Late-glacial and Holocene palaeohydrology of the lower Vychegda river, western Russia

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1 INTRODUCTION

The palaeohydrology of the taiga zone of European Russia has been little studied. Fundamental reviews have been undertaken (Goretskiy, 1964), and several palaeohydrological reconstructions (Panin et al., 1992; Sidorchuk & Borisova, in press) have been conducted for the rivers of the southern part of the East European Plain. However, there have been only a few attempts to reconstruct the development of the drainage network in the European taiga zone. Research on the evolution of the Northern Dvina, Mezen', and Pechora Rivers has been carried out (Kvasov, 1979; Potapenko, 1975), but this did not include palaeohydrological investigation of the ancient rivers. Nevertheless, this region contains a great deal of valuable information on past hydrological conditions (Sidorchuk et al., in press). Palaeochannels (often incised) are widespread in the small- and medium-sized river valleys in the region and their widths and meander lengths are commonly much larger than those of the recent river valleys. Fragments of palaeochannels of smaller sizes than those of the modern rivers also often occur. These morphological features reflect significant variability in humidity and water yield within this region in the past.

2 THE VYCHEGDA RIVER BASIN

The Vychegda River is the main right bank tributary of the Northern Dvina River. It is 1,130 km in length and the basin area is c. 121,000 km^2. The source of the river lies on the Timan Ridge between 200 to 300 m above sea level. The main part of the basin is a dissected plain with mean altitudes ranging from 140 to 160 m. The mean annual precipitation is 700 mm and of this 350 mm falls during the winter-spring period. January is the coldest month of the year (mean air temperature at Kotlas is −14°C), and July is the warmest with a mean air temperature of 17.2°C. The mean annual air temperature is 1.2°C. Mean annual water discharge at the mouth of the Vychegda River is c. 1160 m^3/s with a mean maximum value of 7500 m^3/s. The runoff depth is 300 mm, including 200 mm for the spring flood period. On average about 56% of the river flow passes during the flood. The flow distribution during the year is uneven as 61% of the flow occurs in spring (April to June), 30% in summer and in autumn (July to November), and only 9% in winter (December to March). Karst features control the water regime in the northeastern part of the basin.

The basin is densely forested (up to 98%), and its northeastern part is dominated by swamps. Swamps occupy up to 5 to 10% of the basin area. Interfluve areas are covered by spruce forest together with some birch and pine forests occupy sandy river terraces. In the southwestern part of the basin the spruce forests include fir and lime. Grasslands occur mainly on the lower levels of the floodplain and cover no more than 0.3% of the basin area.

3 FLUVIAL GEOMORPHOLOGY OF THE LOWER VYCHEGDA

The morphology of the lower Vychegda valley was investigated within a 120 km reach near the confluence with the Northern Dvina River. Within this reach valley bottom width increases from 8 to 10 up to 35 to 50 km at which point the valley of the Vychegda joins that of the Northern Dvina. Several terraces and a floodplain with complicated morphology have been identified in the area (Fig. 1).

A broad third terrace occupies up to 65% of the valley bottom. Its relative height is up to 15 to 25 m above low flow stage. The elevation of the third terrace decreases with distance down the lower Vychegda from about 80 m above mean sea level at 100 km from the mouth, to 65 m above mean sea level at the river mouth. The longitudinal slope of the terrace also decreases along this section from 0.2 to 0.12‰. Below the Vychegda River junction within the Northern Dvina valley, this terrace has a constant altitude above sea level of c. 65 m, such that its relative height increases by 35 m. The sediments which un-

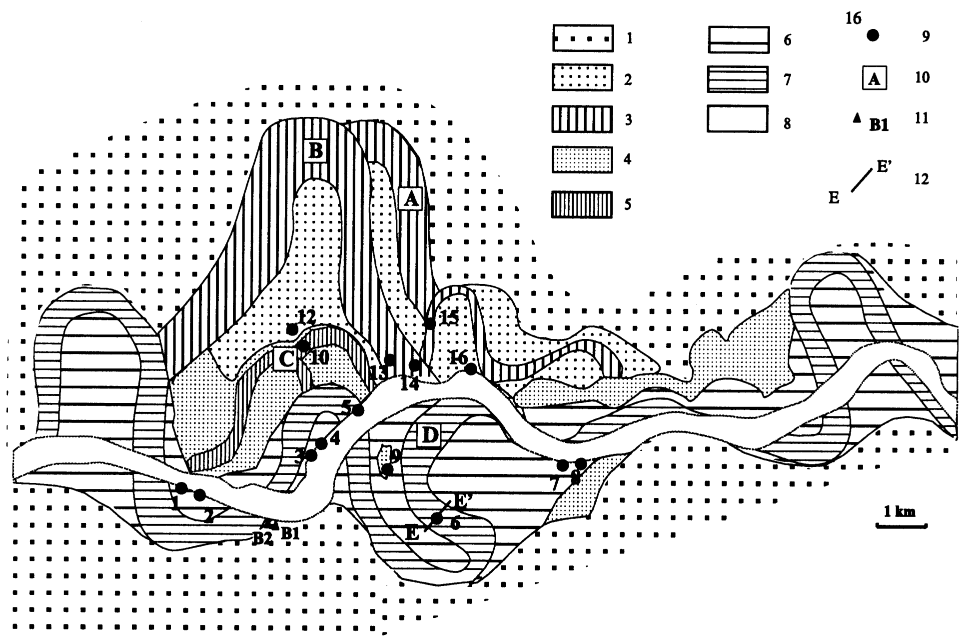

Figure 1. Morphology of the lower Vychegda valley: 1) the third terrace; 2) the second terrace; 3) palaeochannels within the second terrace; 4) the first terrace; 5) palaeochannels within the first terrace; 6) floodplain; 7) palaeochannels within the floodplain; 8) modern river channel; 9) numbers of sites with radiocarbon dates; 10) palaeochannel index; 11) location of sections Baika-1 and Baika-2; 12) location of the cross-section, shown on Figure 2.

derlie the third terrace are composed of fine- and medium-grained sand with horizontal and cross-bedded structures, with layers of loam and peat. The exposed section in the left bank near Baika village shows characteristic elements of this sedimentary sequence. There are nine main layers in the outcrop named Baika-1 (Table 1). Some of these layers were dated on the basis of their pollen spectrum and some (with larger quantities of organic matter) were dated by radiocarbon. It is important to point out that only non-calibrated radiocarbon dates are used in this work.

The surface of the third terrace is covered by (fluvial?) elongated, elliptical (on the plane and in profile) dunes. Individual dunes are 1 to 3.5 km long, 0.5 to 1 km wide and 3 to 7 m high. The dunes have an alternating pattern and their long axes have a general northwestern orientation.

Table 1. The sedimentary seqeunece beneath the third terrace of the Vychegda River near Baika village (16 km from the river mouth).

Depth	Sediment texture and structure	Sediment age based on radiocarbon dating or palynology
0.0-0.5 m	Red-brown clay loam and clay with wavy structure. Upper 10 to 15 cm transformed by podsolic soil formation.	
0.5-1.4 m	Yellow-brown fine sand with small wedges of red-brown loam.	
1.4-1.65 m	Red-brown clay loam and clay with abundant spots of iron oxidation.	
1.65-8.5 m	Yellow horizontal (in the upper part) and cross-bedded (in the lower part) well sorted fine sand. Sand wedges penetrate through the sediments. Rare lenses of fine gravel and small and medium size boulders (from 0.15 to 1.0 m in diameter) are in sharp contrast with the general fine texture of the sediments.	
8.50-9.1 m	Red-brown clay loam and clay. Thin (up to 1-1.5 mm) lenses of sand displaying a wavy structure in the loamy sediments.	Post Last Glacial Maximum time (palynology)
9.1-10.9 m	Yellow-brown horizontally bedded medium sand with rare layers of coarse sand (in the upper 30 cm of sediments) and sandy loam (mainly in the lower 80 cm of sediments).	The Last Glacial Maximum (palynology)
10.9-11.4 m	Dark grey to black clay loam. The lower 20 cm contain organic particles in increasing proportion, so that the lowermost 5 cm are represented by pure compressed peat.	^{14}C, 43,600 ± 2100 (Ki-6397)
11.4-15.1 m	Yellow-brown loamy fine sand with layers of grey sandy loam. Sand layers are horizontally and wavy bedded, their thickness being 15-30 cm. Layers and lenses of loam are 3-5 cm thick, with wavy boundaries. Narrow (35 cm at the top) sand wedges penetrate through the lower 60 cm of sediments.	
15.1-16.3 m	Grey soft loam with thin layers of grey sandy loam. The bottom 30 cm are filled with plant detritus. The layer continues below the water level.	^{14}C, 52,350 ± 3000 (Ki-6398)

The second terrace has a relative height of 12 to 14 m above low river stage and a total width of c. 2 to 4 km. Its altitude decreases along the lower Vychegda. It is 65 m above mean sea level 130 km from the mouth, and 55 m above mean sea level at the river mouth. The average longitudinal slope of the terrace in this part of the valley is about 0.08‰. An outcrop in the right bank of the river near Sol'vychegodsk revealed a sequence which comprised yellow horizontal and cross-bedded fine sands. A lens of grey sandy silt 1.5 m thick underlies the sand at the base of this outcrop. This silt layer continues under the water level. The organic matter extracted from the silt has a radiocarbon age of 34,200 ± 2900 (Ki-6410). This means that the sediments at the base of this exposure beneath the second terrace have the same Middle Valdai (Weichselian) age as those of the third terrace.

There are several steps of different age on the surface of the terrace, the younger features cutting across the older ones. The primary fluvial forms are quite clearly seen on the surface of these steps: there are palaeochannels, mid-channel and alternating bars, and former floodplains with levées and chutes. The curved bluff of the third terrace forms the right margin of the oldest palaeochannel A (Fig. 1) on the highest step of the second terrace. The palaeochannel is completely filled with very fine deposits and peat. The surface is now 6 to 7 m above the level of flooding. Its width is about 1200 m (Table 2). A chain of aeolian dunes traces the left margin of the oldest palaeochannel. This part of palaeochannel A was not dated directly. One of the secondary channels on the lower step of the terrace cut palaeochannel A, which indicates that the latter is older. This secondary channel was active more than 9200 years ago, because peat and plant remnants infilling deposits at sites 15 and 16 (Fig. 1) have yielded radiocarbon ages of 9255 ± 65 (Ki-6406) and 8950 ± 50 (MGU-1454) years BP.

The age of peat filling a similar large palaeochannel on the second terrace near the mouth of the Lokchim River and near the village of Gam (middle Vychegda valley) is 10,500 to 10,900 years BP (Potapenko, 1975; Arslanov et al. 1980). A section of palaeochannel A is also exposed near the village of Baika following erosion by the Vychegda River (Baika-2 section). There are eight main layers of sand, loam and peat in the outcrop and they are described in Table 3.

Table 2. Morphology of the palaeochannels in the lower Vychegda valley.

Surface	Relative altitude (m) above low stage	Channel pattern	Bankfull width (m)	Bankfull depth (m) at the riffle/ pool	Main meander wavelength (km)	Wavelength (km) of secondary sinuosity
Second terrace high step	13-14	Meandering with braids	1200	?/~16	~13	?
Second terrace low step	10-11	Meandering with braids	1300	9/?	13	8
First terrace	9-10	Meandering	600	6/?	7	-
Floodplain high steps	6-7	Meandering	800	6/12	9	-
Floodplain low steps	5-6	Sinuous with braids	1100	7/14	12	7

Table 3. The palaeochannel infilling at the Baika-2 section (16 km from the Vychegda River mouth). Radiocarbon dates are uncalibrated.

Depth, m	Sediment texture and structure	Sample depth (m)	Laboratory number	Radiocarbon age in years BP
0.0-0.7	Grey - brown soft loam with layers of grey sandy loam and very fine sand.			
0.7-1.3	Light brown peat with wood remnants.	0.70-0.74	Ki-7026	860 ± 60
	The lower 20 cm contain layers of gyttia.	0.98-1.02	Ki-7027	1120 ± 55
		1.26-1.30	Ki-7028	1670 ± 60
1.3-1.73	Dark grey sandy loam with wood remnants. The lower part contains tree trunks.	1.60-1.65	Ki-7029	2430 ± 50
1.73-2.45	Dark-brown peat with wood remnants.	1.75-1.79	Ki-7030	3250 ± 65
	The lower 35 cm contain layers of gyttia	1.89-1.91	Ki-7031	3840 ± 55
	and thin layer of fine sand at the bottom.	2.09-2.13	Ki-7032	4505 ± 50
		2.31-2.35	Ki-7033	5820 ± 50
		2.41-2.45	Ki-7034	6155 ± 60
2.45-4.9	Grey sandy loam with wood remnants and	2.60-2.70	Ki-7526	8050 ± 70
	layers of fine brown sand at the lower part.	2.90-2.95	Ki-7527	8240 ± 60
	At a depth of 4.5 m pine cones were	4.5-4.55	Ki-7122	8775 ± 70
	found. The layer continues to below the		Ki-7024	8825 ± 60
	water level.		Ki-6403	8705 ± 65

A well-preserved meandering palaeochannel B with islands and alternating bars is found on the lowermost step of the second terrace near Sol'vychegodsk. Its mean width is 1.3 km (up to 1.5 km in broader sections). The wavelength of the main meander is about 12 to 14 km. Elongated aeolian dunes 7 to 10 m high on the older step of the second terrace mark the right margin of this palaeochannel. Coring at the riffles of the palaeochannel shows that the bankfull depth was about 8 to 10 m. The riffles are composed of fine sand. Plant remnants in the top layers of these alluvial sands related to the initial phase of palaeochannel filling, and have an age of 8655 ± 60 (Ki-6413) at site 12 (Fig. 1), 8630 ± 60 (Ki-6405) at site 13, and 8400 ± 70 years BP (Ki-6407) at site 14. Palaeochannel B was filled with very fine silty sand, sandy loam and peat, but the deposition was not sufficient to completely cover the primary fluvial relief. This very fine material covers well-sorted fine- and medium-grained alluvial sands. It is 1.5 to 2 m thick on the ancient bars, and about 4 to 5 m thick in the channels at the riffle sites. The surface of the second terrace within the palaeochannel is generally 3 to 4 m higher than the modern floodplain, but the lowermost sections are still susceptible to inundation by the river during flood events.

The first terrace is about 2 to 4 km wide and has a relative height above low flow level of 9 to 10 m. Several systems of meandering palaeochannels (C in Fig. 1) with natural floodplain levées and chutes are well preserved on its surface. Their mean widths are about 600 m and meander wavelengths are about 7 km. The longitudinal slope within these palaeochannels is about 0.07 to 0.08‰. The palaeochannels are filled with very fine silty sand, loam and peat. The layer covering the alluvial fine sand is about 3.5 m thick. Plant remains in the top layers of alluvial fine sand at site 10 (Fig. 1) have yielded a radiocarbon age of 8120 ± 50 years BP (Ki-6404).

The floodplain of the lower Vychegda River is 5 to 7 m high above the low water level. Its total width is about 8 km and the floodplain can be subdivided into four main steps of different age. Well preserved remnants of meandering palaeochannels (D in Fig. 1) with natural levees, chutes and oxbows exist on two higher steps. The palaeochannel is 800 m wide, meander wavelength is 9 km, and the bankfull depth on the riffles is 6 to 8 m. Water surface slope within the channel was 0.05 to 0.06‰. The palaeochannel is filled by sandy loam 1 to 2 m thick at the point bars and by sandy loam and silty fine sand up to 9 m thick at the former pools (Fig. 2). Some of the former pools remain in the modern relief as oxbow lakes up to 12 m deep (Table 2). Peat in the depressions between adjacent natural levées on the floodplain has an age of 4200 ± 50 (Ki-6401) at site 7 (Fig. 1), 4470 ± 60 (Ki-6402) at site 8, and 4670 ± 60 (Ki-6409) at site 5. Plant remnants and charcoal in the oxbow deposits (Fig. 2) are 3980 ± 60 (Ki-6395) and 1900 ± 50 (Ki-6390) years old respectively.

The modern meandering-braided channel of the Vychegda River forms the two lowermost steps of the floodplain. The river has a sinuous pattern with numerous braids within the main channel. The total width of the river is about 1100 m at the crossings, meander wavelength is about 12 km and the water surface slope is 0.07-0.08‰. Bankfull depth is about 7 m at the riffles and up to 12-14 m at the pools. Channel alluvium is composed of

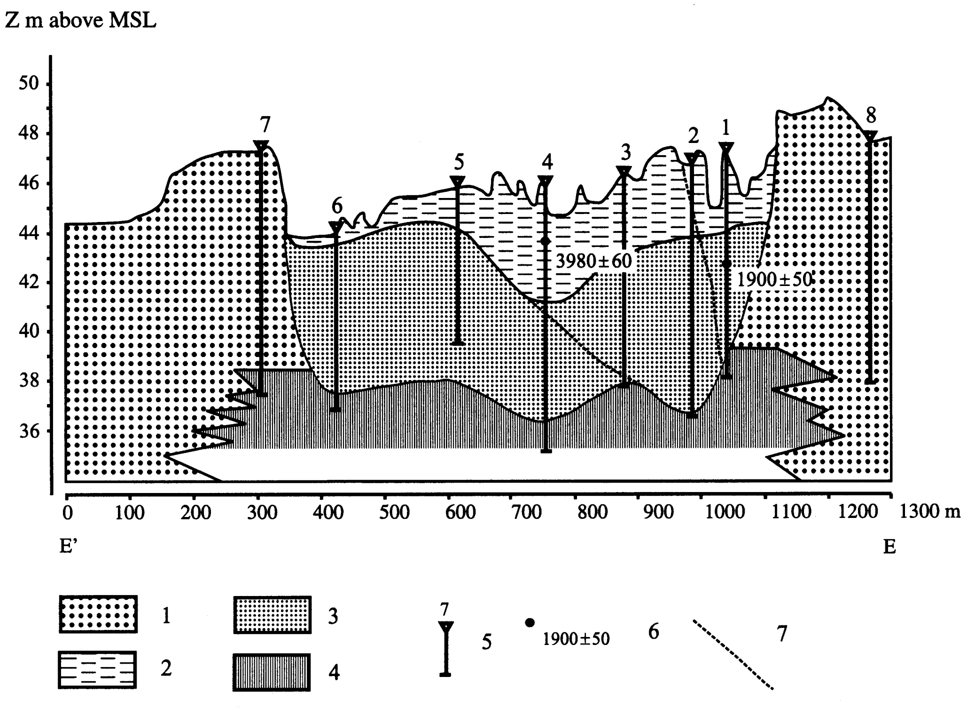

Figure 2. Cross-section of palaeochannel D on the high floodplain of the lower Vychegda River: 1) fine and medium sand; 2) sandy loam; 3) very fine sand; 4) clay loam; 5) core locations and numbers; 6) location of radiocarbon dates (years BP); 7) proposed depositional sequence (cross section location is shown on Figure 1).

fine and medium sand with the lenses of fine gravel. The floodplain is composed of fine and very fine sand with a loam cover 0.5 to 1 m thick. Peat in the depressions between adjacent natural levées on the floodplain has given radiocarbon ages of 1700 ± 70 (Ki-6391) at the site 1 (Fig. 1), 2040 ± 60 (Ki-6392) at the site 2, 2250 ± 60 (Ki-6393) at the site 3, and 2570 ± 60 (Ki-6394) at the site 4.

4 RADIOCARBON DATING

Radiocarbon dating of alluvial deposits involves specific difficulties, as the content of organic matter in them is usually very low, and plant macrofossils seldom occur. Most of the deposits filling in palaeochannels were dated in the Radiocarbon Laboratory of the State Scientific Centre of Environmental Radiogeochemistry (Ukraine). The organic matter used for dating was extracted from peat, wood and plant remnants. Dispersed organic material from the fossil soils was also used.

Radiocarbon dating is a complex process with many stages. It includes initial chemical treatment of the sample, obtaining lithium carbide and acetylene, converting it into benzol, purification, the addition of scintillators and assessment of its β-activity by sensitive low-background luminescent counters. To estimate the degree of isotope fractionation it is necessary to determine the ratio of stable carbon isotopes. The reliability of the results obtained depends fully on the correct execution of each operation.

The aim of the initial treatment of the samples is primarily to extract the reliable dating fraction of the carbon-containing matter and to clear out accidentally introduced carbon-containing substances, which distort the true age. Each sample is practically unique because of its environmental conditions. That is why it is necessary to find an optimum mode of treatment in each case. Universally accepted standard acid-alkaline treatment of carbon-containing substrata of vegetative origin often results in losses of useful material. This is brought about by dissolution of half-decomposed cellulose in the course of alkaline extraction of humic acids. The technique of selective extraction of introduced organic matter worked out in our laboratory makes this stage much safer and straightforward. The kernel of the method is in treatment of the samples of vegetative origin with 1-3% solution of hydrofluoric acid. In this case the covering silicate layer dissolves first. This layer is formed due to redeposition of the soil silicic acid and has a great sorbing capacity. When dissolving this layer, we transfer all absorbed humic and fulvic acids into a jelly-like state.

A new method of obtaining the lithium carbide by 'vacuum pyrolysis' considerably simplifies and accelerates two important types of radiocarbon dating application, such as dating of wood and of the soil organic matter (Skripkin & Kovaliukh, 1998). Prior to pyrolysis, samples of wood are crushed into 3 to 10 mm fragments, then after removing the roots of modern plants, they are treated with dilute hydrofluoric acid (1-3%). The main advantage of such a treatment over the standard acid-alkaline one is the maximum preservation of organic matter even from highly disintegrated wood. After washing and drying, the wood is placed into a reactor over melted lithium at 800°C in vacuum. Intense thermodestruction of wood takes place there, while the pyrolysis products are absorbed by lithium. In a certain temperature interval, only carbon and oxygen are absorbed while the hydrogen goes into a free state and can be removed by vacuum pump.

After complete destruction of the organic matter, the solid residue (charcoal) is also added to the reaction mixture. Thus, all carbon from the sample passes into the lithium carbide with minimum losses. The synthesis proceeds in one stage and takes only 20 to 30 minutes instead of 3 to 5 hours as in the traditional method.

Application of the 'vacuum pyrolysis' method for dating soil organic matter has even more advantages. In this case preliminary extraction of humic acids in the pure state is not required for soil samples with relatively high organic content (over 5%). The samples of soil are treated by hot water to remove fulvic acids. At the same time the roots of modern plants should be removed. After centrifuging, drying, and rough estimation of the content of organic matter, the sample should be mixed with the calculated quantity of manganese dioxide and placed into the reactor for synthesis of lithium carbide by vacuum pyrolysis. Heating the sample in a vacuum causes the thermodestruction of organic matter accompanied by absorption of the gaseous products of pyrolysis by lithium. After reaching 500°C, eduction of gaseous products of pyrolysis chiefly terminates, and the manganese dioxide begins to educe oxygen. Oxygen is educed gradually in the interval between 500 and 950°C. It oxidises the solid carbon resulting from pyrolysis in the entire sample of soil. Carbon monoxide and dioxide formed during the process are also absorbed by lithium. As a result of these reactions, practically all the carbon of the soil organic matter transforms into lithium carbide in one stage.

Implementation of direct synthesis by the vacuum pyrolysis method is inefficient for soil types with a low organic content. Nevertheless, the advantages of the new method make it possible to simplify the traditional method. One can use chemical reagents in high concentrations and boiling to extract pure humic acids. Using non-organic coagulants it is also possible to rapidly precipitate all the humic acids from an alkaline solution. In contrast to the traditional methodology, salts and amorphous silicon oxide, which fall out at this stage, do not contaminate lithium carbide with sulphur and phosphorus in the process of vacuum pyrolysis.

For the samples of loamy and sandy soils the following technique is used. The sample is macerated in hot water and filtered through a fine sieve to remove the roots of modern plants. Simultaneously, the major portion of fulvic acids passes into the hot water. After decanting or centrifuging, the sample is treated with 1% hydrochloric acid to destroy those soluble calcium and magnesium salts of humic acids that are not easily soluble. The mixture is separated again by decanting or centrifuging and then treated with hot sodium alkali (2 to 5%). In such conditions humic acids dissolve rapidly and with high yield. The solution of humic acids is separated from the mineral residue by centrifuging. After adding a coagulant (sodium sulphate), it is neutralised with hydrochloric or sulphuric acids to pH 4 to 6. Decanting or centrifuging separates the jelly containing amorphous silicon oxide and all kinds of humic acids. Later, if necessary, it is possible to fractionate the humic acids and to date them separately or selectively. Our experience of dating soil organics suggests that there is no need for such separation in the great majority of cases. In practically all cases, the predominant fraction of humic acids is dated.

After drying and determining the percentage of carbon in the obtained mixture of silicon oxide and humic acids, the calculated quantity of manganese dioxide is added, and the mixture is placed into the reactor for vacuum pyrolysis. These processes are identical to those for the soils rich in organics, described above. Silicon and other harmful impurities do not pass into carbide, which allows benzol to be obtained with high counting responses. The method of intensive extraction of humic acids in combination with that of vacuum pyrolysis makes it possible to minimise losses of carbon and to reduce the time needed in the chemical treatment of each sample.

A useful attribute of the manganese dioxide is its ability to link sulphur and phosphorus in the course of vacuum pyrolysis. An absence of minute amounts of phosphorus and sulphur compounds in acetylene is a necessary condition for further catalytic synthesis of benzol. In our laboratory we use a highly selective Vanadium catalyst. This Vanadium catalyst is very sensitive to harmful impurities but it allows purer and more stable benzol to be obtained from acetylene. The chemical installation for the purification and polymerisation of the acetylene comprises materials that do not absorb it. The interior volume of the vacuum line was minimised due to the optimum construction of the elements of the system and the use of a cryogenic pressure stabiliser. Therefore, the process of benzol synthesis is free of a 'memory effect'.

To completely standardise the counting responses of the obtained benzol we perform an additional chemical treatment. The calculated quantity of sulphuric acid is added to the freshly obtained benzol. In three hours the acid is removed with the help of a micropipette. For complete removal of sulphur-containing compounds dissolved in benzol, a small quantity metallic sodium foil is placed into the glass vessel for 48 to 72 hours. Then benzol is distilled off by the method of low-temperature sublimation. Such distillation allows avoiding drop transfer of harmful impurities as well as losses of benzol. This is especially important for dating samples with a low carbon content such as loamy fluvial and lacustrine sediments or micro-samples of wood and bone. After adding a complex of scintillators, the benzol is placed into Teflon vials of optimum size. Size optimisation makes it possible to minimise the influence of cosmic irradiation on accuracy and to achieve stability in determining the β-activity.

The radiocarbon content is measured by 'Quantulus-1220T'. To take into consideration all distorting factors when calculating a sample age, corrections based on the ratio of stable carbon isotopes are made. In our laboratory this ratio is determined in the fully purified benzol. A microscopic portion of benzol (1to 5 milligrams) is oxidised to carbon dioxide and tested with the use of a MI-2001 mass-spectrometer.

5 LANDSCAPE EVOLUTION IN THE LOWER VYCHEGDA VALLEY

To reconstruct the landscape and climatic conditions that existed at various stages in the evolution of the Vychegda valley, palynological studies of alluvium, peat, and lake sediments were carried out on three sections in the river terrace and floodplain sequence that were dated by radiocarbon methods. The use of palaeobotanical data for palaeoclimatic and palaeolandscape reconstruction implies that the flora of a particular region, or the composition of plant species growing there, is directly related to the natural environment as a whole and the climate in particular. The method used here of reconstructing vegetation and climate from the composition of fossil floras was developed by Grichuk (1969, 1985), based upon an earlier concept developed by Szafer (1946). Geographical analysis of the modern spatial distribution of all the plant taxa of certain fossil flora allows the location of the closest modern floristic analogue to the past vegetation at the site to be found. By identifying the region where all the species of plants 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 plants of a given fossil flora can be found within a comparatively small area. The present-day features of plant communities and main climatic indices of such a region-analogue should be close to if not identical to those that existed at the site in the past.

A series of 15 samples of fluvial deposits was subjected to detail palynological study. An attempt was made to achieve the highest possible taxonomic resolution: pollen identifications have been made to species or genus levels for arboreal plants and for certain groups of herbaceous plants. Where identifications were possible only to the family level, they were not included in the resulting lists of fossil floras. For three pairs of successive samples the floristic lists were combined to obtain more complete fossil flora. This was possible in the case of close resemblance between pollen spectra of successive samples. Landscape and climatic reconstructions using the palaeofloristic method were accomplished for eleven resulting fossil floras whose the radiocarbon ages range from 52,000 to 1400 years BP (Table 4).

Table 4. Fossil floras of the lower Vychegda River deposits found in the outcrops Baika-1 and Baika-2 (according to palynological analysis).

1. Baika-1, lower peat, ~52,000 yr. BP	*Alisma plantago-aquatica; Alnus glutinosa; A. incana; Betula alba; B. humilis; Corylus avellana; Cystopteris sudetica; Ephedra distachya; Equisetum scirpoides; Hydrocharis morsus-ranae; Larix sp.; Lemna sp.; Lycopodium annotinum; L. selago; Menyanthes trifoliata; Nuphar luteum; Nymphaea alba; Osmunda cinnamomea; Picea abies; Pinus silvestris; Polemonium coeruleum; Polygonum bistorta; Sanguisorba officinalis; Selaginella selaginoides; Thalictrum angustifolium; Tilia cordata; Ulmus laevis; Valeriana officinalis;*
2. Baika-1, upper peat, ~44,000 yr. BP	*Betula alba; B. humilis; B. nana; Centaurium; Encalypta; Ephedra distachya; Larix sp.; Lycopodium tristachyum; Picea abies; Pinus silvestris; Polygonum bistorta; Selaginella selaginoides; Thalictrum flavum;*
3. Sol'vychegodsk, aleurite, ~ 34,000 yr. BP	*Alnaster fruticosus; Alnus incana; Betula alba; B. humilis; B. nana; Chenopodium album; Cystopteris sudetica; Ephedra distachya; Filipendula ulmaria; Lycopodium annotinum; Picea abies; Pinus sibirica; P. silvestris; Sanguisorba officinalis; Saxifraga sp.; Thalictrum minus;*
4. Baika-1, lower loam layer, estimated age: Last Glacial Maximum	*Alnaster fruticosus; A. incana; Betula alba; B. humilis; B. nana; Botrychium boreale; Chenopodium album; Cystopteris sudetica; Encalypta sp.; Lycopodium annotinum; L. appressum; L. pungens; L. selago; L. tristachyum; Picea abies; Pinus silvestris; Riccia sp.; Saxifraga sp.; Selaginella selaginoides;*
5. Baika-1, upper loam layer estimated age: Post the Last Glacial Maximum	*Abies sp.; Alnaster fruticosus; Alnus incana; Atriplex hastata; Betula alba; B. humilis; B. nana; Chenopodium album; C. botrys; C. viride; Cystopteris sudetica; Eurotia ceratoides; Kochia prostrata; Lycopodium annotinum; L. clavatum; Picea abies; Pinus sibirica; P. silvestris; Pteridium aquilinum; Saxifraga sp.; Selaginella selaginoides;*

Table 4. (Continued).

6. Baika-2, loam, depth 435-445 cm, ~ 8800 yr. BP	*Alnaster fruticosus; Alnus glutinosa; A. incana; Betula alba; B. humilis; Cystopteris sudetica; Dryopteris phegopteris; Filipendula ulmaria; Lycopodium annotinum; L. clavatum; L. selago; L. tristachyum; Nuphar pumilum; Nymphaea candida; Picea abies; Pinus sibirica; P. silvestris; Polygonum amphybium; Selaginella selaginoides; Thalictrum simplex; Tilia cordata; Ulmus laevis; Valeriana officinalis;*
7. Baika-2, loam, depth 320-325 cm, ~ 8400 yr. BP	*Alisma plantago-aquatica; Alnus glutinosa; A. incana; Betula alba; B. humilis; Chenopodium album; Corylus avellana; Cystopteris sudetica; Lycopodium annotinum; L. clavatum; L. tristachyum; Lythrum salicarya; Menyanthes trifoliata; Picea abies; Pinus sibirica; P. silvestris; Sagittaria sagittifolia; Thalictrum angustifolium; Tilia cordata; Ulmus laevis;*
8. Baika-2, peat, depth 231-255 cm, ~ 6000 yr. BP	*Acer platanoides; Alisma plantago-aquatica; Alnus glutinosa; A. incana; Betula alba; B. humilis; Corylus avellana; Cystopteris sudetica; Lycopodium annotinum; L. clavatum; L. complanatum; L. selago; L. tristachyum; Lythrum salicarya; Nuphar luteum; N. pumilum; Nymphaea alba; Picea abies; Pinus silvestris; Quercus robur; Tilia cordata; Ulmus glabra; U. laevis; Valeriana officinalis; Viburnum opulus;*
9. Baika-2, peat, depth 209-211 cm, ~ 4500 yr. BP	*Alisma plantago-aquatica; Alnus glutinosa; A. incana; Betula alba; B. humilis; Corylus avellana; Cystopteris sudetica; Filipendula ulmaria; Lycopodium annotinum; L. clavatum; Lythrum salicarya; Menyanthes trifoliata; Nuphar luteum; Picea abies; Pinus silvestris; Quercus robur; Rhamnus frangula; Thalictrum angustifolium; Tilia cordata; Ulmus laevis; Viburnum opulus;*
10. Baika-2, peat, depth 175-191 cm, ~ 3500 yr. BP	*Acer platanoides; Alnus glutinosa; A. incana; Betula alba; B. humilis; Chamaepericlimenum suecicum; Corylus avellana; Lycopodium annotinum; L. clavatum; Lythrum salicarya; Menyanthes trifoliata; Picea abies; Pinus silvestris; Quercus robur; Rhamnus frangula; Tilia cordata; Ulmus laevis; Utricularia sp.; Viburnum opulus*
11. Baika-2, peat, depth 100-130 cm, ~ 1400 yr. BP	*Abies sibirica; Alnus glutinosa; Alnus incana; Athyrium crenatum; Betula alba; B. humilis; Corylus avellana; Calluna vulgaris; Filipendula ulmaria; Juniperus sp.; Lycopodium annotinum; L. clavatum; L. complanatum; Lythrum salicarya; Menyanthes trifoliata; Picea abies; Pinus sibirica; P. silvestris; Rhynospora alba; Ribes sp.; Tilia cordata; Ulmus laevis; Viburnum opulus;*

The earliest fossil flora (Number 1 in Table 4) derived from the palynological study of the peat layer at the base of the Baika-1 section (the third terrace of the Vychegda River) belongs to the relatively warm stage at the beginning of the Middle Valdai period. The region currently inhabited by the listed species was determined from map sources by superimposing their modern ranges. It lies in the Southern Ural Mountains, in the eastern part of the lower Ufa River basin. Cool mixed broad-leaved to dark coniferous forest (*Picea abies* with minor presence of *Ulmus laevis*, *Tilia cordata*, and *Corylus avellana*) and light coniferous mountain forest of Southern Ural type (*Larix sibirica, Pinus silvestris*) occupy the area at present. Tree birch in this region form both open forests and grow in the light coniferous forests. The area is characterised by a more continental and severe climate than that of the study area today. As climate is a key factor restricting the ranges of plants, it is assumed that the climatic indexes at the time when these species grew together in the lower Vychegda basin were identical to the present indexes of the region-analogue. This comparison indicates that the mean temperature of the coldest month (January) was 2°C lower than the present-day one, while the mean July temperature was close to the modern one at the site. Annual precipitation was about 750 mm.

Flora 2, which characterises the upper peat layer in the Baika-1 section with a radiocarbon age of 43,600 ± 2100 yrs BP, is similar to the first one, though the pollen assemblage reflects considerable changes in the composition of vegetation. It is likely that these changes occurred due to the cooling of climate, possibly accompanied by a decrease in precipitation. Birch forest became dominant in the area, while the dark coniferous taiga almost disappeared.

Fossil flora 3 obtained from the silt layer at the base of the sequence beneath the second terrace of the Vychegda River near Sol'vychegodsk (34,200 ± 2900 yr. BP), is very similar to the first one. At this time the dark coniferous forests had recovered their position due to an amelioration in climate. Such second order climatic oscillations are characteristic of the Middle Valdai period in the Russian Plain, and it is usually referred to as the 'mega-interstadial' to emphasise its complex structure. The region currently inhabited by the species of flora 3 lies at the headwaters of the Ufa River where dark conifer forest (*Picea abies, Pinus sibirica*), birch forest and light conifer (pine) forest with steppe elements in the herbaceous layer are found. The climate at this time interval was warmer than at the previous one but still slightly colder than in the first Middle Valdai warming characterised by flora 1. Mean January temperature was –17°C, that of July was about 17°C, and annual precipitation was 650 mm.

Pollen assemblage 4 of the lower loamy layer at a depth of 10 m in the Baika-1 section is separated from the previous one by a considerable period. As no organic material for radiocarbon dating was found in this layer, its age was estimated as being close to that of the maximum spread of the last (Late Valdai) glaciation in the area. At that stage an ice-dammed lake occupied part of the lower Vychegda valley. The pollen assemblage of this time interval is strongly dominated by spores of *Sphagnum*, Polypodiaceae and *Lycopodium*. It consists mainly of spores and pollen produced by local plant communities, which probably existed near the shoreline of the cold ice-dammed lake, while the tundra-like vegetation in the area fringing the ice-sheet margin was sparse and had very low pollen productivity. The flora includes such typical cryophytes as *Lycopodium pungens*, *Botrychium boreale*, and *Selaginella selaginoides* along with plants growing on barren (eroded) ground (*Riccia*, *Encalypta*). It is assumed that scarce pollen grains of spruce, pine and possibly also tree birch found in the sample were brought by wind from some distance, while the area at the time was treeless. A modern floristic analogue for this vegetation can be found in the Malozemelskaya tundra, near the Barents Sea coast. The region is characterised by very low summer temperatures (10-12°C), as well as by a very short frost-free period (c. 90 days). It is also situated within the limits of the permafrost zone.

Pollen assemblage 5 (loamy layer at 8.5 to 9.1 m depth in the Baika-1 section) reflects the spread of specific cryoxerotic vegetation of the Last Glacial Maximum – the so-called periglacial forest steppe (Grichuk, 1989). This pollen assemblage is characterised by the highest *Artemisia* pollen percentage and the greatest diversity of the Chenopodiaceae species of all the studied samples. Flora 5 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. An important characteristic of this assemblage is the spread of periglacial steppe communities including such xerophytes as *Ephedra distachya*, *Eurotia ceratoides*, *Kochia prostrata* and others, relatively indifferent with regard to temperature. At present these species grow in plant communities of dry steppe and semi-desert environments. *Ephedra*, however, occurs in the Pamir Mountains up to an altitude of c. 4000 m above sea level. Cryophytes (*Botrychium boreale*, *Selaginella selaginoides*) are also typical of periglacial flora, and are commonly found growing on barren (eroded) ground. This type of flora has no direct contemporary analogue. The closest modern region-analogue is situated on the western slope of the Altai Mountains, east of the headwaters of the Irtysh River basin (Bukhtarma River). Within this small area, dark coniferous mountain forests (*Picea abies*, *Abies sibirica*) grow next to mountain meadow steppes and patches of wormwood-grass dry steppe. The area is characterised by a cold semi-arid and extremely continental climate. The mean January air temperature is –18°C and that of July is about 15°C. Positive temperatures occur on between 90 and 100 days per year and the mean annual precipitation varies between 500 and 600 mm, including 200 mm for the period from November until March. The region is situated near the boundary of the permafrost zone. This flora also has an additional centre of concentration in the Malozemelskaya tundra.

As the data published by Potapenko (1975) show, periglacial vegetation persisted in the Vychegda basin until the beginning of the Holocene. In the middle part of the Vychegda basin, three radiocarbon dates were obtained for a thin layer of peat in the sandy alluvial deposits: 10,900 ± 1300 (MGU-128), 10,560 ± 90 (MGU-90), and 10,460 ± 20 (St-3327). Pollen spectra from this layer are characterised by high concentrations of non-arboreal pollen (up to 60%), including about 20% of *Artemisia* pollen. The flora shows all the important features of the periglacial type, as it includes cold-resistant arboreal species, such as tree, shrub and dwarf birch, shrub alder (*Alnaster fruticosus*), typical cryophytes (*Selaginella selaginoides*, *Lycopodium pungens*) along with xerophytes (*Ephedra distachya*).

Fossil floras 6 to 11 characterise successive layers of the Baika-2 section (Fig. 3B). The alluvial deposits are represented by loam and sand with two layers of peat in the upper part of the sequence. These deposits accumulated during the Holocene. The pollen assemblages are dominated by spruce, pine and birch pollen throughout the whole sediment sequence, but substantial changes nevertheless took place in the composition of the vegetation. These changes are reflected by 'migration' of modern floristic analogue regions over the East European Plain beginning from the Middle and Southern Urals, as far west as the Sukhona River basin, and back to the site under study at the downstream end of the Vychegda River (Table 5, Fig. 3A).

A modern floristic analogue of flora 6 (~8800 yr. BP) is located at the headwaters of the Kolva River, at the boundary between dark coniferous mountain taiga forests (*Picea abies*, *Pinus sibirica*) and middle- and southern taiga pine forests (*Pinus silvestris*). The present-day climate of this region is much more continental and severe than that at the Vychegda site. Mean January temperature was 3.5°C lower and mean July temperature

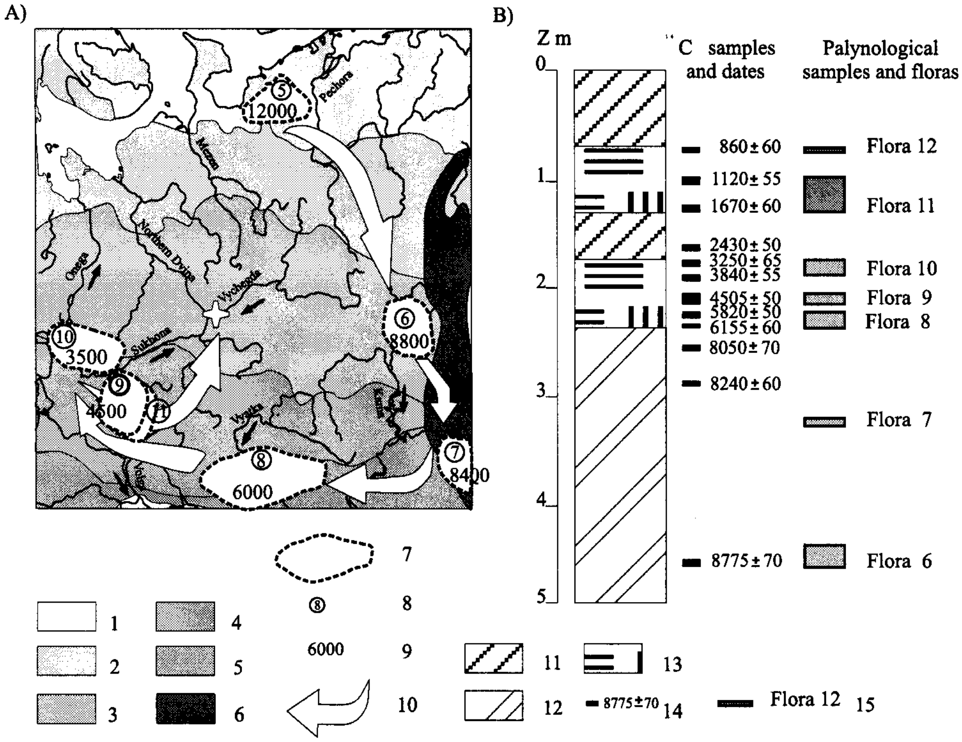

Figure 3. Evolution of the landscape in the lower Vychegda region during the Late-glacial to Holocene based on contemporary region-analogues (A), derived from the dated samples from the Baika-2 section with palaeofloristic analysis (B): 1) tundra and forest-tundra; 2) northern taiga; 3) middle taiga; 4) southern taiga; 5) broad-leaf forest; 6) mountain forest; 7) area of region-analogue; 8) number of region-analogue (the same as for fossil flora); 9) age of region-analogue; 10) sequence of region-analogues; 11) loam; 12) sandy loam; 13) peat; 14) radiocarbon sample location and date; 15) palynological sample location and fossil flora number as shown in Table 4.

0.5°C lower than at present (Table 5). The mean annual temperature was slightly below 0°C and annual precipitation exceeded the modern value by more than 150 mm.

A region-analogue for flora 7, with the age estimated by interpolation between the closest ^{14}C dates as 8400 yrs BP, lies near the headwaters of the Chusovaya River. In this area broad-leaved-dark coniferous mountain forests of the Ural type are found in the vicinity of dark coniferous mountain taiga forests (*Picea abies* with *Pinus sibirica*). The continentality of climate was still very high at this time, as the temperature of the coldest month was still 2.5°C lower than at present, while that of the warmest month was almost 1°C higher. Mean annual temperature was already above 0°C. The duration of the frost-free period was slightly longer than the present-day equivalent. Annual precipitation was slightly less than the present-day mean (630 mm).

A considerable shift to the west of the modern analogue for flora 8 (about 6000 yrs BP) corresponds to the rise in summer temperature, which exceeded the present-day mean by

Table 5. Positions of the paleofloristic analogues and contemporary hydro-climatic characteristics of the regions discussed in the text.

Fossil flora numbers as shown in Table 4	Region-analogue	Co-ordinates of the centre of each area		Region age, years BP	Recent air temperature (°C)		Recent runoff depth (mm)		Recent precipitation (mm)		Recent evapotranspiration (mm)	
		Northern latitude	Eastern longitude		January	July	Annual	Winter-spring	Annual	Winter-spring	Annual	Winter-spring
4-5	Malozemel'skaya tundra	67°	49°	~12000	–17	11	420	270	600	300	180	30
6	Kolva River basin	61°	57°	8800	–17.5	16.5	380	260	850	410	470	150
7	Chusovaya River basin	57.5°	59°	8400	–17	18	190	140	630	310	440	170
8	Middle Vyatka River	57.5°	49°	6000	–14	19	200	160	640	360	440	200
9	Unzha River basin	58.5°	44°	4500	–13	18	250	180	720	360	470	180
10	Headwaters of Sukhona River	59.5°	39.5°	3500	–13	18	330	220	750	400	420	180
11	Unzha River basin	58.5°	44°	1400	–13	18	250	180	720	360	470	180
	Vychegda River basin	61.3°	47°	recent	–14	17	300	200	700	350	400	150

2°C, while the winter temperature reached the present level. This region, in the middle part of the Vyatka River basin, is covered at present by broad-leaved, dark coniferous sub-Volga forests (*Picea abies* with *Quercus robur* and *Tilia cordata*). The frost-free period at that stage was almost one month longer than at present, though the annual amplitude of air temperature was still greater than now. Precipitation was approximately 640 mm.

A modern analogue for fossil flora 9 (4500 yr. BP) can be found in the northern part of the southern taiga dark coniferous forest in the Unzha River basin. The boundaries of the present-day ranges of such species as Quercus robur and Thalictrum angustifolium form its eastern boundary. Present-day climatic conditions of the region show that for the Vychegda River site, the mean January temperature exceeded the present value for the first time by about 1°C, while that of July decreased by 1°C compared to the previous stage. A substantial increase in precipitation is also suggested (by c. 80 mm per year). The continentality of climate reached its minimum value for the Holocene at this time and the period characterised by fossil floras 8 and 9 can be regarded as the climatic optimum of the Holocene.

A region-analogue for flora 10 (about 3500 yr. BP) is found in the Sukhona River basin, near the northern limit of the southern taiga dark coniferous forest, where large peat bogs are widespread. At that stage the mean January temperature was still about 14°C (1°C higher than the present), and that of July was about 18°C. Annual precipitation reached 750 mm – approximately 50 mm more than at present.

The modern analogue for fossil flora 11 is again found towards the east, into the Unzha River basin, where southern taiga dark coniferous forests are present along with middle- and southern taiga pine forests of the North European type. The climatic conditions of this region, indicate that the climate of the lower Vychegda basin around 1400 yrs BP was still warmer and less continental than at present. The precipitation was about 720 mm per year.

The fossil flora of the upper peat layer in the Baika-2 section dated by ^{14}C as 860 ± 60 yr. BP (Ki-7026) does not include any taxa which are absent from the modern flora of the region, where the studied section is located. This suggests that the climatic conditions at that time were essentially similar to those of the present-day.

6 PALAEOHYDROLOGICAL RECONSTRUCTION

Close relationships between river morphology (channel pattern, width, depth, slope, meander wavelength) and grain size of alluvial sediments on the one hand and the main hydrological and hydraulic characteristics of the river flow (discharge, velocity) on the other hand represent the basis of morpho-palaeohydrology. Hydro-morphological (regime) relationships were first obtained by Fergusson for the Ganga River in 1883 (according to S. Leliavski, 1955). Later they were broadly used for investigations of both river channels and canals. After the works of Dury (1964, 1965) and Schumm (1965, 1968) hydro-morphological formulas have been widely used in palaeohydrological reconstructions (see, for example, Maizels, 1983; Williams, 1988; Starkel et al., 1996).

The evolution of the hydrological characteristics of the lower Vychegda was reconstructed on the basis of palaeochannel morphology (Table 2) and a relationship between mean annual discharge $\bar{Q}$ (m^3/s) and bankfull channel width W_b (m). This relationship was established for 185 sections of meandering rivers with broad floodplains on the Russian Plain, in western and eastern Siberia (Fig. 4). The long-term observations of the Russian

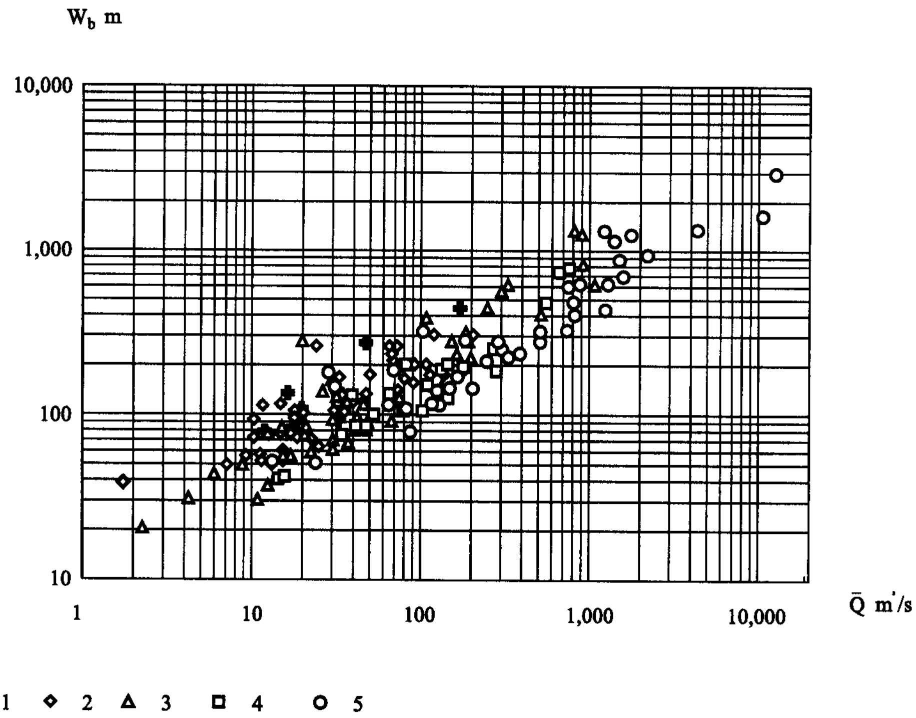

Figure 4. Correlation between channel bankfull width W_b and mean discharge Q for meandering rivers of the East European and West Siberian plains. Point symbols indicate the discharge variability within a year $y = 100\ Q/Q_{max}$. 1 – $0 \leq y < 5$; 2 – $5 \leq y < 10$; 3 – $10 \leq y < 15$; 4 – $15 \leq y < 20$; 5 – $y \geq 20$.

Federal Hydrometeorological Survey were analysed. The average discharge values were calculated for the whole period of measurements (based mainly on data from the 1950s to 1980s). A width for each river site was estimated from width-stage relations for the initial stage of floodplain submersion. Regression analysis of these data leads to the formula

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

This formula allows calculation of the discharge with a multiple regression correlation coefficient of 0.9. The parameter y was used to decrease scatter in the relationship between $\overline{Q}$ and W_b. This parameter is related to the variability of river discharge during the year and can be calculated as $y = 100\ (\overline{Q}/Q_{max})$. Here Q_{max} is the average of annual maximum discharges for the period of measurement. It is evident from (1), that for the same mean discharge a river with a more variable hydrograph has a wider channel. The points on the graph corresponding to the rivers of the north-eastern Russian Plain have a general distribution similar to that of rivers of other regions.

The variability of discharge within the year, which is related to parameter y, changes significantly over the territory of the north-eastern Russian Plain and depends on the river basin area A (km²):

$$y = aA^{0.125} \tag{2}$$

Parameter a in this formula reflects the geographical distribution of the discharge variability (Fig. 5). Its value is minimal (about 2) in the north-eastern part of the territory with a tundra landscape, while the south-eastern part – with broad-leaved forests and forest-steppe landscapes – shows maximum discharge variability within the year. Parameter a generally increases in the taiga zone from northern to southern taiga. Within the taiga zone significant latitudinal differentiation occurs in discharge variability within a year. It is minimal (maximum values of the parameter a) in the western and eastern parts of the zone, and maximal (minimal values of a) in the central taiga zone.

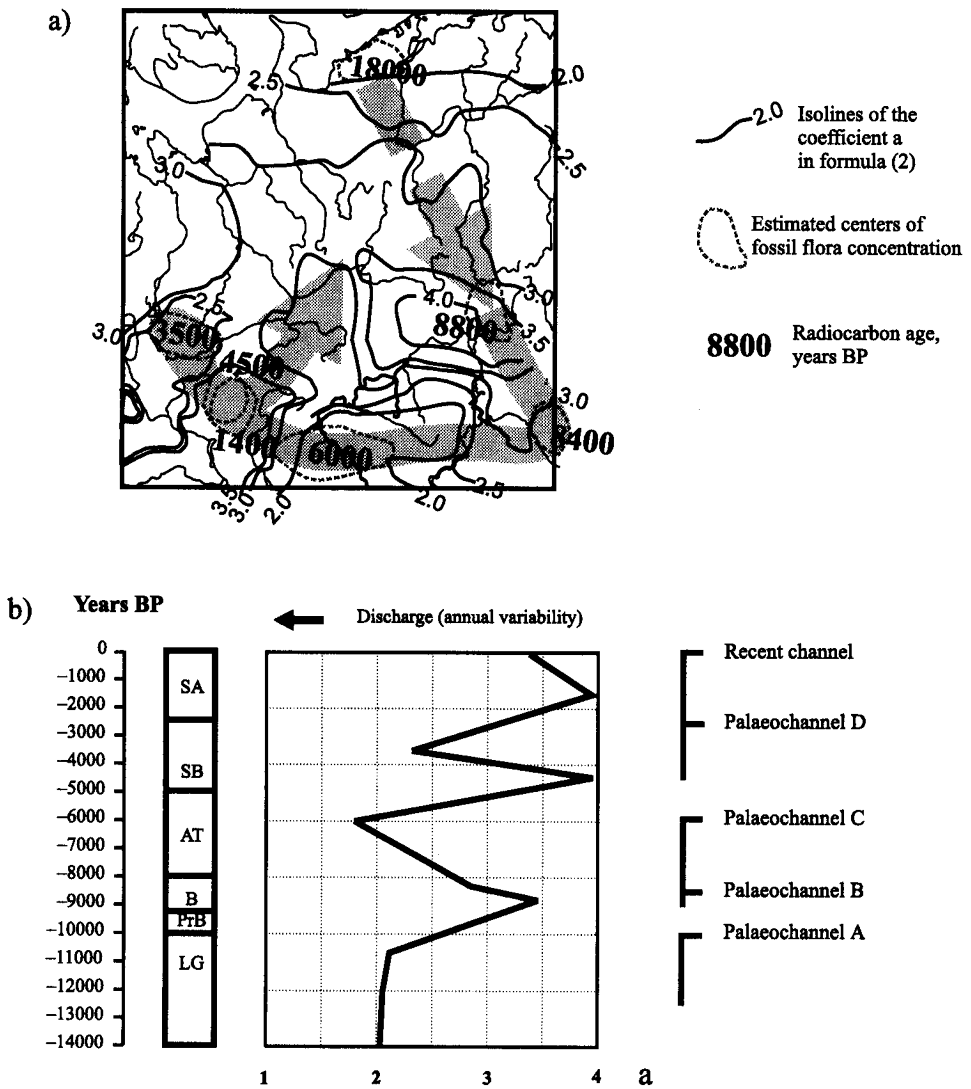

Figure 5. Annual discharge variability as characterised by coefficient a in Formula (2). (a) Spatial distribution in the north-eastern Russian Plain. (b) Change over time at the Vychegda study site.

The initial information for palaeohydrological calculations can be obtained from Tables 2 and 5. The region's vegetation analogue for the time of palaeochannel formation gives an estimate of parameter a in Formula (2), annual precipitation P_a, evapotranspiration E_a, and runoff depth X_a, and those for the winter-spring season P_{ws}, E_{ws}, and X_{ws} (Table 5). Mean annual discharge at the time of palaeochannel formation can be calculated directly from the palaeochannel width with the use of Formula (1), and parameter y estimated with Formula (2) for a given region – analogue. Mean maximum discharge is calculated from the mean discharge with the use of parameter y:

$$Q_{\max} = 100\overline{Q}/y^{*} \tag{3}$$

Annual runoff depth equals to

$$X_a = 31.536\overline{Q}/A \tag{4}$$

that for a winter-spring period – to

$$X_{ws} = \frac{X_{ws}^{*}}{X_a^{*}} X_a \tag{5}$$

A precipitation depth per annum is calculated from annual runoff depth with the use of the water budget equation:

$$P_a = X_a + E_a^{*} \tag{6}$$

or

$$P_a = \frac{P_a^{*}}{X_a^{*}} X_a \tag{6a}$$

For the winter-spring season it can be estimated from the water budget equation for this period:

$$P_{ws} = X_{ws} + E_{ws}^{*} \tag{7}$$

or

$$P_{ws} = \frac{P_{ws}^{*}}{X_{ws}^{*}} X_{ws} \tag{7a}$$

Formulae (6a) and (7a) are used if evapotranspiration in the region-analogue can not be accurately estimated. The characteristics taken from region-analogues (Table 5) are marked with and asterisk.

Reconstructions of the Late-glacial landscapes and palaeohydrology of the north-easten part of European Russia have been produced by several workers including Potapenko

(1975), Kvasov (1979) and Arslanov et al. (1980). The majority of researchers believe that a lake occupied the lower Northern Dvina and Vychegda River valleys during the period of damming of these valleys by the last ice sheet. Kvasov (1979) reconstructed the level of this lake up to 170 m above mean sea level so that surplus water presumably drained over the watershed into the Kama River valley.

The composition of the sediments comprising the third terrace in the lower Vychegda valley bears evidence of complicated processes of formation. Sediment structure and texture, radiocarbon dates and pollen analyses allow the deposits to be sub-divided into two main beds. The lower bed (layers 1-3 in Table 1 from the bottom) represents floodplain deposits of the Vychegda River which accumulated during Middle Valdai times. These deposits include layers of floodplain lake sediments (layers 1 and 3, and the lower silt layer near Sol'vychegodsk), and sediments of irregular flood flows (layer 2).

The upper bed is composed mainly of fine-grained horizontal and cross-bedded well sorted sand (layers 6, 8). These sands were transported by flows with velocities of approximately 0.3 to 0.5 m/s. The flow was apparently rather uniform over time, as the sediment grain size does not vary significantly. The inclination of cross beds indicates the general north-westward direction of the flow. The slope of the third terrace is in the same direction. The sand deposits include layers 5, 7, and 9 of red-brown loam with a wavy cryogenic structure. These layers could have been formed by sedimentation in a lake and by solifluction from adjacent slopes during periods of flow shifting to the opposite (right) bank of the valley. In general, the upper bed of the sediments beneath the third terrace represents the depositional stage of a broad delta formation in an ice-dammed lake.

The termination of the ice-dammed lake at the Northern Dvina and Vychegda valleys is correlated with the Bolling Interstadial (Kvasov, 1979). After recession of the Last Glacial ice sheet about 12,500 years ago the base level lowered considerably. River incision into deposits of the third terrace had begun, and the sequence of erosional terraces was formed. The most ancient surface of the second terrace on the lower reaches of the Vychegda corresponds to the initial stage of the valley evolution, which began after c. 12,500 years ago. The large size of palaeochannel A on this step indicates a high channel-forming discharge during that period. The presence of deep chutes and secondary channels on the former floodplain also evidence a high water yield during floods.

The most likely age of this ancient palaeochannel in the lower Vychegda valley is 12,500 to 10,000 years BP (the Late-glacial). Fossil floras 4 to 5 (Table 4) show that tundra and forest-tundra in north-eastern European Russia represent the regional vegetation analogue for that period. The hydrological regime of rivers of that area was used as a contemporary hydrological analogue. The mean value of coefficient a in equation (2) is 2.02 for those rivers. The annual discharge variability was rather high during the Late-glacial (for the lower Vychegda mean $y = 8.7$), so that the mean maximum discharge of 10,300 m^3/s corresponds to the relatively low mean annual discharge of 900 m^3/s. The depth of the mean annual runoff was 235 mm. According to the same analogue, the depth of winter-spring runoff was 180 mm. In conditions of continuous permafrost, the runoff coefficients were very high, the mean annual value being about 0.7, and that for a flood period up to 0.9. The mean annual precipitation depth estimated with equations (6a) and (7a) is 335 mm, that of the winter-spring period is 200 mm, and that of the summer-autumn period is 135 mm.

On the basis of palaeobotanical data the Late-glacial period is usually characterised as an extremely dry period (Khotinskiy, 1977). The palaeohydrological information allows some amplification of this supposition. For the Vychegda River basin, annual precipitation was half the recent value. Such a deficit of humidity was probably related almost entirely to the summer and autumn period. The palaeobotanical data for the Late-glacial show the presence of typical xerophytes in the vegetation of this period. Their spread can be explained by a relatively warm and dry summer, though it was short (not longer than three months). The precipitation (mainly in the form of snow) during a long winter – spring period was not lower than in recent tundra. In combination with low permeability of the ground due to the permafrost, the thawing snow during the spring led to sharp high floods and to the formation of large wide river channels.

Palaeochannel B on the lower step of the second terrace was abandoned about 8400-8600 years ago. It was still active during early Boreal time between c. 8500 and 9000 years ago. According to palaeobotanical data, the region-analogue for that time is situated at the south-eastern part of the middle taiga. The territory was already free of permafrost, and the depth of seasonal freezing of the ground was close to the contemporary level. The hydrological analogues give a mean value of the coefficient in Formula (2) of a = 3.48. The annual distribution of the water flow during the early Boreal was also close to the present-day distribution (for lower Vychegda, mean y = 15). A large and wide palaeochannel under conditions of low discharge variability corresponds to a relatively high mean annual discharge of c. 1500 m^3/s. Mean maximum discharge was about 9900 m^3/s. The depth of mean annual runoff was 390 mm and the depth of spring runoff was 265 mm. In conditions of seasonal ground freezing the runoff coefficients were close to recent ones: they were about 0.45 for the whole year and up to 0.63 for a flood period. The air temperature and evapotranspiration at the lower Vychegda valley were close to those in the region-analogue. This gives a rather high estimate (860 mm) for the mean annual precipitation. Precipitation in the winter-spring period was twice that of the previous time interval (415 mm), and that of the summer and autumn period increased even more – up to 445 mm.

The hydrological regime of the lower Vychegda River changed significantly during the transition from the Late-glacial to the Holocene. The annual water yield increased by a factor of 1.7 and this was mainly due to a more humid low flow period. At the same time, maximum flood discharges decreased slightly due to more regular water flows in the basin and greater flood duration. Flood volume was rather stable during this transition, therefore the size and pattern of the river channel did not change. A meandering channel together with alluvial bars and islands shifted by 600 m down the valley and incised by about 3 m in approximately 2500 years.

Palaeochannel C on the first terrace of the lower Vychegda was abandoned about 8200 years ago. It was active during late Boreal time around 8200 to 8500 years ago. According to the palaeobotanical reconstruction the region – analogue is situated at the eastern part of the southern taiga. The depth of seasonal freezing of the ground was close to the contemporary level. The hydrological analogue gives a mean value of coefficient a in Formula (2) of 2.8. The annual distribution of flow during the late Boreal was more variable than at present, and humidity at that time was significantly lower. The palaeochannel on the first terrace is smaller than all other palaeochannels. Its width and curvature correspond to a mean annual discharge of about 440 m^3/s and the mean maximum discharge was about 3700 m^3/s. The depth of mean annual runoff was 115 mm and the depth of spring runoff was 90 mm. This corresponds to the minimum value of the winter-spring precipitation depth (260 mm) for the whole period studied. Mean annual precipitation was about 555 mm.

There are numerous palaeochannels of relatively small size on the first terrace of the Viled' River, a left bank tributary of the Vychegda (Fig. 6). The width and meander lengths of these palaeochannels correspond to the mean annual discharge of 29 m^3/s, which is about 1.6 times less, than the recent one. One of the latest palaeochannels of Viled' was abandoned about 7700 years ago (point 11 in Fig. 6). It means that the stage of low humidity belonged to the Atlantic period of the Holocene.

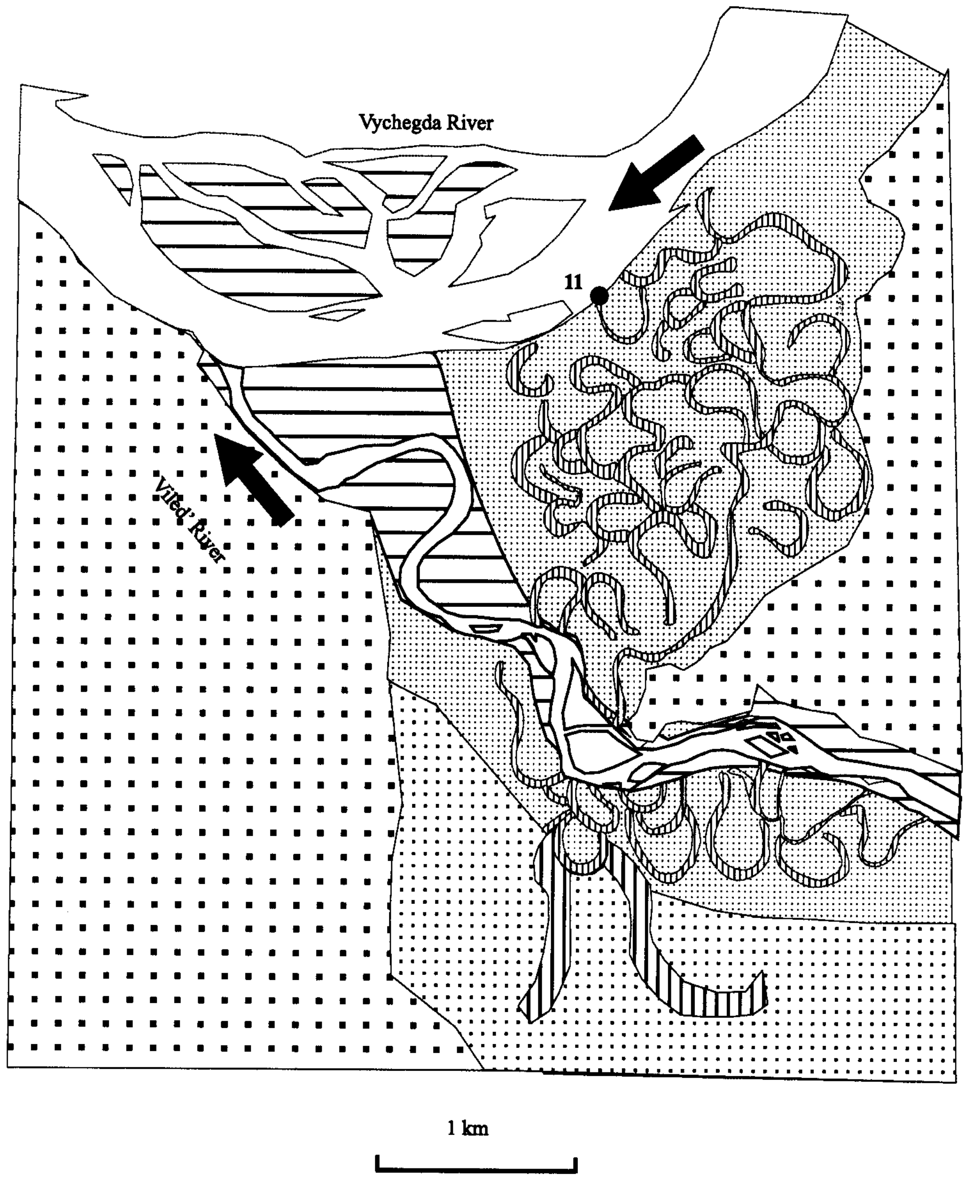

Figure 6. Morphology of the lower Viled' river valley. See Figure 1 for legend.

The region-analogues for this period, found by the palaeofloristic method, are also characterised by low precipitation. Palaeohydrological calculations for this period were conducted with the use of interpolated values of palaeochannel width (Table 6). Minimum water flow occurred at the lower Vychegda at the end of Atlantic, about 6000 years ago. The chain of aeolian dunes along the right border of the early Boreal palaeochannel of the second terrace presumably was formed during this relatively dry period. This was also a time of interruption in deposition on the floodplain at the Baika-2 section.

The most recent palaeochannel (D) in the lower Vychegda valley is well-preserved on the oldest steps of the floodplain. This channel evolved during the Sub-boreal period and was abandoned at the beginning of the Sub-atlantic, about 2500 years ago. The geometry of natural levées and chutes on the floodplain mark the main paths of a migrating meandering channel. The rate of channel migration down-valley is estimated to have been 1.6 m per annum near Durnitsino village for the period 4200-4500 years ago, according to radiocarbon dating of a sequence of natural levées and depressions between them (points 7 and 8 in Fig. 1). The migrating channel reworked deposits that form the first terrace and several remnants of this surface were preserved within the floodplain. The development of curved omega-shaped meanders indicates the low erosivity of the flow on the floodplain. It probably also indicates relatively low annual variability in water discharge.

As the location of the region-analogues 9 and 10 show, the Sub-boreal palaeochannels were formed during a time that experienced a significant decrease in climate continentality. The morphology of the last palaeochannel corresponds to these climatic conditions. Its width and curvature were formed by a mean annual discharge about 840 to 670 m^3/s, and the mean maximum discharge was about 5000 to 6700 m^3/s. The annual distribution of flow was characterised by low variability (mean $y = 16.4$) at the beginning of the period. It increased towards the end of the formation of the palaeochannel (Table 6). The depth of mean annual runoff was 175 to 220 mm and the depth of winter-spring runoff was 115 to 150 mm. Together with the evapotranspiration value for the region-analogue, this gives a mean annual precipitation depth equal to 600 to 690 mm. Precipitation in the winter-spring period was about 290 to 330 mm.

At the beginning of the Sub-atlantic period the morphological character of the river channel changed again as it developed a braided-meandering form. The stream then abandoned the omega-shaped meanders of palaeochannel D, which are preserved as oxbows. This was connected with an increase in the maximum discharge at the end of Sub-boreal period and with the general humidity of the climate during the Sub-atlantic. Palaeodischarge calculations indicate that flow and precipitation reached their maximum about 1500 years ago, at the period of lowest intra-annual flow variability. By recent times both the calculated mean annual discharge and precipitation depth decreased to 1170 m^3/s and 700 mm respectively, and the mean maximum discharge increased to 7900 m^3/s due to a greater discharge variability within the year (Table 6).

7 DISCUSSION AND CONCLUSIONS

One of the main problems associated with palaeohydrological reconstruction is its accuracy. This depends on the appropriateness of the main palaeogeographical hypothesis, on the validity of the empirical formulas used, and on the errors in the input data.

Table 6. Runoff and precipitation at the lower Vychegda River basin in the Late-glacial and Holocene, reconstructed from palaeochannel (and recent channel) morphology and contemporary hydro-climatic characteristics of region-analogues (see Table 5).

region-analogue	^{14}C age (years BP)	Palaeo channel index	Palaeo channel width (m)	Coefficient a in Equation (2)	Discharge (m^3/s)		Runoff depth (mm)		Precipitation (mm)	
					Mean	Mean maximum	Annual	Winter-spring	Annual	Winter-spring
input					reconstruction					
Malozemel'skaya tundra	~12000	A	1200	2.02	900	10300	235	180	335	200
Basin of Kolva River	8800	B	1300	3.48	1490	9910	390	265	860	415
Basin of Chusovaya River	8400	C	600*	2.80	440	3670	115	90	555	260
Middle Vyatka River	6000	C	700*	1.80	400	5110	105	85	545	285
Basin of Unzha River	4500	D	800	3.99	840	4970	220	150	690	330
Headwaters of Sukhona River	3500	D	900*	2.32	670	6710	175	115	595	295
Basin of Unzha River	1400	recent	1100*	3.99	1270	7720	330	225	800	405
Basin of Vychegda River	recent	recent	1100	3.66	1170	7950	300	205	700	355

* – interpolated values.

The main palaeogeographical hypothesis formulated here as the principle of palaeogeographical analogue (Sidorchuk & Borisova, in press) postulates an opportunity to transform the present-day spatial (geographical) relationships into localised temporal relationships. G. Kalinin (1966) demonstrated that this hypothesis is based on an ergodic theorem. Broad experience of interpolation and extrapolation of hydrological parameters in space and time suggested the possibility of using this theorem in palaeohydrology. Geographical influences on river flow bring about similar hydrological regimes of rivers in similar landscapes (Evstigneev, 1990). Geographical controls over river flow and their applications to palaeohydrology lead to the principle of palaeogeographical analogy:

1. Similar hydrological regimes were characteristic of palaeorivers in similar palaeolandscapes;
2. The hydrological regime of a palaeoriver within some palaeolandscape would be similar to that of a present-day river within the same type of landscape.

The second statement forms the basis of the method of palaeogeographical analogy. Palaeohydrological reconstructions are connected to the reconstructions of palaeolandscapes. The hydrological regime of modern rivers in a certain type of landscape can be used for estimations of palaeohydrological regime in the same type of landscape.

Successive application of the principle of palaeogeographical analogy employs indices selected to describe the spatial distribution of hydrological features. These include hydrological parameters, such as the maximum, annual and daily discharge, etc., statistical moments of their distributions, and the coefficients in empirical formulae. For example, maps of elements of the water budget are available for the entire globe. Maps of mean annual and mean maximum discharges and their temporal variability were compiled for the former Soviet Union. Special maps, including those portraying parameters of flood hydrographs or discharge distribution within the year, are available for some regions or can be compiled from existing information (e.g. Fig. 5). The principle of palaeogeographical analogy can be applied only to zonal bioclimatic landscapes and to river basins of representative size. For the East European Plain the representative basin has an area not less than 10,000 km^2 to overcome the influence of local factors, and not more than 75,000 to 100,000 km^2 to avoid inter-zonal effects.

The accuracy of space – temporal transformation depends on the ability to locate a potential region – analogue on the map, as much as on the accuracy of the age control. A centre of concentration of fossil flora can be determined with some degree of accuracy dependent both on the completeness of the fossil flora record and on topographical data for the geographical ranges of modern plant species. The area of a region-analogue is usually about 10,000 to 40,000 km^2. Variability of the estimated parameter within this area causes errors in spatially-dependent data. Difficulties may also be associated with the age control for palaeohydrological events. Erosive relief has to be dated with the use of samples taken from correlative sediments. Channel, bar and floodplain deposits of the period of palaeochannel development are the most reliable sources of samples for dating. Usually these deposits are composed of well-washed sand with organic matter contents that are too low even for AMS methods of radiocarbon dating. In most cases the samples for dating are obtained from the lowers layers of fine sediments, which already fill abandoned palaeochannels. The lag between the time of channel activity and the time of fine sediment deposition can make the age control for palaeohydrological events less certain.

Two empirical hydro-morphological Formulae, (1) and (2) were used here for palaeohydrological analysis. Formula (1) describes a well-known relationship between the mean annual discharge and channel width (Leopold et al., 1964). Usually hydro-morphological formulae are designed for morphological and hydrological parameters measured in a river channel for a certain water stage. This rule is broken in Formula (1), where the bankfull width is related to the mean annual discharge, although the latter generally corresponds to a lower water level and a smaller width. Such a hydro-morphological relationship was chosen due to the specific objectives of palaeohydrological reconstructions and the uncertainty in estimation of palaeochannel parameters. In the conditions of the Vychegda River, only the bankfull width of the palaeochannels can be reliably measured, while the mean and maximum discharges are the most important hydrological characteristics.

Usually hydro-morphological formulae with two variables allow calculation of a dependent value with some scatter. The correlation coefficient for the simple relationship $\overline{Q} \sim W^b$ for the same set of data, that was used to derive Formula (1), is 0.82 (Table 7). Additional parameters have to be used to reduce the scatter. The choice of additional parameters is also an empirical procedure. The proposed parameter y is well suited to the goals of palaeohydrological calculations. This parameter has a clear hydrological meaning, as a measure of the discharge variability within a year. It is clear that with an increase in variability, the channel width which corresponds to the same annual flow would also increase. This proposition is confirmed by the data on natural rivers used to derive Formula (1). Application of parameter y in hydro-morphological formulae increased the multiple correlation coefficient to 0.90. The mean relative error of discharge estimation with Formula (1) is ±18.6%.

Discharge variability within a year generally decreases with an increase in river basin area A. The parameter y also depends on basin area. This dependency is described by Formula (2). As Figure 5 shows, coefficient a in this formula has a distinctive spatial distribution. The map of coefficient a makes it possible to use the method of palaeogeographical analogue. Formula (2) describes the $y \sim A$ relationship only in the first approximation. Further analysis may also help to discover spatial differentiation of the exponent in Formula (2).

In some cases coefficient a varies significantly within a region-analogue (at the boundaries of hydrological regions). This variability also causes errors in palaeohydrological calculations. The relative error varies from one region-analogue to another from ±2 to ±10%. The accuracy of palaeochannel width measurements depends on the degree of preservation of an ancient fluvial form and on the extent to which the exact definition of the former river bank location can be identified. Width usually changes along the river channel and the bankfull width of meandering channels is greatest at the apexes of meanders

Table 7. Coefficients, exponents, and correlation statistics for various hydro-morphological relationships.

A	*b*	*c*	*R*	formula
0.028	1.55		0.82	$\overline{Q} = a\,W^b$
1.41	1.55		0.38	$\overline{Q} = a\,y^b$
0.012	1.36	0.73	0.90	$\overline{Q} = a\,W^b y^c$

and lowest at their crossovers (riffles). For palaeohydrological calculations the channel width should be measured at the crossovers, at the point of alteration of the curvature sign. Repeated measurements of the same width by several operators show that the relative error of measurements can be up to ±10% depending on palaeochannel preservation.

The maximum relative error of the combined application of Formulae (1) and (2) (including the errors of measurements) is ±20 to 40% (see the bars on Fig. 7). The relative errors in calculations of the hydrological parameters of modern rivers with the use of their modern analogues are mainly within ±10%, and up to 40%. Relative errors of palaeohydrological reconstructions are closer to the upper limit of this interval. The main way to decrease these errors is to increase the number of data points to derive equation (1) more accurately. The errors in the input values of palaeochannel width and parameter y vary randomly from site to site, so that it is impossible to decrease these errors in general.

The depth of runoff for each time interval, reconstructed from palaeochannel morphology, was compared with the depth of runoff for the modern river basins in the corresponding region-analogue (Fig. 7). The latter can be estimated with some level of accuracy, depending on the extent of the region-analogue and the variability of river flow within this area. The relative errors of this estimation are shown by open rectangles on Figure 7. This comparison shows good qualitative and quantitative correspondence between the two sets of data. Of course, these data are not fully independent: they are connected by parameter y, defined for the same region-analogues. But the influence of this parameter on the shape of the reconstructed curve is much less than the influence of palaeochannel width, which is totally independent from the location of the region-analogue. Such a similarity of the values of flow depth, obtained by significantly independent palaeohydrological and palaeofloristic methods, indicates the reliability of both of them.

The morphology of palaeochannels on the low terraces and the floodplain of the lower Vychegda River changes considerably through time during the Late-glacial and Holocene. Palaeochannels were larger than the modern ones in the Late-glacial to early Boreal period. They were significantly smaller than the modern ones during the late Boreal to Atlantic period, and increased again from the Sub-boreal until the present. The mean maximum discharge of the Vychegda changed in the same way. It reached its maximum during the Late-glacial, and was greater than the present value at the beginning of the Boreal period. It was half of the present-day maximum discharge during late Boreal to early Atlantic times, and since the end of Atlantic increased up to its modern values. These reconstructions seemingly contradict a general belief of the Late-glacial as a very dry period, and of the Atlantic as a relatively humid period.

The method of palaeogeographical analogy has been used to estimate not only the maximum flow, which is directly related to river channel size, but also other important parameters. The hydrological region-analogues were determined using the palaeofloristic method for several time periods. For each of these levels the ratio of mean annual and mean maximum discharges, the ratio of annual and winter-spring flow, and evapotranspiration were obtained from corresponding maps for the region-analogues. This provides an opportunity to calculate mean annual and mean maximum discharge, annual and seasonal flow depth, and annual and seasonal precipitation with Formulae (1)-(6) (Table 6).

Assessments of the flow distribution within a year (river regime) may provide an explanation for the first contradiction mentioned above. The Late-glacial period was characterised by very high differentiation of flow (marked seasonality). Precipitation during a long winter-spring period (mainly in the form of snow) was not less than in the present-day

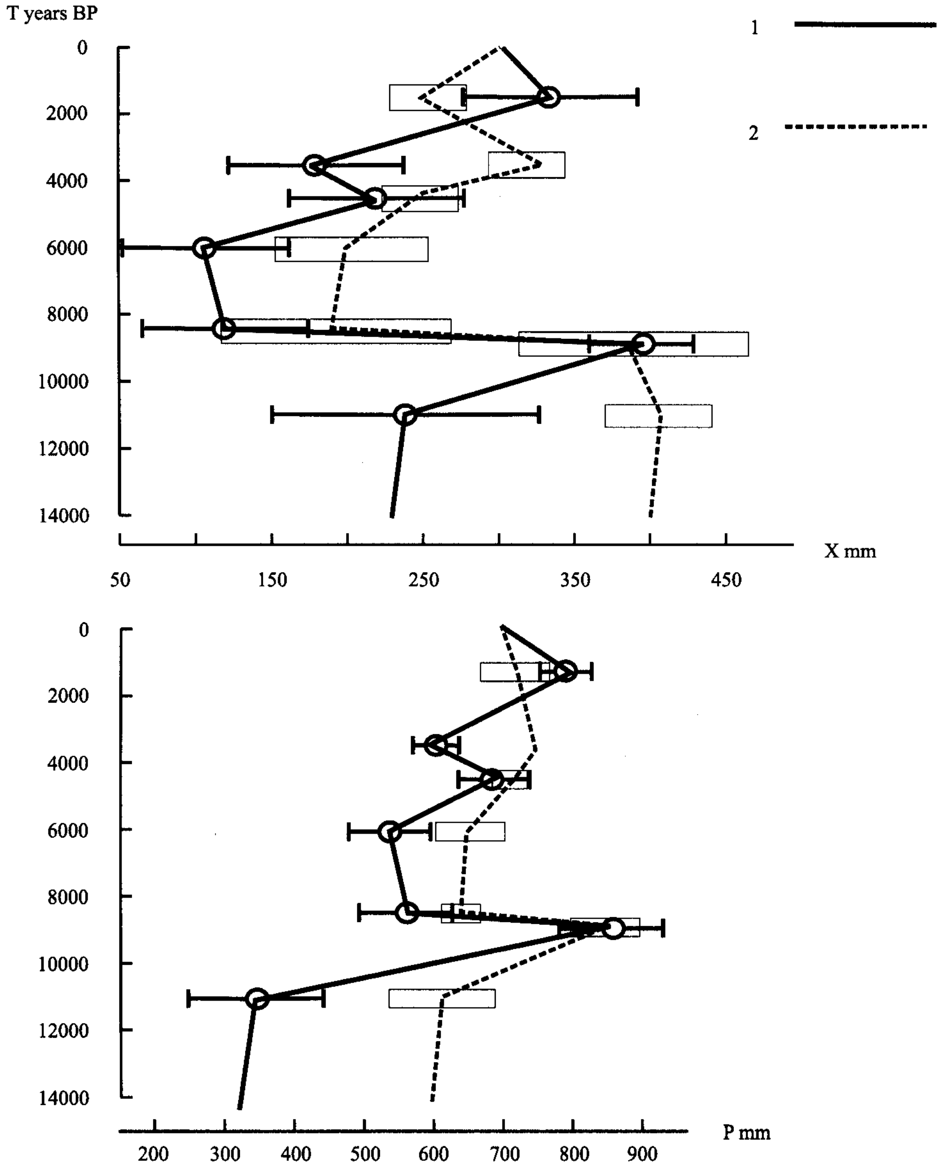

Figure 7. Comparison of annual runoff depth *X* and precipitation *P*, reconstructed with palaeochannel morphology (1) and obtained from floristic region – analogues (2). Bars shows the errors associated with the palaeohydrological calculations, boxes shows the variability of the characteristic within region-analogue.

tundra. Due to low ground permeability in the permafrost zone, the spring thaw led to sharp high floods and to the formation of large wide river channels. But the annual flow was less than the modern one. The apparent humidity deficit was related entirely to the summer-autumn season. In the Vychegda River basin summer precipitation was nearly half the present value. The large periglacial river channels were almost dry throughout the summer due to low precipitation inputs and negligible ground water flow. The same situation is common in modern periglacial landscapes, for example, on the Yamal Peninsula in arctic West Siberia.

The large palaeochannel of the early Boreal age was formed by much more uniform flows. The degradation of permafrost led to a decrease in the runoff rate and an increase in summer-autumn ground water inputs. In conditions of seasonal ground freezing, the runoff coefficients were close to the recent values. Estimates of the mean annual precipitation depth for the period are rather high (860 mm). Precipitation in the winter-spring season was double that of the previous period (415 mm) and the summer-autumn total increased even more – up to 445 mm. A large difference in precipitation regime between the Late-glacial and early Boreal time was derived from the reconstructed intra-annual flow distribution for these two periods. Palaeochannel magnitude is very similar during these time intervals.

The late Boreal and Atlantic periods were less humid. Minimum precipitation and runoff depth was calculated for the late Boreal to middle Atlantic. This temporal shift cannot be explained only by changes in flow variability. The main information about humidity during this period is derived from palaeochannel morphology. The calculated humidity minimum (Fig. 7, Table 6) is related to the smallest palaeochannels formed at that time. In the Sub-boreal and Sub-atlantic periods, the runoff depth and precipitation had a general tendency to increase. This trend was also calculated mainly from an increase in channel size, only local maximum and minimum on the curve being related to changes in flow variability.

The later direct palaeohydrological evidence for the lower Vychegda region contradicts recent climatic reconstructions for the Holocene of Europe. For example, Guiot et al. (1993) showed that the Atlantic period was the most humid in Europe, and humidity decreased during Sub-boreal and Sub-atlantic times. This apparent contradiction can be explained in terms of the metachronous principle (Markov, 1965). Khotinskiy (1977) showed that according to this principle the alteration of more and less humid periods in the territory of northern Eurasia in the Holocene varied significantly in different regions. In the western regions (East European plain) with a more oceanic climate, the Atlantic was more humid than the early Boreal and modern times, and the maximum of humidity took place during the Sub-boreal to Sub-atlantic. In the central regions of Siberia with a continental climate, the maximum of humidity was related to the Boreal period, and the minimum to Sub-boreal times. The climate of the lower Vychegda was more continental than at present during the Boreal and Atlantic times. The region – analogues for this period are situated at the eastern part of taiga zone near the Ural mountains. The change in humidity then followed with a continental climate scenario. During the Sub-boreal and Sub-atlantic, the climate of the lower Vychegda region was more oceanic than the present day, and the trend in humidity change follows the onset of an oceanic climatic scenario.

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