern channels are incised into the paleochannels because of glacioisostatic uplift and changes in local erosion basis (*e.g.* draining of ice-dammed lakes).

III. *The region with macromeanders at the level of modern floodplain* forms a wide belt within the forest - steppe and steppe zones. In this region point bars and filled palaeochannels constitute floodplains of recent valleys. Small and medium rivers in this region are characterised by very high ratios of the floodplain width to the channel width.

Table 1 shows typical examples of macromeander parameters in relation to recent channels. For this study only well-preserved ancient fluvial features were chosen to perform an accurate measure of palaeochannel parameters on topographic maps.

Table 1. Meanders and macromeanders parameters of the rivers on the Russian Plain

Index	River	F km^2	**Q_r m^3/s**	λ_r m	W_r m	**Q_p m^3/s**	λ_p m	W_p m	Latitude N	Longitude E
33	Oma	4100	**47.2**	610	75	**66**	1750	150	66°41′	46°24′
26	Vym’	2700	**38.0**	300	40	**54**	1450	150	64°10′	51°32′
25	Chisva	1000	**11.5**	150	15	**33**	1000	120	63°33′	51°20′
17	Veslyana	3940	**42.9**	500	60	**118**	2800	250	62°50′	51°20′
19	Ched'yev	180	**1.8**	80		**18**	500		62°37′	49°20′
18	Yarenga	2450	**11.1**	270	40	**57**	1300	200	62°35′	49°28′
21	Paden'ga	1040	**12.5**	260	40	**40**	1250	125	61°52′	42°34′
22	Sheren'ga	300	**1.8**	50	10	**9**	310		61°46′	42°40′
23	Vamsheren'ga	300	**1.8**	45	10	**13**	430		61°46′	42°45′
24	B. Churga	560	**6.7**	190	40	**21**	750	80	61°29′	42°22′
16	Lokchim	6040	**52.8**	640	100	**286**	2900	1000	61°36′	51°36′
20	Luza	18100	**137.7**	1500	250	**266**	4630	450	60°35′	47°15′
27	Yug	4600	**38.0**	430	100	**124**	2000	380	59°53′	45°30′
7	Nemnyuga	800	**7.2**	230	35	**24**	750	100	65°25′	43°46′
6	Sula	1040	**11.4**	310	35	**33**	1130	100	64°53′	48°27′
4	Khar'yaga	970	**10.7**	230	50	**32**	810	150	67°09′	56°35′
5	Adz'va	8700	**100**	1540	175	**80**	1810	180	67°05′	60°07′
3	Soz'va	1400	**15.4**	480	50	**41**	1080	150	66°35′	52°53′
14	Laya	9530	**104.8**	2000	200	**139**	2200		66°25′	56°22′
1	Ersa	1800	**19.8**	250	50	**36**	1000	125	66°09′	53°21′
2	Slepaya	230	**2.5**	85		**13**	470	70	66°11′	53°21′
10	Tobysh	3250	**35.8**	530	100	**71**	1700	200	66°04′	51°10′
8	Lyzha	6000	**66.0**	810	140	**197**	3080		65°44′	56°19′
12	Pizhma	5470	**52.5**	580	100	**69**	1500	200	65°23′	52°01′
13	Neritsa	2900	**31.6**	380	70	**49**	1250	150	65°13′	52°37′
9	Lem'yu	3850	**42.4**	570	120	**319**	4800		63°58′	56°38′
11	Ayyuva	1970	**19.9**	500	60	**76**	2100	180	63°45′	54°10′
15	B. Lyaga	1330	**16.7**	450	50	**45**	1400	125	62°37′	56°46′
65	Vychegda	121000	**1100**	6000	1100	**900**	7000	1200	61°16′	46°44′
66	Moskva	9000	**67.2**	700	150	**180**	2500	500	55°38′	37°47′
60	Protva	2170	**11.6**	380	80	**45**	800	180	55°12′	36°31′
59	Zhizdra	1970	**9.9**	150	40	**55**	1000	250	53°51′	35°07′
62	Kerzhenets	4500	**24.0**	370	50	**114**	1250	500	56°28′	44°48′
51	Alatyr’	10500	**40.7**	410	80	**80**	1250	250	54°48′	46°11′
52	P’yana	7930	**38.1**	270	70	**96**	1300	300	55°31′	44°19′
32	Pil’va	890	**8.0**	170	35	**51**	1200		60°43′	55°57′
31	Veslyana	3900	**33.2**	180	35	**92**	1700		60°26′	52°42′
28	Ya’va	5230	**62.8**	830	120	**169**	2800	500	59°08′	57°02′
30	Usta	6030	**42.2**	340	60	**93**	2200	200	56°55′	45°28′
44	Dyema	12500	**42.3**	210	60	**70**	1200	220	54°31′	55°23′

64	Urshak	3130		230	50	**40**	860	200	54°29′	55°52′
45	Ikk	7660	**31.9**	140	40	**87**	1440	290	54°47′	53°34′
46	B.Kinel'	5970	**19.4**	160	25	**57**	920	200	53°22′	51°16′
47	B.Izgiz	2110	**3.3**			**22**	800	100	52°15′	49°54′
48	M.Uzen'	9490	**6.8**			**60**	1000	200	50°28′	47°38′
35	Ubort'	5260	**10.7**	175	30	**43**	880	120	51°55′	28°30′
34	Seym	10700	**37.1**	170	40	**141**	3000	400	51°39′	35°20′
49	Svapa	6310	**29.1**	120	30	**75**	1400	250	51°39′	35°20′
37	Uday	6120	**11.4**			**83**	1500	300	50°18′	32°32′
36	Sula	14200	**28.5**	170	30	**146**	2500	400	50°15′	33°21′
38	Psyel	11300	**30.5**	330	40	**92**	1250	330	49°38′	33°46′
40	Orel'	9400	**21.6**	200	50	**113**	1790	350	48°49′	34°24′
53	Lesnoy Voronezh	1740	**6.5**	160	50	**35**	690	150	53°01′	40°38′
58	Bityug	7330	**18.2**	200	40	**115**	1300	350	51°42′	40°31′
55	Medveditsa	7610	**18.4**	320	40	**77**	1200	250	51°31′	44°38′
41	Khopyer	19100	**67.0**	360	60	**453**	2500	800	51°19′	42°22′
57	Vorona	9540	**31.3**	430	70	**147**	1700	420	52°04′	42°15′
56	Savala	7720	**20.4**	250	50	**77**	800	250	51°08′	41°27′
54	Tersa	7320	**14.5**	250	40	**77**	1000	250	50°48′	44°24′
42	Buzuluk	6830	**9.7**	460	35	**85**	1380	300	50°32′	42°34′
43	Ilovlya	8730	**8.0**			**44**	850	150	49°47′	44°30′

* λ - meander length is measured as a straight distance between the adjacent points of curvature change; W – channel bankfull width at crosses; Q – mean annual discharge; F – basin area. (index "r" refers to recent river channels, "p" refers to paleochannels)

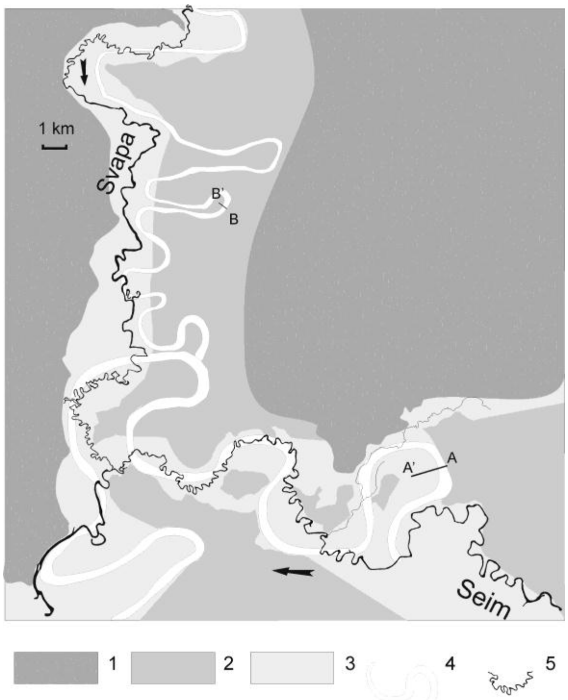

Fig. 3. (a) Morphology of the Seim and Svapa Rivers valley. 1 – II terrace; 2 – I terrace (floodplain at the period of macromeander formation); 3 – modern floodplain; 4 – paleochannels; 5 – modern channels. (b) Lithological cross-sections of the Seim (I) and Svapa Rivers (II) paleochannels. 1 – sandy loam; 2 – peat; 3 – silty clay; 4 – clay; 5 – fine-grained sand; 6 – medium-grained sand; 7 – numbers of boreholes; 8 – radiocarbon age, years B.P.

A typical example of macromeander morphology is the Seim River valley near its confluence with Svapa River (Fig. 3a). It is situated near the northern border of region III. During late glacial time periglacial forest - steppe occurred there, while at present it is near the boundary between broad-leaved forest and the forest-steppe. The modern channel of the Seim has a typical meandering pattern, with a width of 40 m, a floodplain width of 4-6 km, and a meander length of 170 m. The Svapa River has a similar pattern, with a channel width of 30 m, a floodplain width of 3-6 km, and a meander length of 120 m.

The paleochannel in the Seim River valley is situated within the floodplain. Only natural levees along the paleochannel at present are not flooded in spring. The modern floodplain topography was produced primarily by ancient fluvial processes. This explains the great relative width of the floodplain (100:1). The paleoriver formed omega-shaped bends with meander lengths (λ= half wavelength) of 3,000 m and the length along the channel (S) of 7,000 m. The factor of the meander shape S/λ is 2.3. That is more than an optimum value (1.6) for a meandering river. A coring profile was taken perpendicular to the axis of paleochannel (Fig. 3b). It crossed the pool/point bar pair with a typical triangular cross-section. The channel alluvium consists of fine- and medium-grained sand (mean diameter 0.21-0.28 mm), and the point bar is composed of fine sand overlain by silt. Radiocarbon dating shows that after the channel was abandoned about 14,000 years B.P., 5 m of lacustrine silts and clays filled the pool. At the last stage of filling, which began 9,000 years B.P., the lake gradually transformed into a sedge bog. The thickness of peat formed in this bog is more than 1.8 m.

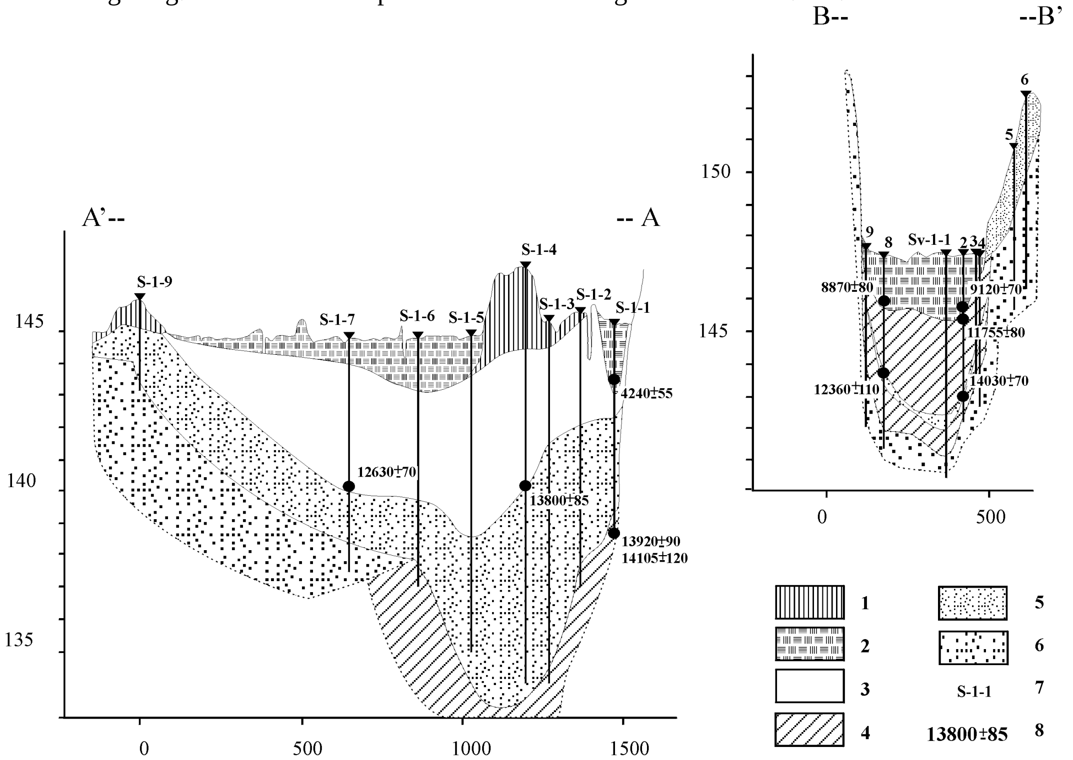

Fig. 3. (b) Lithological cross-sections of the Seim (I) and Svapa Rivers (II) paleochannels. 1 – sandy loam; 2 – peat; 3 – silty clay; 4 – clay; 5 – fine-grained sand; 6 – medium-grained sand; 7 – numbers of boreholes; 8 – radiocarbon age, years B.P.

The paleochannel in the Svapa River valley is situated within the first terrace. Only the lowermost segments of paleochanels are intermittently submerged during spring floods. The paleoriver formed steep bends, with meander lengths of 1,400 m and lengths along the channel of 3,800 m. An average factor of the meander shape is 2.8, but several hairpin bends reached 11, exceeding the optimum for a meandering channel. This can be explained by the high stability of the surface of the former floodplain, which was consolidated by permafrost more than 14,000 years ago. There are numerous remnants of cryogenic features such as ice-wedge casts. A similar pattern of meandering rivers with hairpin bends can be found at present on the Yamal Peninsula (in the north of West Siberia) which also has broad floodplains and permafrost.

A borehole profile was taken perpendicular to the axis of the Svapa River paleochannel and crosses the channel at a former riffle such that a typical rectangular cross-section was produced (Fig. 3b). The channel alluvium is composed of fine- and medium-grained sand (mean diameter 0.21-0.25 mm). After the channel abandonment about 14,000 years B.P. 4 m of grey lacustrine silts and clays filled the channel section. The lake changed into low sedge bog at the last stage of filling 9,000 – 12,000 years B.P. The peat layer that formed in this bog is more than 2.0 m thick.

The large rivers that formed the paleochannels were active during the Late Valdai. Age estimations in the range 10,000-11,000 years B.P. are typical for the beginning of filling of the paleochannels in Poland in the Vistula River basin (Starkel, 1995). Thermoluminescent and radiocarbon dating show that the transformation of large rivers on the Russian Plain occurred earlier in the southern part of the periglacial zone than in the regions close to the ice-sheet. The large periglacial paleochannel of the Vychegda River (index 65 in table 1) was abandoned about 10,000 years B.P., but even during the early Boreal (up to 8,500 years B.P.) the river channel was larger than the modern one (Sidorchuk *et al*., 1999). Plant remnants in the top layers of alluvial sands relate to the initial phase of paleochannel filling with an age of 8,655±60 (KI-6413), 8,630±60 (KI-6405), and 8,400±70 years B.P. (KI-6407). The begining of the filling of the Protva River channel (index 60 in table 1) is dated to about 13,000 years B.P. (KI-7312 radiocarbon date 12,700±110 yr. BP). The large channel of the Khoper River (index 41 in table 1) was active about 17,000±400 years B.P. (RTL-808 thermoluminescent dating of alluvial sands in Moscow State University laboratory). Its filling began about 12,000 year B.P. (KI-5305 radiocarbon date 11,900±120 yr. BP). The large channels of Seim and Svapa Rivers (indexes 34 and 49 in table 1) were abandoned about 14,000 years B.P. (Fig. 3b). All radiocarbon dates were obtained in the Radiocarbon Laboratory of the State Scientific Centre of Environmental Radiogeochemistry (Ukraine).

Considerable differences in morphology of modern and ancient channels indicate a drastic change in the hydrological regime and water flow which took place at the end of the last glaciation. The paleohydrology of the periglacial rivers can be reconstructed on the basis of their morphology using paleogeographic analogues.

Methods of paleohydrological reconstruction.

Most of the empirical relationships between different hydrological parameters, or between hydrological parameters and governing factors, vary in space and time due to the geographical control over hydrologic processes. The study of geographical controls on river flow and their application to paleohydrology has led to the principle of paleogeographic analogy (Sidorchuk and Borisova, in press). The hydrological regime of a paleoriver within a given paleolandscape is inferred to be similar to that of a present-day river within the same type of landscape. The empirical hydrological relations derived for the rivers in certain landscapes and of certain morphological types should be applied to rivers in the same landscapes and of the same morphology. Paleohydrological reconstructions therefore depend on the reconstructions of paleolandscapes and on the selection of the region analogue with similar landscape.

To reconstruct the landscape and climatic conditions which existed at various stages of paleochannel development, palynological studies of alluvium, lake and peat sediments are necessary. The use of paleobotanical data for paleoclimatic and paleolandscape reconstructions assumes that the flora of a particular region is primarily controlled by climate. The method of reconstructing vegetation and climate from fossil flora was developed by V.P. Grichuk (1969), who used a concept from W. Szafer (1946). By identifying the region where the majority of plant species found in a fossil flora grow at the present time, it is possible to determine the closest modern landscape and climatic analogue to the past environment under consideration. Usually the conditions suitable for all the species of a given fossil flora can be found within a comparatively small area. The present-day features of plant communities and the main climatic indices of such a region analogue would be close if not identical to those that existed at the site in the past.

Close relationships between river morphology (channel pattern, width, depth, slope, meander wavelength) and grain size of alluvial sediments on one hand and the main hydrological and hydraulic characteristics of the river flow (discharge, velocity) on the other hand represent the basis of hydro-morphological (regime) approach. Dury (1964,1965) was the first to use the morpho-hydrological formulae for quantitative paleohydrological reconstructions. Later these formulae were adopted by many investigators (Maizels, 1983; Williams, 1988; Starkel *et al.*, 1996). A common hydro-morphological formula in paleohydrological reconstructions is the relationship between mean annual discharge (Q) and bankfull channel width (W_b). This relationship was established for 185 sections of meandering rivers with wide floodplains on the Russian Plain, and in West Siberia. Long-term observations by the Russian Federal Hydrometeorological Survey were analyzed. The average discharge values were calculated for the entire period of measurements (mainly 1950s-1980s). The width of each river was estimated from width-stage relations for the initial stage of floodplain submersion. Regression analysis of these data leads to the formula

$$Q = 0{,}012y^{0{,}73}\ W_b^{1{,}36} \qquad (1).$$

This formula allows us to calculate the discharge with a multiple regression correlation coefficient of 0.9. The parameter y was used to decrease the scatter in the relationship between Q and W_b. This parameter is related to the variability of river discharge during the year and can be calculated as $y = 100\ (Q/Q_{max})$. Here Q_{max} is the average of annual maximum discharges for the period of measurements. It is evident from (1), that for the same mean discharge a river with more variable regime has a wider channel.

The variability of discharge within the year, which is related to parameter y, changes significantly over the territory of Russian Plain and depends on the river basin area A (km^2):

$$y=aA^{0.125} \qquad (2)$$

Parameter a in formula (2) reflects the geographical distribution of the discharge variability. Region - analogue for a time of paleochannel formation gives an estimate of the parameter a and characteristics of the water budget. Mean annual discharge (and annual water flow depth) at the time of paleochannel formation can be calculated directly from the paleochannel width with the use of formula (1), and parameter y estimated with formula (2) for a given region analogue.

Results and analysis

Paleolandscape reconstructions

The main landscape and climatic features of the maximum and postmaximum intervals of the Late Valdai Glaciation were reconstructed using fossil pollen at three key-sites situated in different vegetation zones of the Russian Plain. Site 1 is situated in the lower Vychegda valley, within the present-day zone of the middle taiga (dark coniferous forest) (region II), at approximately 61ºN. Fossil flora 1 corresponds to the time interval, preceding the glacial maximum (Sidorchuk *et al.*, 1999). Site 2 is located in the central part of the Plain near Ivanovo (56ºN), in the zone of mixed broadleaf-coniferous forest (Grichuk, 1982). The flora characterizes the stage of maximum cooling of the Late Valdai glaciation, and the beginning of the cryo-xeric stage of the glaciation. Site 3 is situated in the middle part of the Khoper River basin, near the southern limit of the forest steppe zone (50ºN, region III) (Sidorchuk and Borisova, in press). Fossil flora 3 corresponds to the Late Glacial time. The radiocarbon date obtained for the alluvial deposits enriched with organic matter is 11,900±120 yr. BP (KI-5305).

In spite of different compositions, ages and geographical positions of the three fossil florae, our reconstructions reveal a close similarity of the landscape and climatic conditions at the time of their formation. Pollen assemblages with high *Artemisia* and Chenopodiaceae pollen percentages reflect the spread of specific open cryo-xeric vegetation in cold, dry environments typical of the LGM and Late Glacial. The so-called periglacial forest - steppe (Grichuk, 1989) dominated most of the Russian Plain. The role of open woodlands gradually decreased towards the south, where the periglacial steppe was predominant. Periglacial steppe species were broadly distributed, including such xerophytes as *Ephedra distachya*, *Eurotia ceratoides*, *Kochia prostrata* and others. Cryophytes (*Botrychium boreale*, *Selaginella selaginoides*) were also typical for the periglacial flora, as well as plants, growing on the barren (eroded) ground. The florae also include arboreal species of the light coniferous forest (*Pinus syilvestris*, *Larix*), the small-leaved deciduous forest (*Betula alba*), and the dark coniferous forest (*Picea abies, Pinus sibirica, Abies sibirica*), as well as shrub birch and alder. This type of flora has no direct contemporary analogue. The closest modern region analogue to all three florae is found on the western slope of the Altai Mountains, east of the headwaters of the Irtysh River (Bukhtarma River basin). In this region dark coniferous mountain forests (*Picea abies, Abies sibirica*) form a mosaic with the mountain meadow steppes and patches of the wormwood-grass dry steppe. The area is characterised by a cold semiarid and extremely continental climate. The mean January air temperature in this region is -18°C; mean July temperature is about 15°C. Temperatures above freezing occur 90 - 100 days per year, and the mean annual precipitation varies between 500 and 600 mm, including 200 mm for the period November through March.

The reconsruction of past permafrost patterns over the Russian Plain is crucial for the development of our understanding of the process of ancient macromeander development. Paleocryologic studies (Velichko *et al*., 1982) show that the maximum stage of the Late Valdai glaciation was also the time of maximum permafrost expansion over the Russian Plain. Permafrost reached as far south as 45-46°N in western Russia. The largest ice-wedge casts are dated to that time and to the initial stages of deglaciation. The permafrost gradually retreated during the period of subsequent warming. The hydrological analogues of former permafrost areas can be found today in the tundra regions of the northern Russian Plain and western Siberia.

Paleohydrological reconstructions

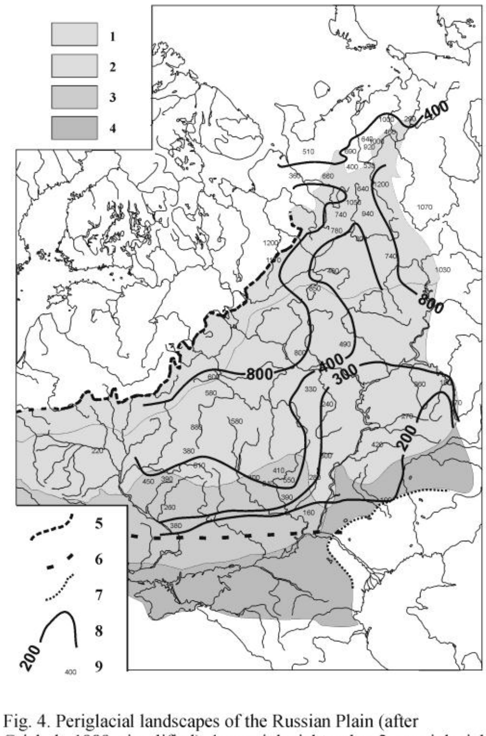

Fig. 4. Periglacial landscapes of the Russian Plain (after Grichuk, 1989, simplified). 1 – periglacial tundra; 2 – periglacial forest–steppe; 3 - periglacial steppe; 4 - dry steppe; 5 – ice – sheet margin; 6 – southern boundary of permafrost at the maximum stage of Valdai glaciation (after Velichko *et al.*, 1982); 7 – northern coast of the Caspian Sea; 8 – calculated runoff-depth contours (mm); 9 – calculated estimates of runoff depth at the basins from table 1.

One of the main difficulties of paleohydrological reconstructions for the Russian Plain region during the Late Valdai period is an absence of direct modern analogues for the previous landscapes. The Altai Mountains are situated beyond the present zone of continuous permafrost, and are perhaps the closest climatic analogue. The contemporary permafrost zone differs from the periglacial zone in climate, but is similar in terms of conditions of flow regimen generation. In this situation, multiple analogues must be used, combining the Altai (as the region with the closest climatic conditions) with the tundra of the northern Russian Plain and the Yamal Peninsula (as the region with the closest hydrologic regime).

Former annual discharges for periglacial rivers (table 1) were calculated using formulae (1) and (2). Coefficient *a* in formula (2) was estimated for the region analogue at the northeastern European tundra. Its value is equal to 2.25. Unlike the modern longitudinal distribution of the runoff depth on the Russian Plain, in the periglacial time its distribution generally followed the shape of the ice - sheet margin (fig. 4). The edge of glacier had northeastern direction in the northwest of the Russian Plain and the latitudinal direction in the east, near the western slopes of Ural Mountains. The maximum runoff depth existed within the area adjacent to the ice-sheet, though none of the rivers used in calculations were fed by glacier meltwater. The excess of annual water flow above the modern one can be explained by greater rainfall and a greater flow coefficient value. The runoff depth reached 800-1200 mm in the basins of the Vaga and

Mezen', and in the upper Pechora River basin. It was about 600-800 mm in the basins of the Oka and upper Volga Rivers. Minimum flow in the rivers of this area was calculated for the basins of the Severnaya Dvina (450-500 mm) and Vychegda (250-400 mm) Rivers. The runoff depth of the periglacial time only slightly exceeded the modern one there.

Runoff depths in the river basins decreased with the distance from the edge of the ice-sheet, presumably with reduction of precipitation and flow coefficient. It was about 450 - 700 mm at the Seim River basin, upper and middle Don and Khoper River basins. Smaller water flow was reconstructed for the rivers of lower Dnieper and Don basins, middle Volga and lower Kama basins. Runoff depths there did not exceed 200 - 450 mm.

The spatial variability of runoff depth in the Late Valdai time was significantly lower (particularly in the east of the Russian Plain) than the modern one. This was caused by much more uniform landscape conditions of flow generation in the periglacial zone, though a zonal pattern of runoff depth was rather distinctive, being correspondent to the shape of the ice-sheet boundary.

Discussion and conclusion

The problem of determining a region analogue for the paleohydrological reconstructions is crucial for the paleogeographical studies of the glacial epochs. In our case the region analogue combined the western Altai mountain region (upper Bukhtarma River basin) as the closest proxy of climatic conditions, and the tundra of the northeastern Russian Plain and Yamal Peninsula as the regions with the closest hydrologic regime. In both regions the main period of high water flow is during spring. The flood wave is formed by snow thaw, being high and brief due to a rather rapid snow thaw and a high rate of slope flow (due to the permafrost in tundra). The flow coefficient for the spring period is high: 0.6-0.7 in the Altai region due to low evapotranpiration during the flood, and up to 0.9 - 1.0 in tundra because of an additional effect of low permeability of frozen ground. The summer average flow is rather low in the Altai region due to high evapotranspiration values (250 – 350 mm), and very low in tundra because of negligible ground water input in permafrost conditions.

Thus the hypothetical hydrological conditions in the periglacial zone on the Russian Plain were probably characterised by high spring water flow. Runoff depth was up to 900 – 1000 mm near the ice-sheet edge and about 600 – 700 mm at the central part of the Plain. The flow coefficient was close to 0.9 – 1.0 due to the permafrost. The flood wave was sharp, and the maximum spring discharge on the periglacial rivers was much higher than current spring discharge peaks. The size of the river channel is determined mainly by maximum discharge rates. The combined influence of greater flow volume and higher maximum discharges caused the formation of very large river channels with macromeanders. The summer was dry and relatively warm with evapotranspiration values of 250 – 350 mm. The ground water input was very low, so the large sandy channels were almost empty of water in summer. The vegetation at the river valleys was scarce, and aeolian processes were active.

Rivers of the Yamal Peninsula represent the closest modern analogues to these earlier river channels. The high flood stage there lasts only 10-15 days, but during that period large maximum discharges form wide, sandy, meandering channels. During the main part of the warm season the channels are nearly dry, and sand bars are reworked by wind, so that aeolian dunes are seasonally active on the floodplains and low terraces. The maximum/mean annual discharge ratio can be up to 100 for those rivers.

The map of annual runoff depth over the periglacial zone of the Russian Plain gives an opportunity to calculate the annual flow volume from the main river basins during the Late Valdai (table 2). On the northern megaslope of the plain, a vast territory was covered by an ice sheet. Although the flow was not affected by melt water from the ice sheet, the total flow volume from the Russian Plain was 380 km^3 – 1.5 times the modern annual flow volume from the same area. The main water flow increases were in the Pechora and Mezen' River basins. In the Volga River basin, the annual flow volume was 585 km^3. This is more that twice the modern value and can explain the high level of the Caspian Sea during the Late Valdai even without a hypothesis of Kvasov (1979), about significant glacial melt water feeding of the Kama River basin. The main water flow increases were in the basins of the Oka and Kama Rivers. They were both 3 – 3.5 times the modern annual flow volume. In the Don River basin, water flow during the Late Valdai was four times that of today.

Table 2. The annual water flow volume of the Late Valdai rivers on the Russian Plain.

River basin	Basin area in the Late Valdai, km^2	Annual flow volume in the Late Valdai, km^3	Modern basin area, km^2	Modern annual flow volume, km^3
Northern Dvina	260	115	357	110
Mezen'	78	45	78	28
Pechora	322	220	322	126
Upper Volga (without Oka basin)	105	77	291	59
Oka and Sura	312	161	312	49
Kama	507	225	507	119

Volga (Volgograd)	1174	500	1360	254
Don	422	110	422	29

The main causes of the dramatic change in the water flow volume, hydrologic regime and river channel morphology were the degradation of permafrost and an increase of soil permeability during the spring. Combined, these factors increased ground water flow throughout the summer and caused a decrease of the runoff coefficient, flood flow, and maximum discharge for a snow thaw period. Changes in the summer ground water regime caused an increase of the average summer flow, and vegetation spread on the bare floodplains and on former sandy bars. Large periglacial channels were abandoned, transformed into floodplain lakes and bogs. New channels were formed under conditions of lower annual flow and a much steadier flow regime. The flood wave became less high and steep, and occurred above the densely vegetated floodplain, so the flow velocities and rate of channel erosion during the high water became significantly reduced. Instead the water level and flow velocities in the channel during the summer became higher, and channel erosion by the low water became more important for channel morphology. Thus new channels had much smaller widths and meander lengths than the ancient periglacial ones. The transformation took place during 14,000–12,000 years B.P. at the southern part of the Plain, and lasted until 8,500 years B.P. in the northern part of the periglacial zone. The degree of this channel metamorphosis was also significantly different in various parts of the Russian Plain due to different levels of the discharge change during the Late Valdai/Holocene transition. This can be illustrated with the latitudinal change of the ratio between recent (Q_r) and past late glacial (Q_p) annual discharges at the same rivers (fig. 5).

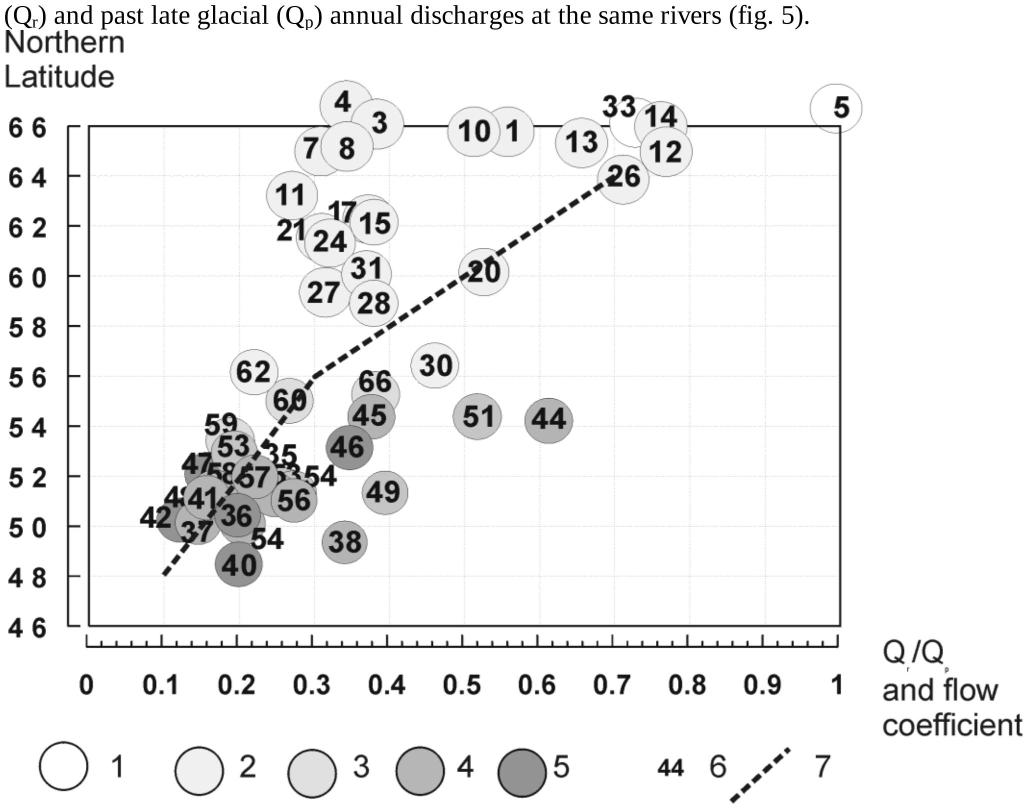

Fig. 5. Changes in water discharges at the rivers of the Russian Plain at the Late Glacial/Holocene transition. Recent / Late Glacial annual discharges ratio Q_r/Q_p versus northern latitude of the river basin outlet. Position of the basin in modern landscape zones: 1 – tundra; 2 - taiga; 3 – broad – leaved forest; 4 – forest – steppe; 5 – steppe; 6 – basin index in table 1. Dashed line shows flow coefficient spatial change in the belt between 42ºE and 54ºE.

The rivers of the tundra zone are still in "periglacial" conditions, and the modern river flow is close to periglacial. The flow coefficient is still close to 0.9 – 1.0. In the taiga zone the annual flow in the recent river basins is about 80 – 85% of the periglacial one in the east of the region and 30 – 60% in the west. In the broad – leaved forest zone it is about 40 – 50% of the periglacial annual flow in the eastern part of the region and 20 – 25% in its western part. In the steppe and forest steppe the modern annual flow is about 40 – 60% of the periglacial one in the east of the region and nearly 10% in its western part. Presumably, the main cause of the different degree of changes in the annual flow was the spatial variability of the flow coefficient decrease during the Late Valdai/Holocene transition. It was maximal in the steppe, where the percolation in spring and evapotranspiration values in summer substantially increased with the permafrost degradation and climate warming. It was less expressed in the taiga zone due to survived seasonal freezing of soils and low soil permeability at the flood period. At the northern part of the taiga zone and in tundra the soil permeability during the flood practically did not change since the Late Valdai glacial epoch.

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