Channel morphology and river flow in the northern Russian Plain in the Late Glacial and Holocene

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Aleksey Sidorchuk
Lomonosov Moscow State University

A. V. Panin
Lomonosov Moscow State University

Olga Borisova
Institute of Geography

Scott A. Elias
University of Colorado Boulder

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A. Y. Sidorchuk · A. V. Panin · O. K. Borisova
S. A. Elias · J. P. Syvistki

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Abstract The relicts of large meandering palaeochannels are found throughout the territory of the periglacial zone of the Last (Valdai=Weichselian) Glaciation on the Russian Plain. Channel widths of macromeanders can be 15 times larger than the recent meanders of the same rivers. Palaeolandscape and palaeohydrological reconstructions show that these periglacial river channels were formed under conditions of high spring water flow, up to eight times greater than the modern discharges, when the flow coefficient was close to 0.9–1.0 due to presence of permafrost, summers were dry and streams lacked ground water supply. Permafrost degradation increased soil permeability in spring and increased ground water flow in summer, causing a decrease of annual flow (due mainly to the flood flow decrease in spring). As a result, large periglacial channels were abandoned and transformed into lakes and bogs. Late Holocene channels have much smaller channel widths and meander lengths. These were formed under conditions of lower annual flows and much steadier flow regime.

Keywords Periglacial landscapes · Palaeochannels · Palaeohydrology · Change of hydrologic regime · Late Weichselian/Holocene · Northern Russian Plain

A. Y. Sidorchuk (✉) · A. V. Panin
Geographical Faculty, Moscow State University, 119899 Moscow, Russia
E-mail: sidor@yas.geogr.msu.su

O. K. Borisova
Institute of Geography, Academy of Sciences, Staromonetny 29, 109017 Moscow, Russia

S. A. Elias · J. P. Syvistki
Institute of Arctic and Alpine Research, Campus Box 450, University of Colorado, Boulder, CO 80309, USA

Introduction

The northern part of the East European or Russian Plain occupies a vast territory (ca. 1,000,000 km^2) on the shore of the Arctic Ocean in the basins of the Onega, Northern Dvina, Mezen', Pechora and other rivers, flowing into the White and Barents Sea. It extends to the Urals in the east and the Baltic Sea Basin in the west. Geologically the territory corresponds to the Russian Platform in the west and to the Timan-Pechora Table in the east, and is consequently characterized by gently undulating fluvial relief with the mean altitude of 170 m above sea level. Numerous highlands within the Timan Ridge have elevations up to 471 m. The northernmost Russian Plain is occupied by tundra and forest tundra over continuous and discontinuous permafrost (Fig. 1). Continuous permafrost with soil temperatures –1.5 to –2.00 °C exists now on the northeast Kola Peninsula, on the northern edge of Kanin Peninsula, and in the Bol'shezemelskaya tundra region north of the line Nar'yan-Mar–Vorkuta. Discontinuous (patchy) permafrost with soil temperatures of –1.0 to –0.00 °C exists on the Kola and Kanin peninsulas, up to the Arctic circle in the western part of Pechora River Basin and up to 65.5°N east of the Pechora River. The forest zone covers approximately 70% of the area, and is represented by northern, middle and southern taiga (Gribova et al. 1980). The northern Russian Plain is characterized by arctic and temperate climate influenced by Westerlies, so that continentality increases toward the east. Winters are long (5–7 months) and summers are short (1–4 months). Mean annual precipitation varies mostly between 700 and 800 mm in the west and between approximately 600 and 700 mm in the east. Precipitation is approximately 700–750 mm on the Timan Ridge and sharply increases to 800–1000 mm at the western slopes of the Urals. The annual runoff is determined by the amount

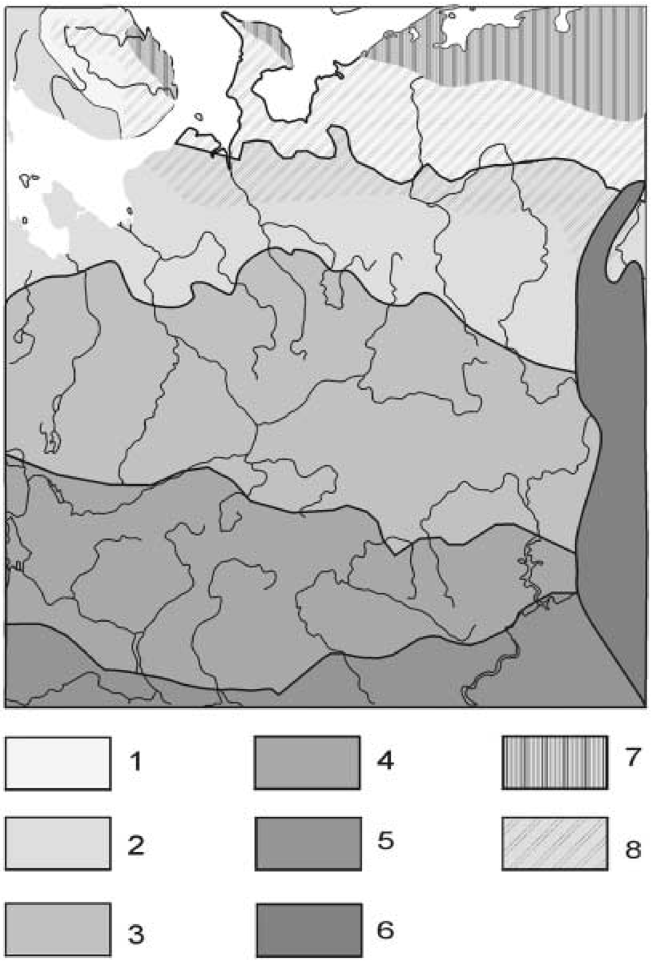

Fig. 1 The landscape of the northern part of the Russian Plain: *1* tundra and forest tundra; *2* northern taiga; *3* middle taiga; *4* southern taiga; *5* mixed forest; *6* mountain taiga; *7* continuous permafrost; *8* discontinuous permafrost

of precipitation (mainly snow) and by the annual runoff coefficient. The latter is greatest in the northeastern part of the territory, within the modern permafrost zone (0.8–0.9). It gradually decreases towards the headwaters of the main rivers to 0.5 in the west and to 0.7 in the east. As a result, annual runoff decreases from north to south, and from west to east from 400 to 500 mm to 250 to 300 mm. In the highlands of Timan Ridge, runoff reaches 450 mm and on the western slopes of the Urals it can attain values of 800–1000 mm. Most of the runoff occurs during the spring flood period. In tundra and forest tundra 72–82% of river flow is discharged during April to June, in the northern taiga it is 57–59%, in the middle taiga it is 55–65%, and in the southern taiga it is 64–74% of the annual flow (Zhila and Alyushinskaya 1972). During the last glaciation, the western part of the northern Russian Plain was covered by the Valdai (Weichselian) ice sheet. During the last glacial maximum (LGM) a vast periglacial zone occupied the ice-free area (Grichuk 1989). The territory was covered by periglacial forest steppe with tundra elements, and was then within the zone of continuous permafrost which reached its maximum extent between 20,000 and 15,000 years ago (Velichko et al. 1982).

Periglacial palaeochannels in the north of the Russian Plain

The relicts of large palaeochannels are found on the lower levels of river terraces and on the floodplains all over the territory of the former periglacial zone. Modern channels are incised mainly into the bottoms of palaeochannels because of glacio-isostatic uplift and changes in local erosion patterns (e.g. draining of ice-dammed lakes). Key sites in the north Russian Plain with well-preserved, large palaeochannels are shown in Fig. 2. Their drainage areas and morphometric parameters (half wavelength λ and bankfull width W) were measured on topographic maps and are shown in Table 1. The majority of the palaeochannels have a meandering pattern. The width of the channels with macromeander can be 15 times larger than the Late Holocene channels of the same rivers.

The territory occupied by the last glacial ice sheet, or regions close to skirting the ice-sheet margin, are generally devoid of macromeanders. The low frequency of palaeochannels with macromeanders across this paraglacial region shows that favourable conditions did not exist for large channel formation following the period of deglaciation. River basins in the tundra and forest-tundra remain within the permafrost zone, so that the hydrological conditions there have not changed significantly during the last 18,000 years. Only several rivers with the basins situated close to the southern margin of this region formed large channels with macromeanders, such as the Adz'va, Khar'yaga and Oma.

The Oma River site is situated near the northeast margin of the last Fennoscan ice sheet (Table 1). During the late glacial period, the landscapes of periglacial forest-steppe dominated this region, whereas presently it is near the boundary between the tundra and forest-tundra. The analysis of satellite images and large-scale topographic maps shows that the palaeochannel in the Oma River valley is situated within the second terrace, which is 2–3 km wide and 13–15 m high (former floodplain at the time of palaeochannel formation). The palaeoriver with a bankfull width of 150 m formed well developed bends with meander length (half of the wavelength) λ=1750 m. The modern channel of Oma River has a meandering pattern with a channel width of 75 m, and a recent meander length of 600 m. The channel is currently at the stage of incision and planform transformation. The width of the transient first-terrace floodplain is approximately 1–1.5 km, and its relative height is 6–7 m. Some of the large palaeomeanders have been abandoned, some of them

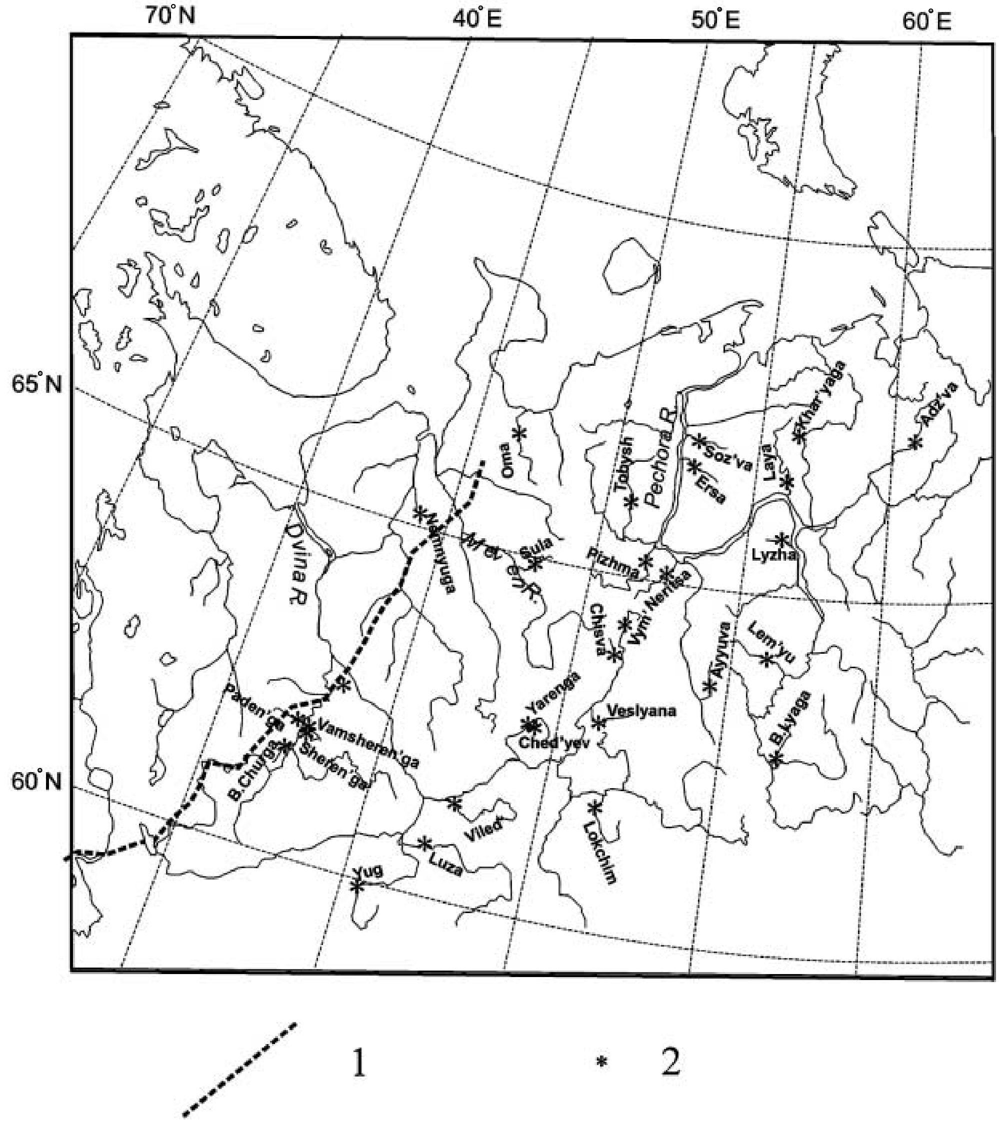

Fig. 2 Distribution of macromeanders on the northern Russian Plain: *1* edge of the maximum stage of the late Fennoscandian glacier; *2* position of well-preserved large paleochannels in the river valleys

were completely reworked by channel erosion, and several large meanders are still used by the modern incised river channel.

The Adz'va River site is situated near the southern margin of the tundra with continuous permafrost. The palaeochannel in the Adz'va River valley (Fig. 3; Table 1) is situated within the first terrace, which is up to 9 km wide and 25–30 m high. The palaeoriver with a bankfull width of 180–200 m formed "omega"-shaped bends with meander length (half of the wavelength) λ=1810 m. The modern channel of Adz'va River has a meandering pattern with a channel width of 175 m, and a recent meander length of 1540 m. As in the case of Oma River, the channel of the Ad'zva River is currently at the incision stage, and the floodplain has been transformed into the first terrace. The width of the transient first-terrace floodplain is approximately 1.5 km, and its relative height is 10–12 m. Most of the large palaeomeanders are abandoned, but the bends, formed by the modern incised river channel, have nearly the same wavelength as ancient macromeanders.

The modern taiga zone (which was periglacial forest steppe during the Late Glacial) is now devoid of continuous permafrost, and discontinious permafrost exists only in the northern taiga (see Fig. 1). This is the main region of large palaeochannels with macromeander distribution. The typical example is the Yug River valley, which is situated near the northern border of the southern taiga zone (Fig. 4). A large meandering palaeochannel is situated within the lower terraces of the modern river. The terrace at the necks of macromeanders (former floodplain) is up to 6 km wide and has a relative height of 25–30 m. The bottom of the palaeochannel is currently represented by the step with a relative height of 12–16 m. The width of this channel (at the crosses) was approximately 400 m. The palaeoriver formed omega-shaped bends with a meander length (λ of 2000 m and a length along the channel (S) of=6500 m (measured from large-scale

Table 1 Meander and macromeander parameters of the rivers at the northern Russian Plain

River	Basin area km^2	λ_r m	W_r m	Q_r m^3/s	λ_p m	W_p m	Q_p m^3/s	X_{annual} (mm)	X_{spring} (mm)	N latitude	E longitude
Oma	4100	610	75	47.2	1750	150	66	510	405	66°41'	46°24'
Vym'	2700	300	40	38.0	1450	150	54	635	495	64°10'	51°32'
Chisva	1000	150	15	11.5	1000	120	33	1045	780	63°33'	51°20'
Veslyana	3940	500	60	42.9	2800	250	118	745	590	62°50'	51°20'
Ched'yev	180	80		1.8	500		18	780	575	62°37'	49°20'
Yarenga	2450	270	40	11.1	1300	200	57	740	575	62°35'	49°28'
Paden'ga	1040	260	40	12.5	1250	125	40	1220	905	61°52'	42°34'
Sheren'ga	300	50	10	1.8	310		9	930	660	61°46'	42°40'
Vamsheren'ga	300	45	10	1.8	430		13	1380	975	61°46'	42°45'
B. Churga	560	190	40	6.7	750	80	21	1170	850	61°29'	42°22'
Lokchim	6040	640	100	52.8	2900	1000	286			61°36'	51°36'
Luza	18100	1500	250	137.7	4630	450	266	465	395	60°35'	47°15'
Yug	4600	430	100	38.0	2000	380	124	850	675	59°53'	45°30'
Nemnyuga	800	230	35	7.2	750	100	24	355	280	65°25'	43°46'
Sula	1040	310	35	11.4	1130	100	33	665	505	64°53'	48°27'
Khar'yaga	970	230	50	10.7	810	150	32	1055	780	67°09'	56°35'
Adz'va	8700	1540	175	100	1810	180	80	290	240	67°05'	60°07'
Soz'va	1400	480	50	15.4	1080	150	41	915	695	66°35'	52°53'
Laya	9530	2000	200	104.8	2200		139	460	380	66°25'	56°22'
Ersa	1800	250	50	19.8	1000	125	36	635	490	66°09'	53°21'
Slepaya	230	85		2.5	470	70	13			66°11'	53°21'
Tobysh	3250	530	100	35.8	1700	200	71	690	545	66°04'	51°10'
Lyzha	6000	810	140	66.0	3080		197	1035	835	65°44'	56°19'
Pizhma	5470	580	100	52.5	1500	200	69	400	315	65°23'	52°01'
Neritsa	2900	380	70	31.6	1250	150	49	535	420	65°13'	52°37'
Lem'yu	3850	570	120	42.4	4800		319			63°58'	56°38'
Ayyuva	1970	500	60		2100	180	76	1210	930	63°45'	54°10'
B. Lyaga	1330	450	50		1400	125	45	1070	805	62°37'	56°46'

λ Meander length (half of wavelength) is measured on the large-scale topographic maps as a straight distance between the adjacent points of curvature change; *W* channel bankfull width at crosses (points of curvature change); *Q* mean annual discharge; *F* basin area; *X* runoff depth; index *r* is used for recent rivers, *p* for past ones

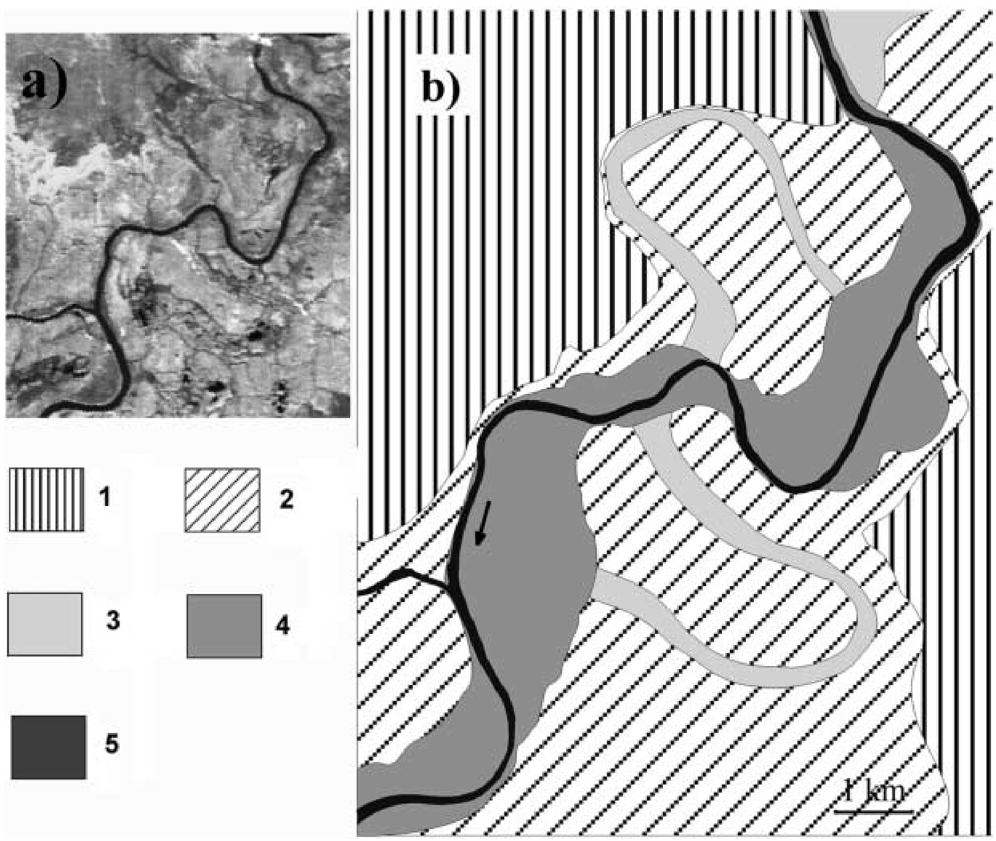

Fig. 3 Morphology of Adz'va River paleochannel on **a** the "RESURS-01" satellite image 24 June 1998, and **b** on the large-scale topographic map: *1* interfluvial area and high terraces; *2* I terrace; *3* bottom of the paleochannel; *4* modern floodplain; *5* modern channel

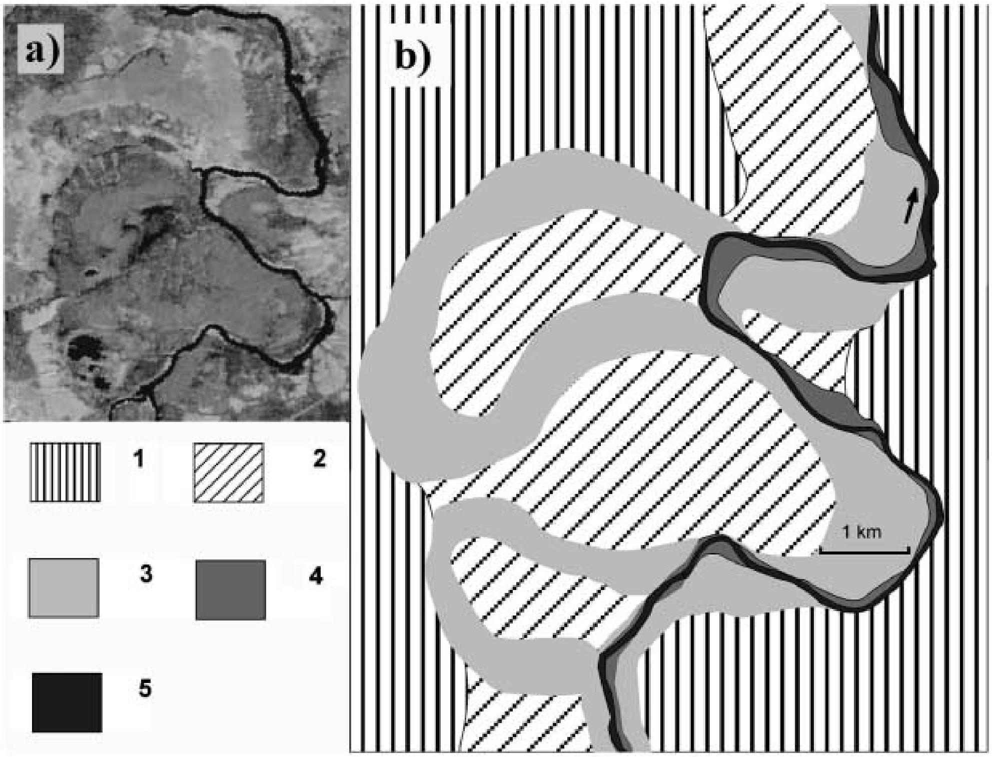

Fig. 4 Morphology of Yug River paleochannel **a** on the "RESURS-01" space image 11 May 1998, and **b** on the large-scale topographic map (for explanations see Fig. 3)

maps). An average factor of meander shape is S/λ=3.25. The bends shape factor exceeded an optimum for meandering channels (1.5–1.6). This is explained by the high stability of the former floodplain surface, which was consolidated by permafrost. A similar pattern of meandering rivers with hairpin bends can now be found on the Yamal Peninsula (in the north of West Siberia) on broad floodplains within the permafrost.

The large ancient rivers, whose remnants are the palaeochannels with macromeanders, were active during the Late Valdai. For example, the first large periglacial palaeochannel of the Vychegda River in the middle taiga zone was abandoned approximately 10,000–9000 years B.P. according to radiocarbon dates 10,900±1300 (MGU-128), 10,560±90 (MGU-90), and 10,460±20 (St-3327) years B.P. for the middle part of the river basin (Potapenko 1975), and 9255±65 (Ki-6406) and 8950±50 (MGU-1454) years B.P. for the lower section of the river channel (Sidorchuk et al., in press). Age estimations in the range 11,000–10,000 years B.P. are typical for the beginning of the filling of the palaeochannels in Poland in the Vistula River basin (Starkel 1995). In the southern part of the Russian Plain the large rivers with macromeanders were abandoned even earlier. Our investigations during the past decade show that the beginning of the filling of the Protva River channel (mixed forest at the point: 55°12' N, 36°31' E) is dated approximately 13,000 years B.P. (Ki-7312 12,700±110 years B.P.). The large channel of the Khoper River (steppe zone at the point 51°19' N, 42°22' E) was active approximately 17,000–14,000 years B.P. (RTL-808 TL dating of alluvial sands 17,000±2000; Ki-7694 radiocarbon date 14430±110 years B.P.). Its filling began approximately 12,000 years B.P. (Ki-5305 radiocarbon date 11,900±120; Ki-7680, 11325±120 years B.P.). The large channels of Seim and Svapa Rivers (forest steppe zone 51°39' N, 35°20' E) were abandoned approximately 14,000 years B.P. (13800±85, Ki-6984; 14030±70, Ki-6997; 13510±85, Ki-6991). Considerable differences in the 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 palaeohydrology of the periglacial rivers can be reconstructed on the basis of their morphology, using palaeogeographic analogues.

Methods of palaeohydrological 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 hydrological processes. The study of geographical controls on river flow and their application to palaeohydrology has led to the principle of palaeogeographic analogy (Sidorchuk and Borisova, 2000). The hydrological regime of a palaeoriver within a given palaeolandscape 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 kinds of landscapes and of the same morphology. Palaeohydrological reconstructions therefore depend on the reconstructions of palaeolandscapes and on selection of the region analogue with similar landscape. 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 formulas for quantitative palaeohydrological reconstruction. Later these formulas were adopted by many investigators (Maizels 1983; Williams 1988; Starkel et al. 1996). A common hydromorphological formula in palaeohydrological 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, in West and East Siberia. Long-term observations by the Russian Federal Hydrometeorological Survey were analysed. 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 equation

$$Q=0.012\ y^{0.73}\ W_b^{1.36}. \tag{1}$$

This equation 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

$$y=100\ (Q/Q_{\max}). \tag{2}$$

Here $Q_{\max}$ is the average of annual maximum discharges for the period of measurements. It is evident from Eq. (1) that for the same mean discharge a river with a more variable regime has a wider channel.

The variability of discharge within the year, which is related to parameter y, depends on the river basin area A (km^2):

$$y=a\ A^{0.125}. \tag{3}$$

Parameter a in Eq. (3) reflects the geographical distribution of the discharge variability. Region analogue for a time of palaeochannel formation gives an estimate of the parameter a and characteristics of the water budget. Mean annual discharge (and annual runoff X_{annual}) at the time of palaeochannel formation can be calculated directly from the palaeochannel width with the use of Eq. (1), and parameter y estimated with Eq. (3) for a given region analogue. The mean maximum discharge $Q_{\max}$ can be calculated with Eq. (2) for a given parameter y and mean annual discharge Q. Then flood runoff depth X_{spring} (mm) can be calculated from $Q_{\max}$ and A with the equation (Evstigneev 1990).

$$X_{spring} = \frac{Q_{\max}(A+b)^n}{K_0 A} \tag{4}$$

Parameters b, n and K_0 can be estimated from published hydrological data (Zhila and Alyushinskaya 1972) for the region analogue.

Results and analysis

Palaeolandscape reconstructions

The main landscape and climatic features of the maximum and post-maximum intervals of the Late Valdai Glaciation were reconstructed through palynology. The studied pollen assemblage (loamy layer at the depth 8.5–9.1 m in the outcrop Baika-1 at the lower Vychegda River site) reflects the spread of specific cryo-xerotic vegetation of the last glacial maximum – so-called periglacial forest steppe (Grichuk 1989). This pollen assemblage is characterized by the highest *Artemisia* pollen percentage and the greatest diversity of the *Chenopodiaceae species* of all the studied samples in this section. The flora includes species of light coniferous forest (*Pinus silvestris*), small-leaved deciduous (*Betula alba*) and dark coniferous forest (*Picea abies*, *Pinus sibirica, Abies sibirica*), as well as steppe and tundra species. The spread of periglacial steppe communities, including xerophytes such as, for example, *Ephedra distachya*, *Eurotia ceratoides* and *Kochia prostrata*, characterizes this period, relatively indifferent with regard to temperature. At present, the aforementioned species grow in plant communities of dry steppe and semidesert types. *Ephedra*, however, occurs in the Pamir Mountains up to altitude of 4000 m above sea level. Cryophytes (*Botrychium boreale*, *Selaginella selaginoides*) are also typical of the periglacial flora, as well as plants growing on barren (eroded) ground. Pollen assemblages with high *Artemisia* and *Chenopodiaceae* percentages reflect the spread of specific open vegetation in cold, dry environments typical of the LGM and Late Glacial. This type of flora dominated most of the Russian Plain and has no direct contemporary modern analogue. The closest modern region analogue is found on the western part of the Altai Mountains, east of the headwaters of the Irtysh River Basin (Bukhtarma River). The mean January air temperature in this region is –18 °C, and mean July temperature is approximately 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 from November to March.

The reconstruction of past permafrost occurrence over the Russian Plain is crucial for the development of our understanding of the process of ancient macromeander development. Palaeocryological studies show that the maximum stage of the 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 (Velichko et al. 1982). The permafrost gradually retreated during the subsequent warming. The hydrological analogues of former permafrost areas are found in the tundra regions of the northern Russian Plain and western Siberia.

Palaeohydrological reconstructions

One of the main difficulties of palaeohydrological reconstructions for the Russian Plain region during the Late Valdai period is the absence of direct modern analogues for the previous landscapes. The Altai Mountains, being the closest climatic analogue, are situated beyond the zone of continuous permafrost. The contemporary permafrost zone differs from the periglacial one 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 and flood period runoff depth for periglacial rivers (Table 1) were calculated using Eqs. (1), (2), (3) and (4). Coefficient a in Eq. (3) was estimated for the region analogue of northeastern European tundra; its value is equal to 2.25. Parameters in Eq. (4) b=1, n=0.17 and K_0=0.0025 were estimated for the same tundra region analogue.

Unlike the modern longitudinal distribution of the water flow depth on the Russian Plain, during the last glaciation the distribution generally followed the shape of the ice sheet margin (Fig. 5). The edge of glacier had a northeastern direction in the northwest Russian Plain and a latitudinal direction in the east, near the western slopes of the Ural Mountains (Borisov 1998). The maximum annual runoff depth existed within the area adjacent to this line. The runoff depth reached 800–1200 mm in the basins of the Vaga and Mezen' rivers in the west, and in the upper Pechora River in the east. Some of the rivers used in our calculations may have received glacial meltwater (e.g. the Paden'ga, B. Churga Rivers). For others the excess of annual runoff above modern levels can only be

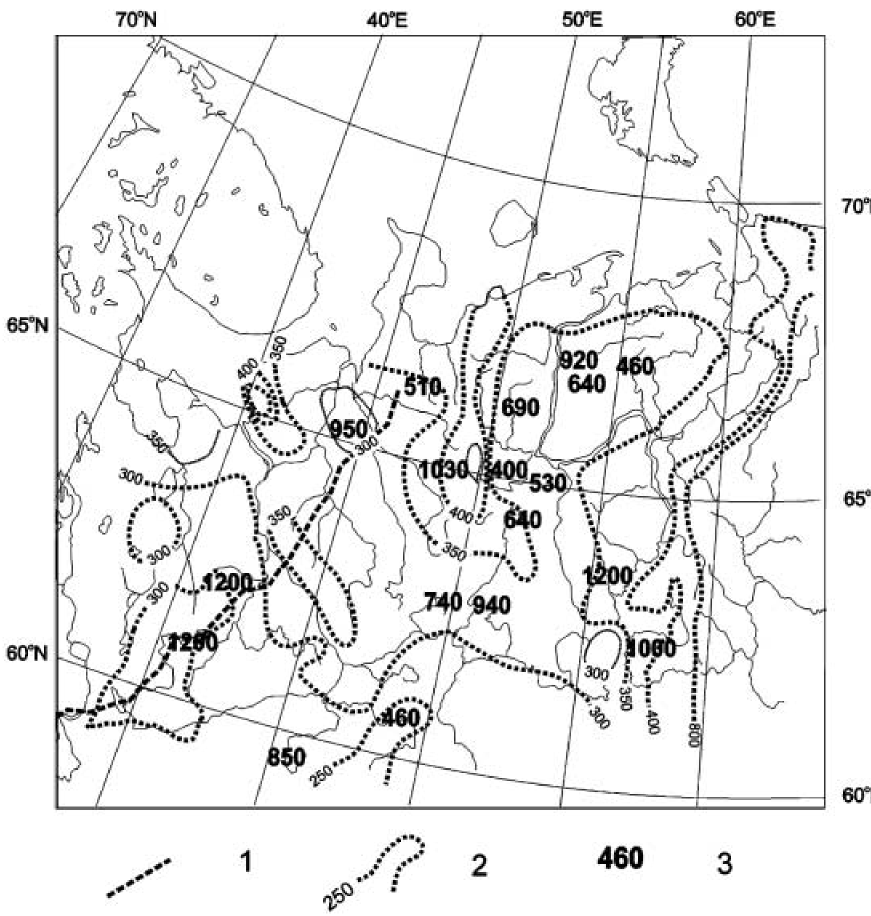

Fig. 5 Changes in runoff depth at the river basins of the northern Russian Plain at the Late Glacial–Holocene transition. *1* Edge of the maximum stage of the late Fennoscandian glacier; *2* isolines of modern runoff depth (in millimeters); *3* values of runoff depth at the Late Valdai time (in millimeters)

explained by greater rainfall and flow coefficient values. Minimum flow for the rivers of this area was calculated for the basin of the Luza (460 mm), Vym' (640 mm), left tributaries of lower Pechora (400–530 mm) and for the rivers in the southern part of the modern tundra zone (ca. 300–500 mm). There, the runoff depth during the last glaciation exceeded modern levels by 1.5–2 times. The annual runoff depth within Timan Ridge was twice the modern level, and more than is found in the surrounding lowlands. The altitude dependence of the former flow depth shows its relation to past precipitation regime. The runoff depth for the spring (April to June) period (Table 1) was approximately 77% of the annual one (the range is 70–85% for the whole area), and had the same spatial distribution. The main part of the river flow during the Late Glacial time was formed at the winter–spring time.

Discussion and conclusion

The problem of complex analogues for palaeohydrological reconstructions is crucial for palaeogeographical studies of glacial epochs. In our case the complex analogue combined the western Altai mountain region as the closest proxy of climatic conditions, and the tundra of the northeastern Russian Plain and Yamal Peninsula as the regions with the closest analogue to the hydrological regime. Thus, the hypothetical hydrological conditions in the periglacial zone on the northern Russian Plain were characterized by high spring water flow: spring runoff depth was up to 600–900 mm near the western and eastern boundaries, and approximately 300–400 mm in the centre. The flow coefficient was close to 0.9–1.0 due to permafrost. The flood wave was sharp, and the maximum spring discharge of the periglacial rivers was much higher than the recent one. Mean annual discharges of the periglacial rivers were also more than recent ones due to higher winter and spring precipitation and, in a few cases, melt water input from the glacier.

The map of annual runoff (Fig. 5) may be used to estimate the annual volume of the river flow from large river basins. These estimates (Table 2) are not very accurate, and are only preliminary. In a first approximation the annual water flow of the Northern Dvina River was close to the modern one, but from a smaller (68% of recent one) basin area. The lower part of the Northern Dvina Basin was covered by an ice-dammed lake. The annual water yield from the Mezen' River was 225% of the modern volume, and from Pechora River basin it was 175% of the modern one. The combined influence of greater flow volume and higher maximum discharges caused the formation of very large river channels with macromeanders. The size of the river channel was determined mainly by maximum discharge rates. The ground water input was very low; thus, the large sandy channels were almost dry in summer. The vegetation at the river valleys was scarce, and aeolian processes were active.

Rivers of the Yamal Peninsula (if not regulated by the lakes) represent the closest modern analogues to such river channels. There, the high flood stage 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 form on the floodplains and low terraces. The maximum mean annual discharge ratio can be up to 100 for those rivers.

During the past 18,000 years, the main causes of dramatic change in the hydrological regime and river channel morphology were the degradation of permafrost, and increasing soil permeability during the spring, combined with increasing ground water flow during the summer. These factors caused a decrease of runoff coefficients, flood flow and maximum discharge for the snow thaw period. Changes in ground water regime during the summer caused an increase in the basic flow, and forest vegetation spread on the floodplains and on former sandy bars. Large periglacial channels were abandoned, transformed into floodplain lakes and bogs. New channels were formed under the conditions of lower annual and maximum flow. These channels had much smaller width and meander length than the periglacial ones. As the Vychegda River example shows (Sidorchuk et al., in press), this transformation lasted until 8500 years ago in the taiga zone. The age of large palaeochannels and degree of channel metamorphosis was significantly different in various parts of the northern Russian Plain, because of different levels of discharge change during the Late Valdai/Holocene transition (Table 1).

In general, the changes in hydrological conditions at the northern part of the Russian Plain at the Late Glacial–Holocene transition were high, but less than in more southern areas. 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 approximately

Table 2 Annual water flow volume of the Late Valdai rivers at the northern part of 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	260,000	115	380,000	107
Mezen'	78,000	45	78,000	20
Pechora	322,000	220	322,000	126

80–85% of the periglacial one in the east of the region and 30–60% in the west. Investigations in the river basins in the broadleaf forest zone shows that the river flow is now approximately 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 approximately 40–60% of the periglacial one in the east 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 the tundra the soil permeability during the flood practically did not change since the Late Valdai glacial epoch.

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