# METHOD OF PALEOGEOGRAPHICAL ANALOGUES IN PALEOHYDROLOGICAL RECONSTRUCTIONS

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One of the main problems of quantitative paleohydrology is a discrepancy between very high (even catastrophic) reconstructed discharges in the paleorivers and results of the majority of precipitation reconstructions in the same territory. To resolve the problem it is necessary to find the closest recent analogue to the hydrological regime of a paleoriver and to calculate the main hydrological and climatic parameters of the former flow with the help of this analogue. This approach to paleohydrological reconstructions is the method of paleogeographical analogues based on two assumptions: 1) similar hydrological regimes were characteristic for the paleorivers in similar paleolandscapes; 2) the hydrological regime of a paleoriver within some paleolandscape would be similar to that of a present-day river in the same type of landscape.

Quantitative paleohydrological reconstruction by paleogeographical analogy calculates a wide range of paleohydrological and paleoclimatic parameters, such as maximum discharge and its return period; mean maximum discharge; mean annual discharge; volume of the floodwave; winter and annual precipitation. A study of the Khoper River paleochannel with a discharge 7 times exceeding the modern one indicates that the paleochannel formation was caused mainly by periglacial conditions with continuous permafrost and very sparse vegetation, while the rainfall increase was only two-fold.

The relative errors in calculations of hydrological parameters for the present-day rivers using their modern analogues are mainly within ±10%, and up to 40%. The relative errors of palaeohydrological reconstructions are probably more close to the latter value.

## INTRODUCTION

Paleohydrology is the hydrology of the past environment (Schumm, 1965). This paleogeographical discipline, among other tasks (Gregory, 1983), involves reconstruction of the morphology of paleochannels and of the water flow in paleorivers. Morpho-paleohydrology mainly uses results of hydrological, hydraulic, geomorphological and sedimentological investigations. One of the first geomorphological works with elements of paleohydrology was that of W.M. Davis (1896) on the Maas River in France. He showed that Maas and some of its tributaries have narrow modern channels in the boundaries of a wide meandering former channel.

The hydraulic basis of morpho-paleohydrology was established even earlier. According to S. Leliavsky (1955), Fergusson in 1863 compiled the first set of morpho-hydrological formulae in the course of his investigations of the Ganga River. These equations showed a close relationship between channel morphology (channel width, meander length) and water discharge in the channel. The work of A. Chezy of 1775, followed by numerous investigations in this field, made it possible to calculate a discharge from morphology of channel cross-section, slope of water surface, and bottom roughness.

G. Dury (1964,1965) described a global distribution of the underfit streams, where changes in hydrological regime are evidenced by disproportion in sizes of the present channel and paleochannel. For quantitative paleohydrological reconstructions Dury used morpho-hydrological formulae, interrelating channel width and meander length with discharge. These calculations showed that paleorivers had bankfull discharges 25 - 60 times greater than the modern ones. Morpho-hydrological formulae in paleohydrology were used later in a majority of investigations. All these works showed very high difference between paleo- and present volumes of flow in the rivers. S. Schumm (1968) conducted investigations of paleochannels on the Riverine Plain of the Murrumbidgee River, Australia. He reconstructed the shape of cross-section and a slope of the paleochannel by coring alluvial sediments in the valley.

Dury (1965) also suggested use of Chezy-Manning formula for the calculation of the former river discharges. Hydraulic equations were broadly used in paleohydrology by V. Baker (1973) and his colleagues (O'Connor and Webb, 1988; Baker *et al.*, 1993) for calculations of maximum paleodischarges and by K. Rotnicki (1983,1991) for estimation of bankfull discharges in paleochannels.

These two main ways in quantitative morpho-paleohydrology (morpho-hydrological formulae and hydraulic equations) were broadly discussed in paleohydrological literature (Maizels, 1983; Rotnicki, 1983; Williams, 1988), but their application is not so wide. For example, at three last conferences of the Commission on Global Continental Paleohydrology (Southampton, UK, 1994, Toledo, Spain, 1996 and Kumagaya, Japan, 1998) only in a few presentations the quantitative approach was presented.

One of the main problems of quantitative paleohydrology is the discrepancy between very high (even catastrophic) reconstructed discharges in the paleorivers and the results of the majority of paleoclimatic reconstructions of the former precipitation for the same regions. This discrepancy led in some cases to a certain distrust of paleohydrological results. To resolve the problem careful paleoenvironmental reconstructions are necessary. One should find the closest recent analogue to the hydrological regime of a paleoriver and calculate the main hydrological and climatic parameters of the former flow. Such an approach to paleohydrological reconstructions will be illustrated by the method of paleogeographical analogues.

## METHODOLOGY

### *The geographical causation of the hydrological regime*

V. Glushkov (1933) developed the geographical approach to calculations of the river flow. He documented the influence of the climatic, geomorphic, geological, soil and vegetation components of landscapes on the water flow and hydrological regime of rivers. The spatial distribution of hydrological parameters depends on that of landscapes. A certain type of hydrological regime largely corresponds to a zonal landscape. For example, in Northern Eurasia 10 main types of hydrological regimes are distinguished. The local peculiarities of landscape conditions modify hydrological features of the river flow. For example, the local occurrence of karst rocks can significantly change the river flow.

Geographical influences on the river flow made possible the principle of geographical analogy (Evstigneev, 1990): similar hydrological regimes are characteristic for the rivers in similar landscapes. This principle can be applied mainly to zonal landscapes and to the 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 an influence of local factors, and not more than 75,000 - 100,000 km$^2$ to avoid interzonal effects.

Successive application of the principle of geographical analogy employs indices selected to describe the spatial distribution of hydrological features. These include statistical moments of distribution of hydrological parameters, such as water discharge, maximum, annual and daily discharge, *etc.* or the coefficients in empirical formulae. For example, maps of elements of the water budget are available for the globe. Maps of mean annual and mean maximum discharges and their temporal variability were compiled for the former Soviet Union. Special maps, including those of parameters of flood hydrographs or parameters of discharge distribution within the year, are available for some regions (Aver'yanov, 1953) or can be compiled from existing information.

### *Paleogeographical analogy*

Geographical controls on river flow and their application to paleohydrology lead to the principle of paleogeographical analogy: 1) similar hydrological regimes were characteristic for the paleorivers in similar paleolandscapes; 2) the hydrological regime of a paleoriver within some paleolandscape would be similar to that of a present river within the same type of landscape. The second statement forms the basis of the method of paleogeographical analogy. Paleohydrological reconstructions are connected with the reconstructions of paleolandscapes. The hydrological regime of modern rivers in the same type of landscapes can be used for estimations of paleohydrological regime.

An important consequence of the principle of paleogeographical analogy is that the empirical hydrologic formulae may be applied only within similar boundary conditions, including zonal landscape conditions. Many investigators of paleohydrology generally accepted this rule. Thus, Schumm (1965) declared that the conclusions resulting from a local or regional study should be extended beyond the limits of the investigation only with great care. L. Starkel and J. Thornes (1981) consider Schumm's formulae to be inapplicable outside the range for which they were worked out. Rotnicki (1983) wrote that there is no such a formula of relation between a discharge and meander wavelength, where coefficients would hold for all rivers of all climatic zones, regions and continents.

Most of the empirical relationships between different hydrological parameters, or between hydrological parameters and governing factors, vary in space and time due to geographical causation of hydrological processes. The empirical hydrological relations derived for the rivers in certain landscapes and of certain morphological types can not be applied to rivers in different landscapes or of different morphologies. For example, Dury's (1983) use of the empirical formula for bankfull discharge by Williams (1978) to calculate the discharge of paleo-Severn was inaccurate because the formula of Williams was derived for rivers in variable and not differentiated environments, while hydrological regime of paleo-Severn was formed in humid conditions. Rotnicki (1991) reconstructed the bankful discharges of the Prosna River for different periods of the Late Glacial and the Holocene with the help of the Chezy-Manning formula, including estimation of the roughness coefficient. For calculation of mean annual discharges he used the same empirical ratio of bankfull and mean annual discharges for all paleochannels of the Prosna River. That is also inaccurate according to the principle of paleogeographical analogy because the landscape and the hydrological regime of Prosna River during the Late Glacial were significantly different from the present ones. To avoid such discrepancies landscape reconstructions based on independent evidence are required.

### *Landscape reconstructions for paleohydrological investigations.*

The use of paleobotanic data for paleoclimatic and paleolandscape reconstructions assumes that flora of a particular region, or the composition of plant species growing there, experience direct influences of the natural environment on the whole and the climate in particular. The method of reconstructing landscape and climate from fossil plant data was developed by V.P. Grichuk (1969, 1985), who used a concept from W. Szafer (1946). The method is based on the composition of the fossil flora at a certain site derived from palynological and plant macrofossil data. Geographical analysis of modern geographical ranges for all the species found in a given fossil flora defines the closest modern floristic analogue to the past vegetation at the site. 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 fit for all the plants of a given fossil flora, particularly if it is composed of the inhabitants of various biotopes, can be found in a comparatively small area. The present-day character of plant communities, the main landscape features, and climatic indices of such a region-analogue would be close if not identical to those existed at the site in the past.

## THE KHOPER RIVER CASE STUDY

### *Study area*

An example of application of the above methods to paleohydrological reconstructions is considered for the Khoper River valley. The research area is situated in the middle part of the Khoper valley, near the northern limit of the herb-grass steppe zone. The woodland patches closest to the site consist of pine and oak. The area is characterised by a temperate continental climate. The mean January air temperature is –10°C, that of July is 20°C. Positive temperatures occur 150 days per year, the mean annual precipitation is about 460 mm. During winter and spring the total precipitation reaches 150-170 mm.

The water yield from the southern Russian Plain varied broadly during the Late Glacial and the Holocene. These changes did not depend on the melt water runoff from the ice-sheet, as the latter was situated far in the north. The transformation of the periglacial landscapes into typical steppe and forest - steppe was accompanied by a period of low soil permeability due to widespread permafrost, by increasing aridity of climate, and later on by permafrost melting and increasing soil permeability. During the period of high surface flow very large rivers drained the Russian Plain, their characteristic palaeomeander length $\lambda_{past}$ (which is half of wavelength) and channel width $W_{past}$ being 5-15 times greater than present meander length $\lambda_{pr}$ and channel width $W_{pr}$ (Table 1).

Large rivers were active in Late Glacial time. The begining of filling of Protva River large channel (index 60 in table 1) is dated about 13,000 years ago (radiocarbon date 12,700±110 yr. BP, Ki-7312). The large channel of the Khoper River (index 41 in table 1) was active about 14-17 thousand years ago (RTL-808 thermoluminescent dating of alluvial sands in Moscow State University laboratory 17±4 thousand years ago, radiocarbon date 14430±110 yr. BP, Ki-7694). Its filling has begun about 12,000 year ago (11,900±120 yr. BP, Ki-5305; 11325±120 yr. BP, Ki-7680). The large channels of Seim and Svapa Rivers (indexes 34 and 49 in table 1) were abandoned about 14,000 years ago (13800±85, Ki-6984; 14030±70, Ki-6997; 13510±85, Ki-6991). Radiocarbon dates were obtained in the Radiocarbon Laboratory of the State Scientific Centre of Environmental Radiogeochemistry (Ukraine), all dates are not calibrated.

Table 1. Meander and macromeander parameters of the rivers in the central and southern Russian Plain

| Index | River | Basin area F km$^2$ | Annual discharge $Q_{pr}$ m$^3$/s | $\lambda_{pr}$ m | $W_{pr}$ m | $\lambda_{past}$ m | $W_{past}$ m | Latitude N | Longitude E |
|---|---|---|---|---|---|---|---|---|---|
| Volga River basin | | | | | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 66 | Moskva | 9000 | 67.2 | 700 | 150 | 2500 | 500 | 55°38′ | 37°47′ |
| 60 | Protva | 2170 | 11.6 | 380 | 80 | 800 | 180 | 55°12′ | 36°31′ |
| 59 | Zhizdra | 1970 | 9.9 | 150 | 40 | 1000 | 250 | 53°51′ | 35°07′ |
| 62 | Kerzhenets | 4500 | 24.0 | 370 | 50 | 1250 | 500 | 56°28′ | 44°48′ |
| 51 | Alatyr’ | 10500 | 40.7 | 410 | 80 | 1250 | 250 | 54°48′ | 46°11′ |
| 52 | P’yana | 7930 | 38.1 | 270 | 70 | 1300 | 300 | 55°31′ | 44°19′ |
| 32 | Pil’va | 890 | 8.0 | 170 | 35 | 1200 | | 60°43′ | 55°57′ |
| 31 | Veslyana | 3900 | 33.2 | 180 | 35 | 1700 | | 60°26′ | 52°42′ |
| 28 | Ya’va | 5230 | 62.8 | 830 | 120 | 2800 | 500 | 59°08′ | 57°02′ |
| 30 | Usta | 6030 | 42.2 | 340 | 60 | 2200 | 200 | 56°55′ | 45°28′ |
| 44 | Dyema | 12500 | 42.3 | 210 | 60 | 1200 | 220 | 54°31′ | 55°23’ |
| 64 | Urshak | 3130 | | 230 | 50 | 860 | 200 | 54°29′ | 55°52′ |
| 45 | Ikk | 7660 | 31.9 | 140 | 40 | 1440 | 290 | 54°47′ | 53°34′ |
| 46 | B.Kinel' | 5970 | 19.4 | 160 | 25 | 920 | 200 | 53°22′ | 51°16′ |
| 47 | B.Izgiz | 2110 | 3.3 | | | 800 | 100 | 52°15′ | 49°54′ |
| 48 | M.Uzen' | 9490 | 6.8 | | | 1000 | 200 | 50°28′ | 47°38′ |
| | | | | Dnieper River basin | | | | | |
| 35 | Ubort' | 5260 | 10.7 | 175 | 30 | 880 | 120 | 51°55′ | 28°30′ |
| 34 | Seym | 10700 | 37.1 | 170 | 40 | 3000 | 400 | 51°39′ | 35°20’ |
| 49 | Svapa | 6310 | 29.1 | 120 | 30 | 1400 | 250 | 51°39′ | 35°20′ |
| 37 | Uday | 6120 | 11.4 | | | 1500 | 300 | 50°18′ | 32°32′ |
| 36 | Sula | 14200 | 28.5 | 170 | 30 | 2500 | 400 | 50°15′ | 33°21′ |
| 38 | Psyel | 11300 | 30.5 | 330 | 40 | 1250 | 330 | 49°38′ | 33°46′ |
| 40 | Orel' | 9400 | 21.6 | 200 | 50 | 1790 | 350 | 48°49′ | 34°24′ |
| | | | | Don River basin | | | | | |
| 53 | Lesnoy Voronezh | 1740 | 6.5 | 160 | 50 | 690 | 150 | 53°01′ | 40°38′ |
| 58 | Bityug | 7330 | 18.2 | 200 | 40 | 1300 | 350 | 51°42′ | 40°31′ |
| 55 | Medveditsa | 7610 | 18.4 | 320 | 40 | 1200 | 250 | 51°31′ | 44°38′ |
| 41 | Khopyer | 19100 | 67.0 | 360 | 60 | 2500 | 800 | 51°19′ | 42°22′ |
| 57 | Vorona | 9540 | 31.3 | 430 | 70 | 1700 | 420 | 52°04′ | 42°15′ |
| 56 | Savala | 7720 | 20.4 | 250 | 50 | 800 | 250 | 51°08′ | 41°27′ |
| 54 | Tersa | 7320 | 14.5 | 250 | 40 | 1000 | 250 | 50°48′ | 44°24′ |
| 42 | Buzuluk | 6830 | 9.7 | 460 | 35 | 1380 | 300 | 50°32′ | 42°34′ |
| 43 | Ilovlya | 8730 | 8.0 | | | 850 | 150 | 49°47′ | 44°30′ |

Further to the west the macromeanders are widespread in Poland. Their development was connected with large Late Glacial paleorivers (Starkel, 1995).

### *Morphology of the Khoper River valley*

The morphology of river valleys in the Don River basin reflects past water flow changes. One of the best preserved systems of paleochannels with the bankfull channel width of 800 - 1400 m, maximum depth of 9 m, and a meander length ($\lambda$) of 2500 m, occur on the ancient floodplain of the Khoper River near Povorino (fig. 1). At present, the Khoper River near Povorino has a channel width of 60 m, maximum depth of 4 m, and a meander length up to 360 m. Radiocarbon and TL analyses show that paleochannels on these parts of floodplain were formed during the Late Glacial 14-17 thousand years ago and were abandoned 11 - 12 thousand years ago.

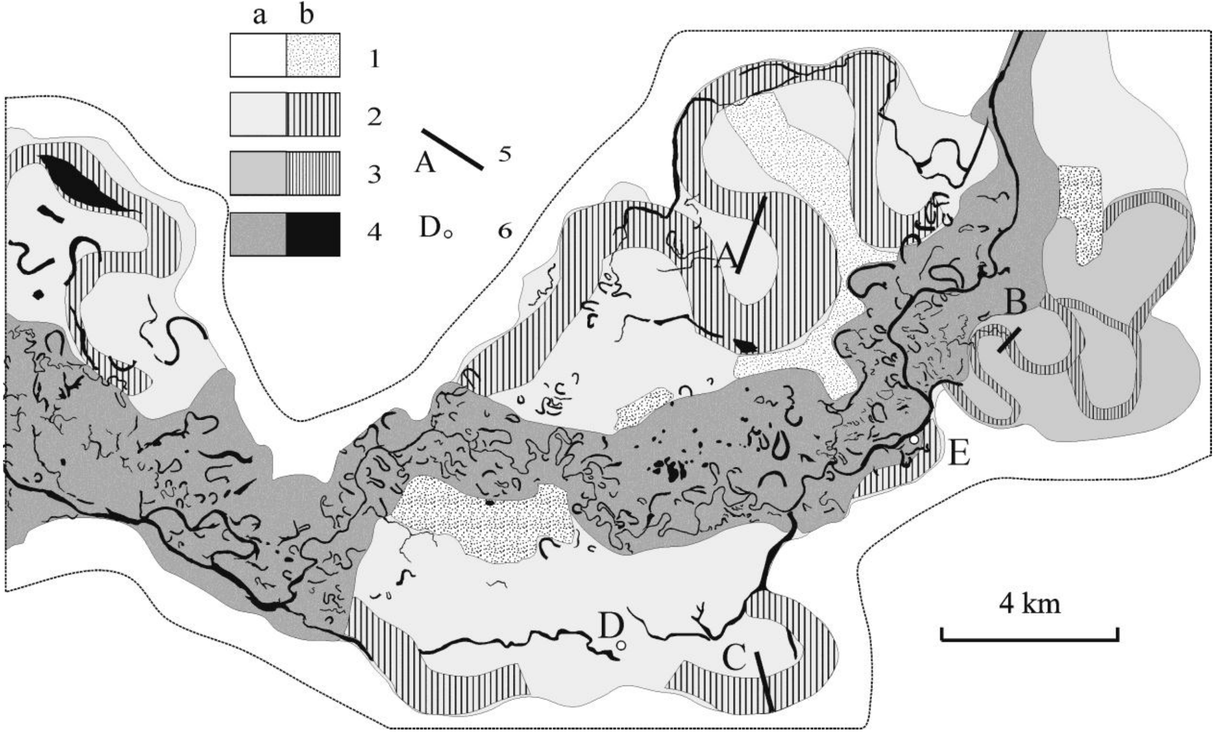


Fig. 1. Main morphological units of the Khoper River valley near Povorino: 1a – high terraces; 1b - low terrace; 2a - Late Glacial floodplain (first generation); 2b – Late Glacial macromeanders(first generation); 3a - Late Glacial floodplain (second generation); 3b – Late Glacial macromeanders(second generation); 4a - Holocene floodplain; 4b - modern river channel and the Holocene oxbows; 5 - coring cross - sections; 6 - isolated bore holes.

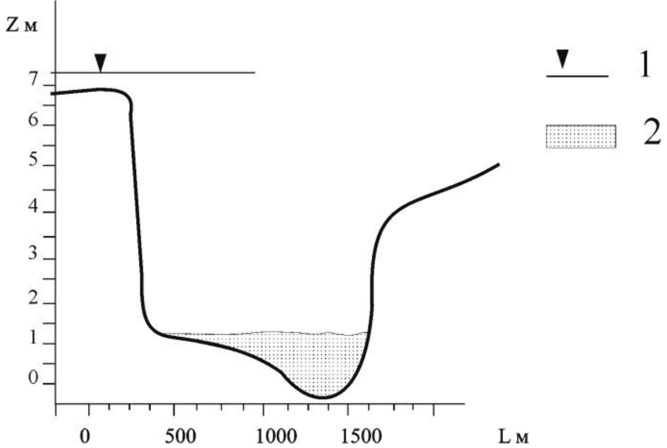


Fig. 2. Cross- section A of the Khoper River paleochannel: 1 – the maximum level of floodplain submersion; 2 – paleochannel infilling.

The thickness of subsequent infilling varied at different parts of the paleochannel. The system of channels following the right bank of the valley has been rarely flooded after it was abandoned, so that the former bottom of the paleochannel is locally exposed. The maximum thickness of the channel filling deposits at the cross-section A does not exceed 1.5-3.0 m (fig.1, 2). There are large eolian dunes on the terrace at the macromeander neck.

The system of channels along the left bank of the valley is situated nearer to the present river. The pools with the maximum depth of 9 -11 m at the point B and cross-section C are completely filled in by fine-grained floodplain alluvium. The riffle deposits at the point D are buried by 3 m of paludal sediments rich in organic matter.

*Paleohydrological reconstructions*

The morphometric parameters of the paleochannel were estimated, including paleochannel slope; paleochannel cross-section area versus altitude; floodplain altitude; paleomeander wavelength, amplitude, angle of deflection; and paleochannel width. The granulometric analysis was used to determine the mean diameter of the alluvium particles for the paleochannel and its floodplain.

The results of morphologic and granulometric analyses were used for stage - discharge hydraulic calculations of the paleochannel. The Chezy formula was used for calculation of the discharge $Q$:

$$Q = UF = FC\sqrt{SD} \qquad (1)$$

The calculations were fulfilled for cross-section $A$, where slope $S$, cross-section area $F$ and mean depth $D$ for a given stage were available (see fig.2).

There are many methods of Chezy coefficient $C$ calculation, the Manning formula being one of the most popular in the international literature:

$$C = \frac{D^{1/6}}{n} \qquad (2).$$

In the Russian research the formula of Pavlovskiy is traditionally used:

$$C = \frac{D^{y}}{n} \qquad (3)$$

Here $y = 2.5\sqrt{n} - 0.13 - 0.75\sqrt{D}\left(\sqrt{n} - 0.1\right)$.

The roughness coefficient $n$ can be taken from special tables (for example, from Chow, 1959). It can be calculated from mean diameter $d$ of the paleochannel bed alluvium using the formula by Karaushev (1969):

$$n = 0.03d^{1/6} \qquad (4).$$

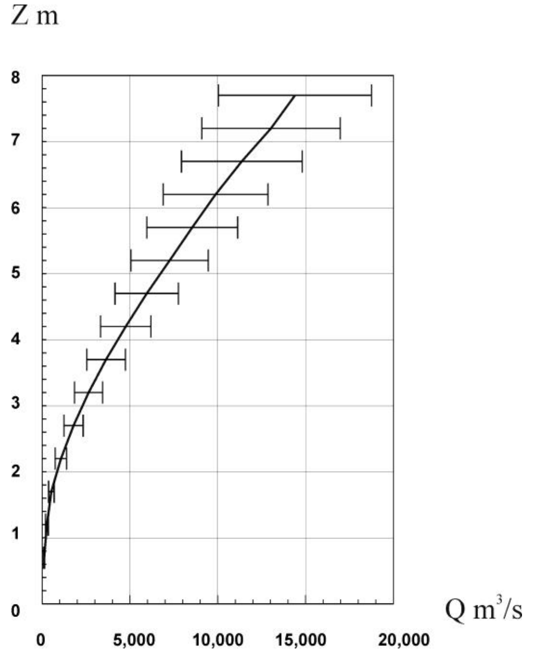
In our calculations the roughness coefficient $n$ was estimated (Table.2) from several modern fluvial analogues. The parameters of the lower Khoper River were used because of its meandering pattern, same grain size of the bed alluvium and similar channel slope, though the size of the present channel is smaller than that of the ancient one. The data on the lower Don River were also used due to its meandering pattern, same size of the channel and similar character of the bed alluvium, but the slope of the present channel is smaller than that of the former one. The mean value of $n$ for the channel flow is 0.029 (with standard deviation $\sigma$ of 0.01). The mean value of $n$ for the flow on the floodplain is 0.088 (with standard deviation $\sigma$ of 0.036).

Table 2. Hydraulic parameters for the channels of the Don River and Khoper River observed in 1952

| N | Date | mean velocity m/s | mean depth, m | slope | Manning roughness coefficient n |
|---|---|---|---|---|---|
| Don River, station Belyavskiy | | | | | |
| 1 | 12.5 | 1.10 | 8.10 | 0.053 | 0.027 |
| 2 | 14.5 | 1.08 | 7.80 | 0.053 | 0.027 |
| 3 | 17.5 | 0.99 | 7.50 | 0.038 | 0.024 |
| 4 | 19.5 | 0.93 | 7.00 | 0.029 | 0.021 |
| 5 | 20.5 | 0.87 | 6.90 | 0.029 | 0.022 |
| 6 | 22.5 | 0.72 | 6.10 | 0.041 | 0.030 |
| Don River, station Razdorskaya | | | | | |
| 7 | 4.4 | 0.58 | 6.30 | 0.014 | 0.022 |
| 8 | 6.4 | 0.65 | 6.90 | 0.014 | 0.021 |
| 9 | 11.4 | 0.63 | 6.90 | 0.015 | 0.022 |
| 10 | 14.4 | 0.63 | 6.90 | 0.009 | 0.017 |
| 11 | 16.4 | 0.61 | 6.80 | 0.014 | 0.022 |
| 12 | 21.4 | 0.64 | 6.80 | 0.008 | 0.016 |
| 13 | 25.4 | 0.54 | 6.40 | 0.006 | 0.016 |
| 14 | 26.4 | 0.51 | 6.30 | 0.013 | 0.024 |
| 15 | 30.4 | 0.54 | 6.20 | 0.025 | 0.031 |
| 16 | 3.5 | 0.56 | 6.40 | 0.009 | 0.018 |
| 17 | 10.5 | 0.43 | 6.00 | 0.008 | 0.022 |
| 18 | 11.5 | 0.28 | 5.20 | 0.003 | 0.019 |
| 19 | 12.5 | 0.20 | 4.80 | 0.012 | 0.049 |
| 20 | 13.5 | 0.13 | 4.30 | 0.005 | 0.045 |
| 21 | 15.5 | 0.17 | 4.40 | 0.005 | 0.035 |
| 22 | 21.5 | 0.17 | 4.60 | 0.003 | 0.028 |
| Khoper River, station Novokhopersk | | | | | |
| 23 | 17.5 | 0.92 | 3.32 | 0.160 | 0.031 |
| 24 | 26.5 | 0.70 | 2.38 | 0.210 | 0.037 |
| Khoper River, station Besplemyanovskiy | | | | | |
| 25 | 20.5 | 0.75 | 3.59 | 0.170 | 0.041 |
| 26 | 21.5 | 0.74 | 3.42 | 0.170 | 0.040 |
| 27 | 22.5 | 0.67 | 3.23 | 0.190 | 0.045 |
| 28 | 23.5 | 0.70 | 3.02 | 0.190 | 0.041 |
| 29 | 24.5 | 0.66 | 2.87 | 0.190 | 0.042 |
| 30 | 26.5 | 0.60 | 2.64 | 0.150 | 0.039 |
| 31 | 28.5 | 0.59 | 2.29 | 0.170 | 0.038 |
| 32 | 30.5 | 0.60 | 2.23 | 0.150 | 0.035 |
| Khoper River, station Dundukovskiy | | | | | |
| 33 | 22.5 | 0.62 | 2.39 | 0.100 | 0.029 |
| 34 | 24.5 | 0.62 | 2.11 | 0.086 | 0.025 |
| 35 | 26.5 | 0.63 | 1.73 | 0.093 | 0.022 |
| 36 | 28.5 | 0.65 | 1.48 | 0.093 | 0.019 |
| 37 | 30.5 | 0.61 | 1.31 | 0.086 | 0.018 |

The main errors in calculated discharges are related to the errors in estimation of the cross - sectional area and that of the roughness coefficient. Within two-sigma variability of the latter the calculated discharge can have two-fold difference in its value, as shown by bars on the fig.3.

Fig. 3. Stage – discharge relationship
for the cross – section A.



The stage - discharge relation is the only characteristic, which does not depend strongly on the accepted hypothesis of the paleoenvironment. It can be reconstructed for a given paleochannel with certainty based on its morphology. For calculations of the absolute maximum, mean maximum, mean annual discharges and their probabilities the landscape conditions of the paleochannel formation have to be reconstructed.

*The landscape at the time of the Khoper paleochannel formation*

The alluvium infill the meandering Khoper paleochannel were studied in two cores by granulometric and pollen analyses. The thickness of these sediments in the core E is 935 cm. The base of the section consists of interlaid fine-grained sand and loam with inclusions of organic detritus at the depth of 700 cm (fig.4). The radiocarbon date obtained for the layer enriched with organic matter is 11,900±120 yr. BP (Ki-5305). The core does not reach the base of the alluvium sediments, but palynological studies reveal the vegetation history in the Late Glacial and Early Holocene (app. from 13 to 9 thousand years ago), including the final stages of the development of macromeanders and subsequent accumulation of fine-grained deposits in them.

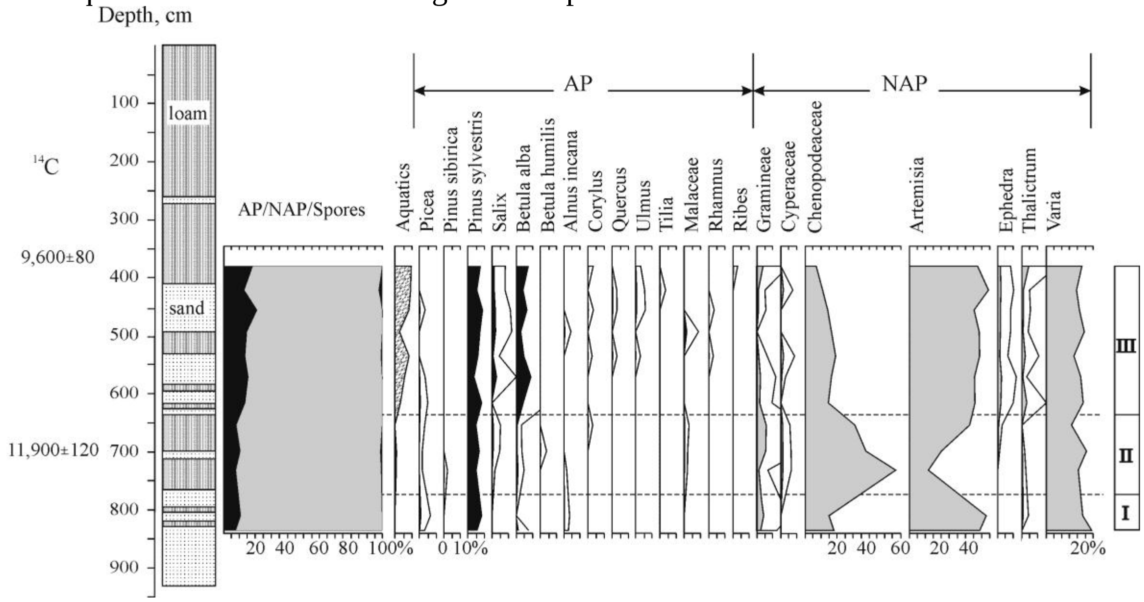


Fig. 4. Pollen percentage diagram of main types for core E

The pollen diagram from the core E distinguishes three pollen assemblage zones. Zones I and II in the lower part of the core correspond to the Late Glacial stages of the landscape and climate development. At the depth of about 600 cm the change in pollen assemblages reveals the Late Valdai/Holocene transition, marked by decrease in non-arboreal pollen, especially that of Chenopodiaceae family, by raise of birch and willow pollen curves, as well as that of aquatic plants, and by appearance of the pollen of broad-leaved trees and such shrubs as *Corylus avellana*, *Rhamnus* and *Ribes*. These changes of pollen spectra are indicative of generally increasing humidity and decreasing continentality of climate, as well as of different facies conditions of sedimentation.

Landscape reconstructions with the paleofloristic method were accomplished for pollen zone II. The pollen assemblage of the zone is characterised by highest NAP values (up to 95%) and the greatest diversity of the herbaceous plants for the whole section. The zone is dominated by Chenopodiaceae and *Artemisia* pollen. The arboreal pollen percentages in this zone remain at 10-15%. These consist mainly of pine (*Pinus sylvestris*) and tree birch (*Betula alba*), but traces of such species as spruce, Siberian pine (*P. sibirica*) and shrub birch (*B. humilis*) are also present in the zone. This type of pollen spectra has no direct contemporary analogue. It indicates a spread of so-called periglacial steppe vegetation (Grichuk, 1989) in the cold semiarid and extremely continental climate.

19 plant species were identified in the pollen zone II at the depth 700-732 cm: *Alisma plantago-aquatica; Atriplex pedunculata; A. verrucifera; Betula alba; B. humilis; Botrychium simplex; Chenopodium acuminatum; C. chenopodioides; Ephedra distachya; Eurotia ceratoides; Kochia scoparia; Picea abies; Pinus sibirica; P. sylvestris; Plantago lanceolata; P. ramosa; Salsola soda; Thalictrum simplex; Typha angustifolia.* A region of the present-day maximum concentration of the fossil flora was determined by cartographic superimposition of present-day ranges of all the species. At present, 18 of these grow in the north-eastern Kazakhstan, in the Bukhtarma River basin (Irtysh River basin) at the boundary between dry steppe and semidesert and close to the region where communities of shrub birch and open dark coniferous forest are spread on the western slopes of the Altai Mountains (fig. 5). The area is characterised by a cold semiarid and extremely continental climate. The mean January air temperature in this region is -18°C; mean July temperature is about 15°C. Temperatures above freezing occur 90-100 days per year, and the mean annual precipitation varies between 500 and 600 mm, including 200 mm during the period from November till March. The region-analogue is situated beyond the permafrost zone but close to its boundary.

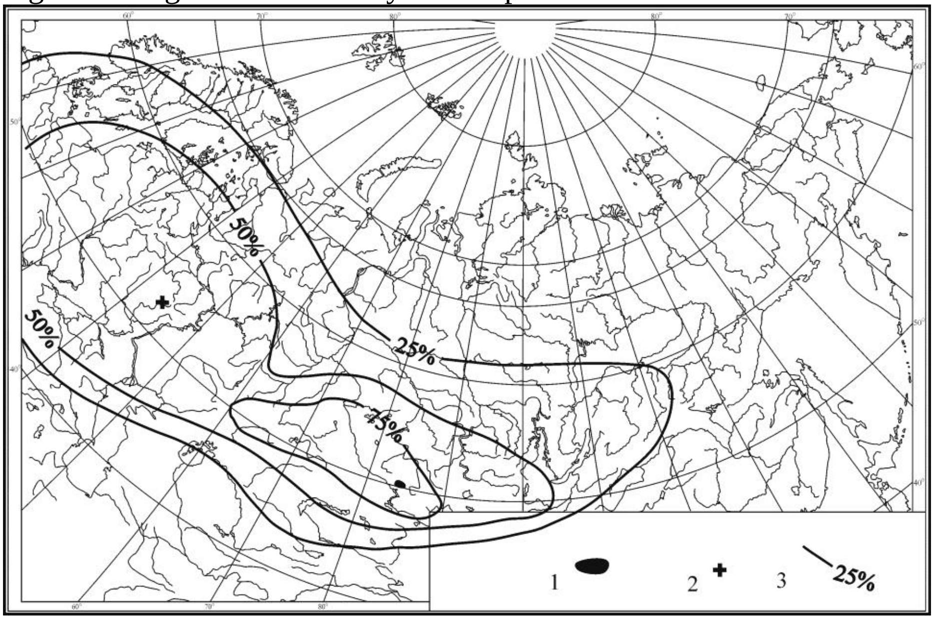


Fig. 5. Location of present-day concentration (1) of species of the fossil flora with the age 11,900 years BP from the Khoper River paleochannel (2). Lines (3) show percentage of species growing together at present.

The problem of permafrost occurrence in the Khoper catchment basin during the time of macromeanders development is crucial for understanding the process. Paleocryological studies (Velichko *et al*., 1982) show that the maximum stage of the Valdai glaciation was also the time of maximum permafrost expansion on the Russian Plain. It reached as far as 45-46°N. Largest ice-wedge casts are dated to that time and to the initial stages of deglaciation. In the course of subsequent warming the permafrost gradually retreated. However, there are some indirect evidences showing that the permafrost persisted in the mid-latitudinal belt of the Russian Plain until the Allerod Interstadial. A mong those, findings of spruce cones indicating that the Siberian spruce (*Picea obovata* or *P. abies ssp. obovata*) grew in the area during the Allerod. This tree is more tolerant to cold than the European spruce (*P. abies ssp. excelsa*). At present it grows in the regions where permafrost lies close to the surface. The drop of winter temperatures at the Younger Dryas cooling was favourable for the permafrost retention and, possibly, reactivation. Cryogenic structures were found in the loess horizon correlated to the Younger Dryas near the Timonovka Palaeolithic site (Velichko, 1981). The constant presence of typical cryophytes in the Younger Dryas florae of the Russian Plain is also indicative of the permafrost existence.

One of the main difficulties of paleohydrological reconstructions for the Russian Plain region during the Late Valdai period is an absence of direct modern analogues for the previous landscapes. The western Altai, 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 lowland tundra of the northern Russian Plain and Siberia (as the region with the closest hydrologic regime).

The evidence described above provides justification for applying runoff coefficients and flow regimen characteristic for the river basins of the continuous permafrost zone (those situated in Bol'shezemel'skaya Tundra, Yamal peninsula, and at the north of East Siberia) to the reconstruction of the paleo-Khoper hydrological regime. Taking into account the present-day conditions of flow regimen formation and the hydrological parameters of the recent rivers in the region-analogue one can calculate a number of paleohydrological and paleoclimatic characteristics, such as mean maximum discharge, mean annual discharge, flow volume for a flood period, mean annual and seasonal precipitation.

*Absolute maximum discharge and its probability*

Meanders of the Khoper paleochannel are well developed and have shapes similar to that of the Greek letter “omega”. There were no avulsions on the floodplain during the paleochannel lifetime. That means, that the velocity of the flow on the floodplain never exceeded the critical velocity required for such an avulsion. The climate was semiarid, and the vegetation on the floodplain was sparse. In such a case the critical velocity can be estimated from mean grain size *d* of the floodplain alluvium. The water depth related to the critical velocity $U_{cr}$ was calculated with the formula of Shamov (1954)

$$U_{cr} = 6.8 D^{1/6} d^{1/3} \qquad (5),$$

combined with Chezy formula for $U_{cr}$. For the floodplain alluvium of the paleochannel with mean grain diameter of 0.49 mm the depth of the critical flow should be 0.7 m (fig. 2). That gives the maximum water level on the highest floodplain of 7.7 m. The maximum discharge is calculated for this stage and the mean value of channel roughness $n$ = 0.029 from the stage - discharge relation: 13,200 m$^3$/s (fig.3).

This value calculated for the case of avulsion may slightly exceed the absolute maximum of discharges in the paleochannel. Its probability is 1 - 2 times during the lifetime of the channel. The lifetime of the paleochannel can be calculated using the model of meander formation. The rate of the deflection angle $\Theta$ change through time $t$ can be calculated with the formula (Sidorchuk, 1996):

$$\frac{\partial \Theta}{\partial t} = \frac{K_e}{L} \frac{J_0^2}{J_0 \frac{\partial H_0}{\partial \Theta} - H_0 \frac{\partial J_0}{\partial \Theta}} \sqrt{Q_m S} \qquad (6)$$

Here $L$ is meander wavelength, $J_0$ is Bessel function of zero order, $H_0$ is Struve function of the zero order, and $Qm$ is mean maximum discharge. The empirical coefficient $K_e$ was calibrated with the data from the Yana River (East Siberia). The meanders of the main river branch within its delta have same length as those of the Khoper paleochannel. They develop in sandy alluvium cemented by permafrost, which is similar to the conditions of the Khoper River paleochannel formation. According to $^{14}$C dating, development of one of the omega-like meanders in the Yana River delta took 840 years (Sidorchuk, 1976). That gives us $K_e = 25$ (if $t$ is measured in years). The lifetime of the Khoper River paleochannel calculated with this coefficient was about 500 years, so the probability $P_m$ of the maximum discharge of 13,200 m$^3$/s was 0.002.

*Mean maximum discharge*

From the given maximum discharge and its probability all other maximum discharges and their probabilities $P$ can be calculated. For such calculations a gamma-distribution of probability density is usually used (Evstigneev, 1990):

$$\frac{dP}{dQ} = \frac{\alpha^{\alpha}}{\Gamma(\alpha)} K^{\alpha-1} \exp(-\alpha K) \qquad (6)$$

$$\alpha = 1/C_v^2; K = Q/Q_m$$

Here $\Gamma$ is gamma-function. The variability coefficient $C_v$ for the Khoper River paleochannel can be estimated from the fluvial analogues both in the north-eastern Kazakhstan and in Bol'shezemel'skaya tundra according to the principle of paleogeographical analogy. For the conditions of the Khoper paleochannel the coefficient $C_v$ =0.3, and calculated mean maximum discharge $Q_m$ is 5,800 m$^3$/s for $P_m$=0.002.

*Mean annual discharge.*

Mean annual discharge can be determined from the above-calculated maximum discharges and their probabilities for the paleochannel, and parameters of the distribution curve for daily discharges of the fluvial analogues. A Gudrich curve is usually used for these calculations (Aver'yanov, 1953):

$$P = 1.0 - 10^{cY^N}$$

$$Y = \frac{Q_m - Q_s}{Q_s - Q_{\min}} \qquad (7)$$

Parameters of the Gudrich curve $c$ and $N$ for the Khoper River paleochannel can be estimated from the fluvial analogues in Bol'shezemel'skaya tundra according to the principle of paleogeographical analogy. For the conditions of the Khoper River paleochannel the coefficient $c$ is 0.017, coefficient N is 0.72 . The calculated mean annual discharge $Q_s$ is 450 m$^3$/s for $Q_m$=5800 m$^3$/s.

*Parameters of a spring flood*

The mean volume of flow during a spring flood can be determined from the above-calculated maximum discharges, their probabilities for the paleoriver and parameters of the flood wave shape for the fluvial analogues. A flood wave can be described with the formula (Evstigneev, 1990):

$$y = 10^{-a\frac{(1-x)^2}{x}} \qquad (8).$$

Here $y = Q_i \big/ Q_{\max}$; $x = t_i / t_u$. Coefficient $a$ and the time of the flood rise $t_u$ are related to the shape of the flood wave, from the rivers-analogues in Bol'shezemel'skaya tundra their values are 0.02 and 6 days respectively. The calculated average flow volume $V$ for a spring flood period is 10 $10^9$ $m^3$ for above used conditions of the maximum flow.

*Precipitation*

Precipitation $p$ (mm) can be determined from the calculated mean annual discharge or flood volume for paleochannel and runoff coefficients $K_R$ of the fluvial analogues as follows.

$$p = k\frac{X}{K_R B_a} \qquad (9)$$

Here $B_a$ is the paleoriver basin area (km$^2$). Coefficient k equals 31,536 for the case of mean annual discharge $X$=$Q_s$, and is 0.001 in the case of flood volume $X$=$V$.

The runoff coefficients for the flood period and for the year were calculated for the rivers in contemporary arctic environments: the Yamal Peninsula in Siberia and the Bol'shezemel'skaya tundra in the northern Russian Plain. During the spring flood the ground there is completely frozen, so that the runoff coefficient is close to 1.0. For the year the runoff coefficient value is about 0.9. The calculations show that the mean annual precipitation there was approximately 830 mm, and winter precipitation forming the volume of spring flood was about 520 mm (63% of the annual) during the Khoper paleochannel formation.

Calculations show, that 11-12 thousand years ago the mean maximum discharge of paleo-Khoper was about 5,800 m$^3$/s, mean annual discharge was 450 m$^3$/s, the runoff depth reached 750 mm and rainfall depth was 830 mm (Table 3).

Table 3. Characteristics of present and past Khoper River

| | Present | Late Glacial | LG/P ratio |
|---|---|---|---|
| Basin area | 19100 | 19100 | ~1.0 |
| Absolute maximum discharge m$^3$/s | 2140 | 13190 | ~6 |
| Mean maximum discharge m$^3$/s | 991 | 5800 | ~6 |
| Mean annual discharge m$^3$/s | 67.8 | 450 | ~7 |
| Runoff coefficient | 0.2 | 0.9 | ~4.5 |
| Annual precipitation mm | 460 | 860 | ~2 |
| Channel width (bankfull) m | 60 | 1400 | ~25 |
| Channel mean depth (bankfull) m | 2.1 | 5.1 | ~2.5 |
| Meander length m | 360 | 2500 | ~7 |
| Channel slope m/km | 0.063 | 0.154 | ~2.5 |
| Bed load mean diameter mm | 0.5 | 0.49 | ~1.0 |
| Channel roughness (Manning coefficient) | 0.0287 | 0.0287 | ~1.0 |

The main cause of the paleochannel formation at a discharge 6-7 times more than recent one, when rainfall increased only two times, is periglacial conditions with huge permafrost and very sparse vegetation.

## DISCUSSION AND CONCLUSION

One of the main applications of paleohydrology is the quantitative reconstruction of paleohydrological features. In the hydraulic approach only few parameters can be calculated with some level of accuracy, such as the bankfull discharge or maximum discharge. For calculation of the majority of paleohydrological and paleoclimatological characteristics it is necessary to use the paleogeographical analogy

A general procedure of quantitative paleohydrological reconstructions with the use of paleogeographical analogy is now supplied with a system of methods, which allow calculating a wide range of paleohydrological parameters. This procedure include estimation of:

- paleochannel cross-section shape;
- paleochannel longitudinal slope and roughness;
- stage - discharge relationship;
- paleolandscape situation of the paleochannel formation;
- present-day analogue of the paleolandscape;
- maximum water stage in the past;
- maximum discharge;
- probability of the maximum discharge;
- mean maximum discharge;
- mean annual discharge;
- volume of flood;
- winter and annual precipitation;
- other paleohydrological characteristics, which can be determined from the fluvial analogues.

The accuracy of calculations in the frame of this procedure is relatively high. For example, the calculated mean annual discharge for the present Khoper River near Povorino (taken as a paleochannel) was 55 $m^3$/s compare to the observed one of 68 $m^3$/s. Main errors in paleohydrological reconstructions are caused by the inaccuracy of the proxy data.

The accuracy of geomorphological reconstructions depends on the degree of preservation of the paleochannel under investigation. The main errors in hydraulic calculations are related to uncertainty of geomorphic interpretations and of the hydraulic methods. One of the main problems for modern hydraulics is the accurate estimation of channel roughness, the latter being an important parameter in calculation of the stage - discharge relationship. Channel bottom roughness can significantly vary through time (table 2) even at one cross-section of the river, causing variability in calculated discharge (fig.3).

Reliability of paleolandscape reconstructions and the choice of the recent analogues depend mainly on the results of detail study of fossil flora by pollen and/or plant macrofossils, preferably at the taxonomic level of species. The list of species, which can be determined by pollen analysis, includes about 100 plants (Grichuk, 1989). Usually a fossil flora consists of 20-30 taxa. Sometimes it is not sufficient to determine a region of the present-day maximum concentration of the fossil flora. This region, when determined, can represent only a partial analogue of the paleolandscape due to a great difference between present interglacial and past late glacial environment. For example, there is no permafrost now at the north-eastern Kazakhstan - the regional analogue for the paleolandscape of Khoper valley 11,900 yr. BP. In such a case several regions have to be used as a complex recent analogue of the paleolandscape.

Within the region-analogue the hydrological parameters of river flow may vary randomly from place to place due to local differentiation of flow generation conditions. This variability also decreases the level of accuracy of paleohydrological reconstructions. The relative errors in calculations of the hydrological parameters of the modern rivers with the use of their modern analogues are mainly within ±10%, and up to 40%. Relative errors of the palaeohydrological reconstructions are probably closer to the upper limit of this interval. The method of paleohydrological analogues can be applied with better results in case of conspicuous difference between the present and past hydrological features of the landscapes.

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## References

Aver'yanov, V.G. (1953). *Vnutrigodovoye Raspredeleniye Rechnogo Stoka,* 328 p. Gidrometeoizdat, Leningrad.

Baker, V.R. (1973). Paleohydrology and sedimentology of Lake Missoula Flooding in Eastern Washington. *The Geol. Soc. Am., Special Paper* 144

Baker, V.R., Benito, G., Rudoy, A. (1993). Paleohydrology of Late Pleistocene Superflooding, Altay Mountains, Siberia. *Science,* 259, 348-350.

Chow, V.T. (1959). Open-channel Hydraulics, McGraw-Hill, New York, 110-113.

Davis, W.M. (1896). The Seine, the Meuse and the Moseile. *National Geographical Magazine,* 7, 189-238

Dury, G.H. (1964). Principles of underfit streams. *US Geological Survey Professional Paper* 452-A, Washington.

Dury, G.H. (1965). Theoretical implications of underfit streams. *US Geological Survey Professional Paper* 452-B, Washington.

Dury, G.H. (1983). Osage-type underfitness on the River Severn near Shrewbury, Shropshire, England. *In*: K. Gregory (Ed), *Background to Palaeohydrology,* pp. 399-412. John Wiley and Sons, Chichester.

Evstigneev, V.M. (1990). *Rechnoi Stok i Gidrologicheskiye Raschety*. Izdatelstvo Moskovskogo Universiteta, Moskva, 304 p.

Glushkov, V.G. (1933). Geographical and hydrological method. *Izvestiya GGI*, 57, pp. 89-95.

Grichuk, V.P. (1969). An attempt of reconstruction of certain climatic indexes of the Northern Hemisphere during the Atlantic stage of the Holocene. *In*: Neustadt, M.I. (ed.), *Golotsen*, pp. 41-57. Nauka, Moskva.

Grichuk, V.P. (1985). Reconstructed climatic indexes by means of floristic data and an estimation of their accuracy. *In*: Velichko, A.A. and Gurtovaya, Ye.Ye. (eds), *Metody Rekonstruktsii Paleoklimatov*, pp. 20-28. Nauka, Moskva.

Grichuk, V.P. (1989). *Istoriya Flory I Rastitel'nosti Russkoi Ravniny v Pleistotsene,* 183 p. Nauka, Moskva.

Karaushev, A.V. (1969). *Rechnaya Gidravlika*. Gidrometeoizdat, Leningrad.

Leliavsky, S. (1955). *An Introduction to Fluvial Hydraulics*. London.

Maizels, J.K. (1983). Palaeovelocity and palaeodischarge determination for coarse gravel deposits. *In*: Gregory, K. (Ed), *Background to Palaeohydrology*, pp. 101-139. John Wiley and Sons, Chichester.

O'Connor, J. and Webb R.H. (1988). Hydraulic Modeling for Paleoflood Analysis. *In*: Baker, V.*et al*. (eds), *Flood Geomorphology*, pp. 393-402. John Wiley and Sons, Chichester.

Rotnicki, K. (1983). Modelling past discharges of meandering rivers. *In*: Gregory, K. (Ed), *Background to Palaeohydrology*, pp. 321-354. John Wiley and Sons, Chichester.

Rotnicki, K. (1991). Retrodiction of palaedischarges of meandering and sinuous rivers and its palaeoclimatic implications. In*:* Starkel, L. *et al*. (eds), *Temperate Palaeohydrology*, pp. 431-470. John Wiley and Sons, Chichester.

Schumm, S.A. (1965). Quaternary Palaeohydrology. *In*: Wright, H. and Frey, D. (eds), *The Quaternary of the United States*, pp. 783-794. Princeton University Press, Princeton.

Schumm, S.A. (1968). River adjustment to altered hydrologic regimen - Murrumbidgee River and palaeochannels, Australia. *US Geological Survey Professional Paper 598*, Washington.

Shamov, G.I. (1954). *Rechnye Nanosy*. Gidrometeoizdat, Leningrad.

Sidorchuk, A.Yu. (1976). The main stages of the Yana River delta evolution. *In*: Ivlev, A. (Ed), *Geomorfologiya i Paleogeografiya Dal'nego Vostoka*, pp. 166-180. Khabarovsk.

Sidorchuk, A. (1996). The structure of river bed relief. *In:* Ashworth, P. *et al.* (eds) *Coherent flow structures in open channels*, pp. 397-421, John Wiley and Sons, Chichester.

Starkel, L. and Thornes, J.B. (1981). Palaeohydrology of river basins. *Technical Bulletin* 28, British Geomorphical Research Group.

Starkel, L. (1995). The place of the Vistula River valley in the late Vistulian - early Holocene evolution of the European valleys. *In*: Frenzel, B. (Ed), *European River Activity and Climatic Change During the Lateglacial and Early Holocene*, pp. 75-88. Gustav Fischer Verlag, Stuttgart.

Szafer, W. (1946). Flora pliocenska w Kroscienku nad Dunajcam. *Rozprawy Wydzialu Matematyceno-przyrodniczego*, Polska academia nauk, 72 (B. 1-2), 98 p.

Velichko, A.A., Berdnikov, V.V., Nechaev, V.P. (1982). Reconstruction of the permafrost zone and stages of its development. *In*: Gerasimov, I.P. and Velichko, A.A. (eds), *Paleogeography of Europe during the Last One Hundred Thousand Years (Atlas-Monograph)*, pp. 74-81. Nauka, Moskva.

Velichko, A.A. (1981). Regarding the question of the sequence and principal structure of the main climatic rhythms of the Pleistocene. *In*: Velichko, A.A. and Grichuk, V.P. (eds), *Voprosy Paleogeografii Pleistotsena Lednikovykh i Periglyatsialnykh Oblastei*, pp. 220-246. Nauka, Moskva.

Williams, G.P. (1978). Bankfull discharges of rivers. *Water Resourses Research*, 14, 1141-1154.

Williams, G.P. (1988). Paleofluvial Estimates from Dimensions of Former Channels and Meanders. *In:* V.Baker *et al.* (eds), *Flood Geomorphology*, pp. 321-334. John Wiley and Sons, Chichester.