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The Large Rivers of the Past in West Siberia: Unknown Hydrological Regimen

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Abstract: The hydrological regime of large meandering rivers of the West Siberian Plain in the Late Pleniglacial/Late Glacial was reconstructed from the hydraulic geometry of palaeochannels. The main tools for the reconstruction were the power law relationship between channel bankfull width and mean maximum discharge, taken in the downstream direction, and relationships between peak flood discharge and the contributing basin area. Reconstructed values of daily maximum surface runoff depth during the snow thaw period in the Late Pleniglacial/Late Glacial were 60–75 mm/day in the north of the plain with tundra and sparse forest and 20–40 mm/day in the south with periglacial steppe. The mean daily maximum surface runoff depth for the entirety of West Siberia was about 46 mm, which is more than five times greater than the modern value. Annual river runoff was calculated with the ratio between mean annual and mean maximum runoff depths, estimated for the modern region's analogues of ancient periglacial landscapes and climates. Total annual flow of the Ob into the ocean was about 1000 km^3. This is three times the current flow from the same basin, so the river was a significant source of fresh water to the Arctic Ocean during the last deglaciation.

Keywords: paleohydrology; large meandering rivers; Late Pleniglacial; Late Glacial; maximum daily runoff depth; mean annual runoff

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1. Introduction

Large meandering rivers of the past were discovered in the late 19th century [1,2]. Their channels were significantly larger than the modern ones in the same drainage basins. Initially, the origin of these large rivers was explained by the local factors: an existence of lakes in river valleys or river piracy. In the 1950s to the 1960s, after the works of Dury [3–5], Schumm [6,7] and Volkov [8,9], it became clear that this phenomenon has a global distribution and is due to global climatic conditions that differed from modern ones. These authors founded the quantitative paleohydrology, mostly based on morphological indicators in hydrology. Three main ways of palaeohydrological reconstruction were used:

1. Calculating the discharge in a paleoriver from paleoclimatic reconstructions with water budget equations.
2. Calculating the flow velocity and discharge in a paleoriver for a given level based on the cross-section geometry and the paleoriver slope and bed resistance to flow.
3. Calculating the flow discharge of a certain return period based on hydraulic geometry of the paleochannel.

The fourth method is based on the relationship between bedload grainsize and critical velocities of particles' movement initiation [10] and is used to estimate the flow velocity in a paleoriver [11]. All of these methods have been widely discussed and applied to river discharge reconstruction around the world [12–20]. As a result, such paleohydrological characteristics as the mean maximum and mean annual discharge were obtained.

These quantitative estimations of paleodischarges of former large rivers were calculated to be much larger than discharges of the modern rivers in the same basin. Dury listed the possible causes of this phenomenon. He wrote [5] (p. 15):

> *"The former discharges presumably represent the sum effect of a combination of causes. Since underfit streams are distributed on a continent-wide scale, they require changes in climate. The separate factors most likely to have operated in former times to promote high discharges are:*

1. *Reduced air temperature*
2. *Increased total precipitation*
3. *Changed regimen of precipitation*
4. *Increased extent of frozen ground*
5. *Changed regimen of runoff*
6. *Increased size of individual rains*
7. *Increased frequency of storms*
8. *Increased wetness of soil*
9. *Changed vegetation cover.*

> *Some of these possibilities clearly overlap with, or involve, others. Changes in vegetation are implied in reductions of air temperature. Wetness of soil must be affected by changes in amount and frequency of precipitation. Changes in regimen of precipitation lead to changes in both regimen and total of runoff".*

This list, compiled more than 60 years ago, is the definite program of investigations in quantitative paleohydrology and is not yet realized completely. Convenient space for such investigations is the lowlands of the Northern hemisphere, particularly the West Siberian Plain with numerous remnants of large meandering paleochannels. In order to carry out the research program outlined by Dury, in this article, we analyze the distribution and size of the paleorivers in the West Siberian Plain, the morphological indicators in hydrology (hydraulic geometry of the paleochannels), the past hydrological regime and the geographical distribution of mean maximum runoff depths in the basins of these paleorivers. The way to estimate the annual runoff from the Ob River basin is also proposed. We use here a novel approach to calculating discharge of paleorivers and discuss its difference from and similarity to the purely empirical method used in previous publications [14–18].

2. Materials and Methods

2.1. General Information

The West Siberian Plain occupies the northwestern part of Asia. General information on the region is available from the National Atlas of Russia [21]. The plain with the area over 3 million km^2 is bounded by the Ural Mountains in the west, by the Yenisei Upland in the east, by the Altai Mountains and Kazakh Hills from the south and by the coast of the Kara Sea in the north. The plain is divided into two parts by a low latitudinal ridge of Sibirskiye Uvaly (the Siberian Ridge) reaching 120–240 m above sea level (a.s.l.). Inland depressions with elevations of less than 100 m a.s.l. are located south of Sibirskiye Uvaly, and coastal lowlands descend toward the Kara Sea coast to the north of the ridge. The plain is drained by the Ob River with tributaries, as well as by Taz, Pur and other rivers flowing into the Ob Gulf, with the total mean annual runoff about 600 km^3. The mean July air temperature increases from the north to the south from 5 °C to 20 °C, and that of January increases from the northeast to the southwest of the plain from −26 °C to −18 °C. The annual precipitation is about 500–600 mm at Sibirskiye Uvaly, dropping to 300 mm both to the north and to the south. The northern part of the plain is occupied by tundra and sparse forest with continuous deep permafrost; its middle part is covered by boreal forest (taiga), partly with discontinuous permafrost, and the southern region of the plain is covered by forest–steppe and steppe.

2.2. Large Ancient Meandering Rivers in the West Siberian Plain

More than 60 well-preserved fragments of large paleochannels within the West Siberian Plain provide the basis for paleohydrological investigations (Figure 1, Table S1). Volkov [8,9] discovered and investigated several such paleochannels in the southern part of the plain approximately at the same time, when Dury [5] and Schumm [7] investigated the paleorivers in the North America and Australia. Volkov achieved the same conclusion: the causes of large rivers formation were climatic changes, and one can estimate these changes from the morphology of paleochannels.

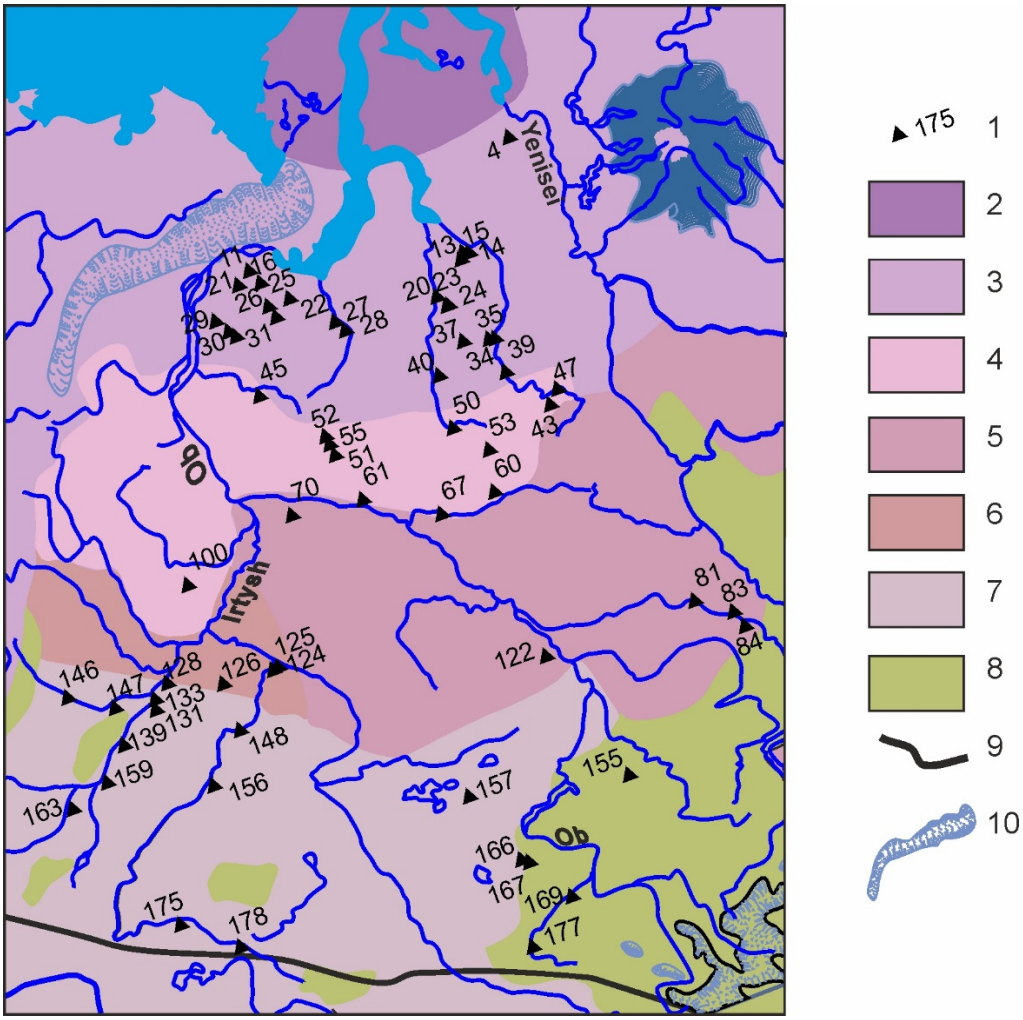


Figure 1. The distribution of well-preserved fragments of large paleochannels of the Pleniglacial age in the West Siberian Plain. 1—data points (Table S1). Vegetation during the Pleniglacial (adapted from [22]); 2—arctic desert; 3—moss and dwarf shrub tundra; locally with birch and spruce open woodlands; 4—spruce and birch open woodlands; 5—meadow steppe with birch and spruce forests and tundra communities; 6—meadow steppe in combination with pine forests; 7—sagebrush–grass and sagebrush–saltwort steppes; 8—pine, spruce and birch forests with steppe communities; 9—southern boundary of continuous permafrost; 10—mountain glaciers.

These large rivers drained periglacial landscapes with continuous permafrost. There are not many dated large paleochannels in Europe [23], and only four dates are available in West Siberia [16,24]. These dates show that large paleorivers were active in the Late Pleniglacial and Late Glacial time. The most favorable climatic conditions for large rivers formation were at the transition from cold and dry to milder and wetter climate. Such

conditions occurred at the transition from the Last Glacial Maximum to the Raunis Interstadial, 16–18 cal ka BP, and at the transition from the Oldest Dryas to Bølling, 13–14 cal ka BP [23].

The large rivers had meandering patterns. The main geometry characteristics of the paleochannels on the plane are the meander wavelength *L* and the width *W*, which can be measured on the space images. The measurement procedure and the related errors were described in [16,17]. The mean wavelength/width ratio of ancient meanders is 11.9, which is similar to that of the meanders of the modern rivers within the same basins—12.6 (Figure 2). This similarity in the morphology indicates a similarity of origin: the meanders of the paleorivers were formed in the same way, as the meanders of modern alluvial rivers and their characteristics can be used in paleohydrological reconstructions.

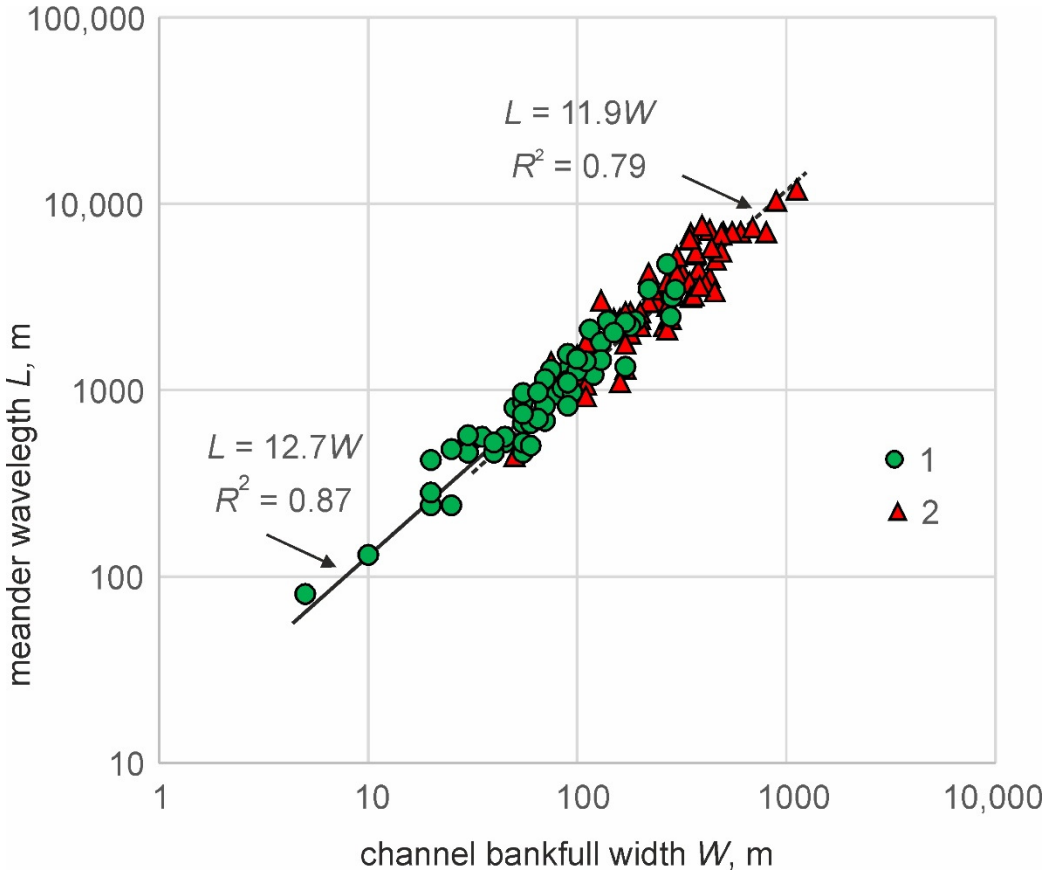
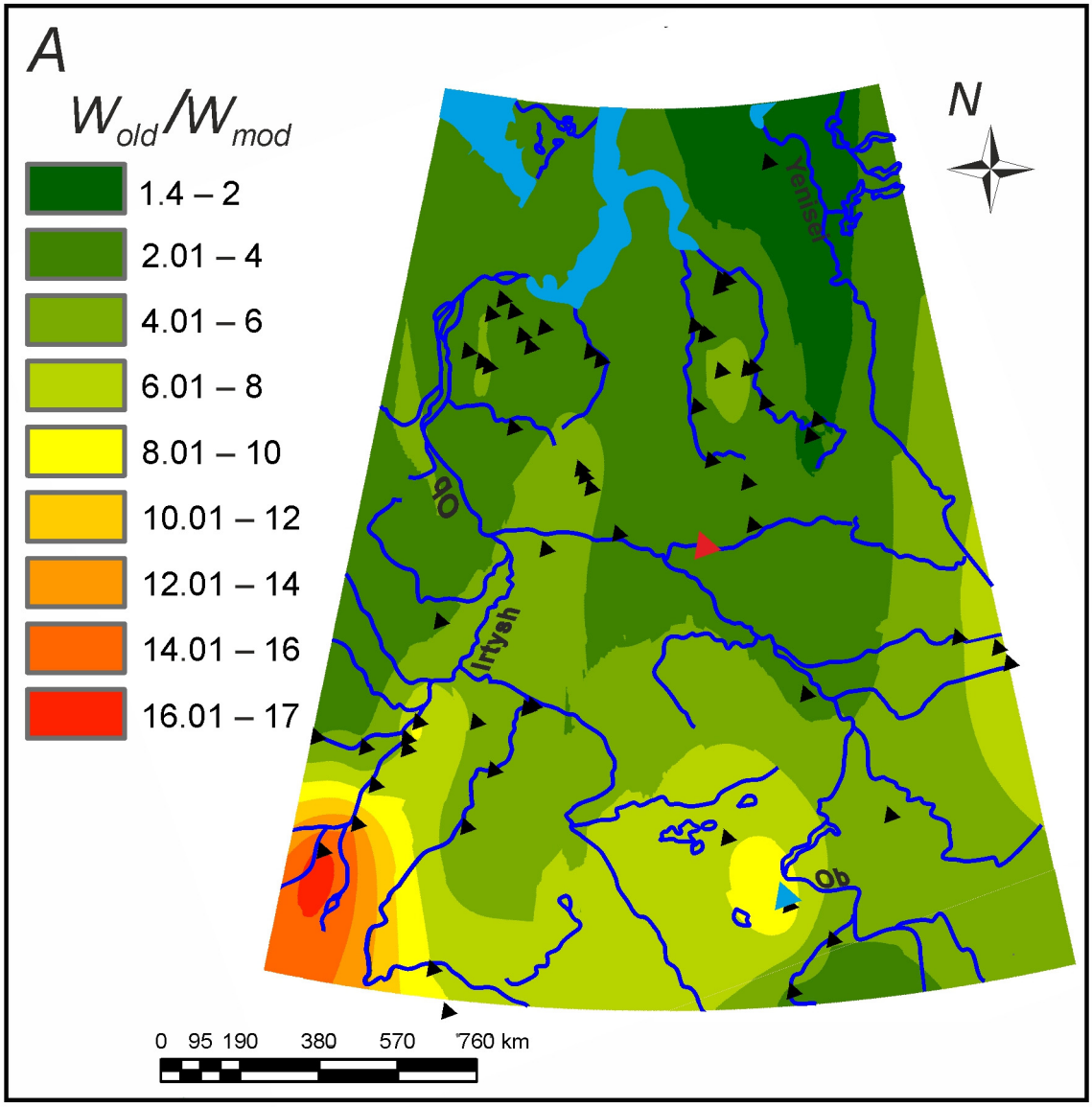


Figure 2. The relationship between the channel widths and meander wavelengths for the modern channels (1) and large paleochannels (2) in West Siberia. The data were adopted from [25] with corrections.

In the West Siberian Plain, the ratios of the widths of large paleochannels (W_{old}) and modern (W_{mod}) channels within the same stretch of a river valley change from the minimum values of 1.4–1.5 in the northeast of the plain to the maximum of 16.3 in the southwest (Figure 3). These significant differences in river channel morphology indicate differences in hydrologic regime of channel-forming flows.


A
W_{old}/W_{mod}
1.4 – 2
2.01 – 4
4.01 – 6
6.01 – 8
8.01 – 10
10.01 – 12
12.01 – 14
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Irtysh
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0 95 190 380 570 760 km

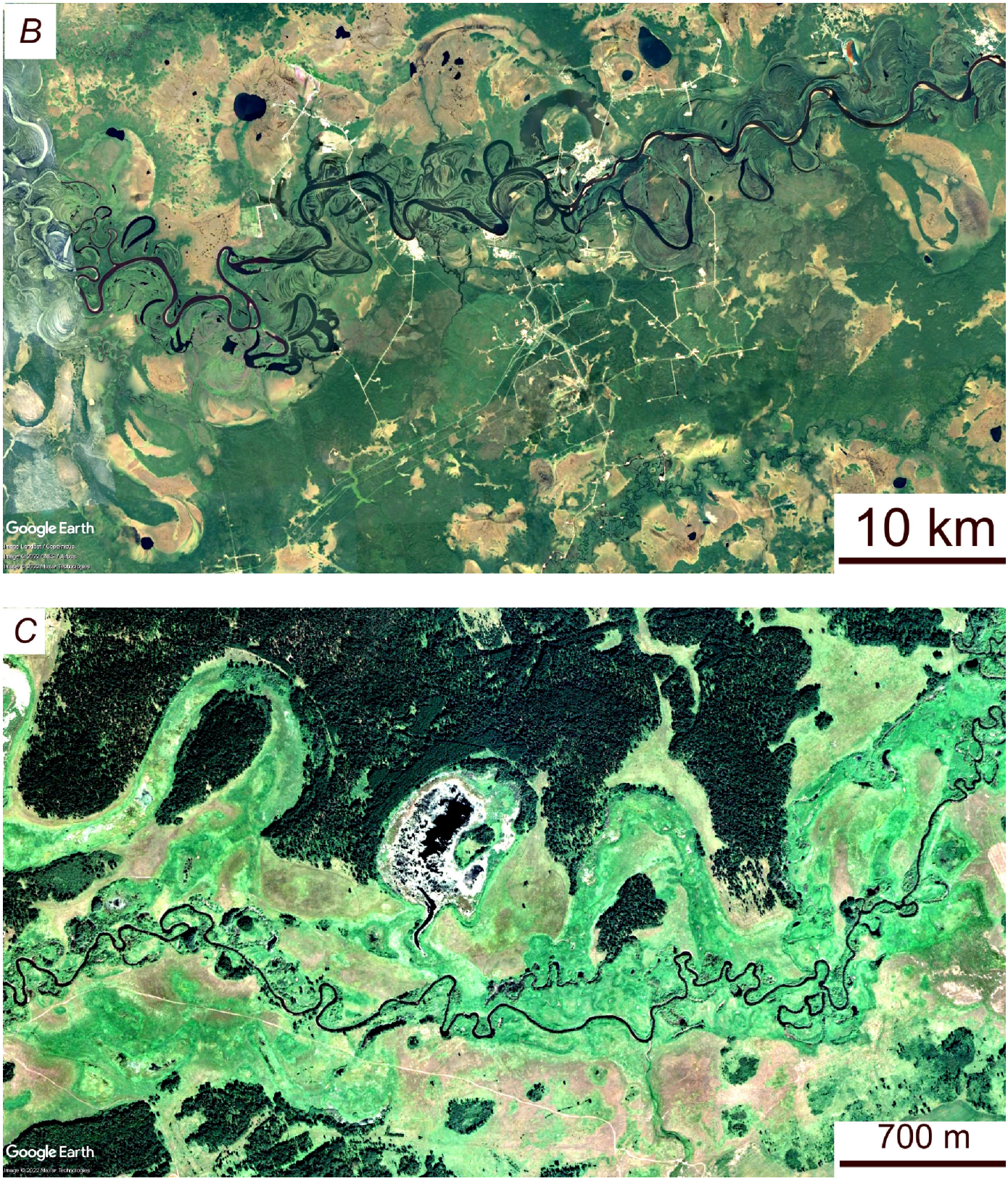

Figure 3. (**Panel A**): The ratios of the widths of large paleochannels (W_{old}, m) and modern channels (W_{mod}, m) within the same stretches of river valleys (Table S1); positions of the sites are indicated by black triangles. Typical examples of large paleochannels: for the northern part of the West Siberian Plain—the Vakh River (**panel B**), index 67 in Figure 1, red triangle in (**panel A**); for the southern part of the plain—the Kulunda River (**panel C**), index 166, blue triangle in (**panel A**).

2.3. The Modern Rivers of West Siberia

The modern rivers of West Siberia drain different landscape zones (Figure 4). The northern part of the area is in the cold environment with tundra and northern taiga landscapes with continuous permafrost and middle taiga with discontinuous permafrost. The southern part is permafrost-free with middle–southern taiga and steppe landscapes.

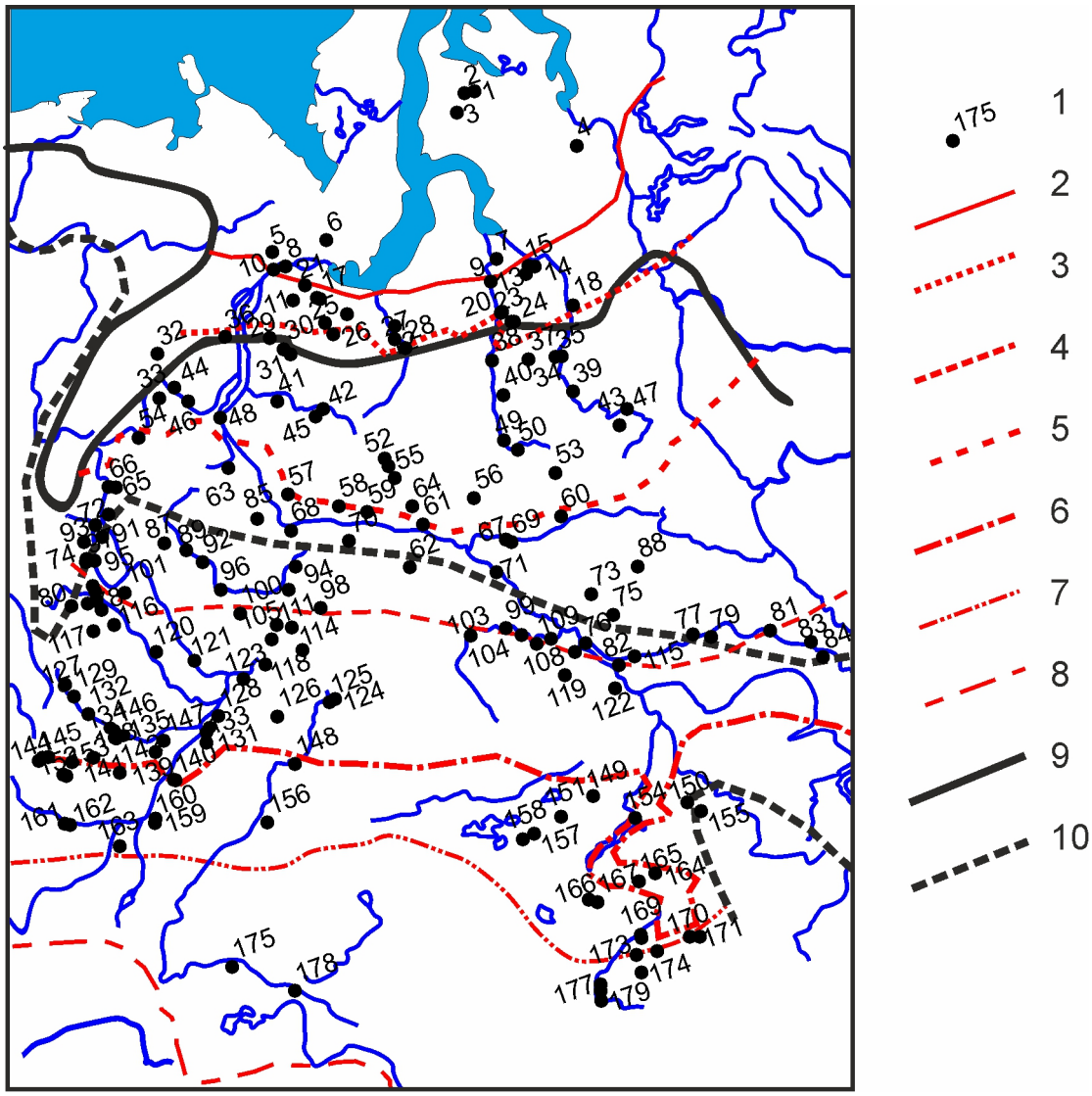

Figure 4. The distribution of hydrologic stations on the West Siberian Plain. 1—data points (Table S2). The southern boundaries of modern vegetation and permafrost zones (adapted from [21]); 2—tundra; 3—sparse forest (forest–tundra); 4—northern taiga; 5—middle taiga; 6—southern taiga; 7—forest–steppe; 8—steppe and Altai piedmont; 9—continuous permafrost; 10—discontinuous permafrost.

For all regions shown in Figure 1, the data are available on basin areas and bankfull widths of the ancient rivers. The database, published in [25], was extended and renewed for this study. For the modern rivers (Figure 4), in addition, mean maximum discharge and mean annual discharges are available. The hydrological information (mean annual and mean flood discharge, basin area) for the modern rivers is available from the State Hydrological Database [26] and published hydrological bulletins [27], as well as from international databases [28]. The bankfull widths were taken from hydrological bulletins [27] and measured on space images of high resolution. The main datasets used in the paper are given in the Supplemental Materials (Tables S1–S4).

2.4. Relationships between River Channel Width and Discharge

The most important tool for palaeohydrological reconstructions is the analysis of river channel hydraulic geometry and development of the regime equations both for modern and ancient rivers.

From a great number of regime equations [29,30], we can use in palaeohydrology only the simplest ones, such as the power law relation between channel width W and flow discharge Q, taken in the downstream direction:

$$W = a_1 Q^{b_1} \tag{1}$$

For downstream hydraulic geometry, channel width and discharge should be chosen for the same water surface profile along the river.

A channel width is quite definite for the bankfull stage, when water fills in the channel but does not inundate floodplain yet. It is believed that the bankfull discharge is close to the channel-forming discharge, and its impact on the channel is equivalent to the impact of the entire range of discharges over a certain period [31]. The return period of bankfull discharge usually varies within 1.2–2 years [32]. Therefore, in the further analysis, the mean maximum (mean annual flood) discharge used is closest to the bankfull discharge.

For the purposes of paleohydrological reconstruction, Equation (1) must be reversed using the initial data of field measurements to obtain an empirical relationship of mean flood discharge from the bankfull width:

$$Q_{max} = a_0 W^{b_0} \tag{2}$$

2.5. Relationships between Mean Maximum Discharge and Basin Area

The regional relationships between maximum discharge and the contributing basin area are widely used to show the differences in hydrological regime in different basins [33]:

$$Q_{max} = a_2 F^{b_2} \tag{3}$$

Equation (3) can be transformed to obtain the formula for the calculation of the mean maximum effective daily runoff depth X_{max}:

$$X_{max} = \frac{Q_{max}}{F+1} = a_2 (F+1)^{(b_2-1)} \tag{4}$$

Here, contributing area F is used with plus one to avoid division by zero. Equation (4) shows that the coefficient a_2 means the effective maximum daily surface runoff depth for a unit basin (including losses and flood wave transformation), and exponent ($b_2 - 1$) is the factor of flood peak routing. This factor is usually close to zero for river basins with areas less than 1000 km^2 in modern periglacial conditions [34] (Figure 5).

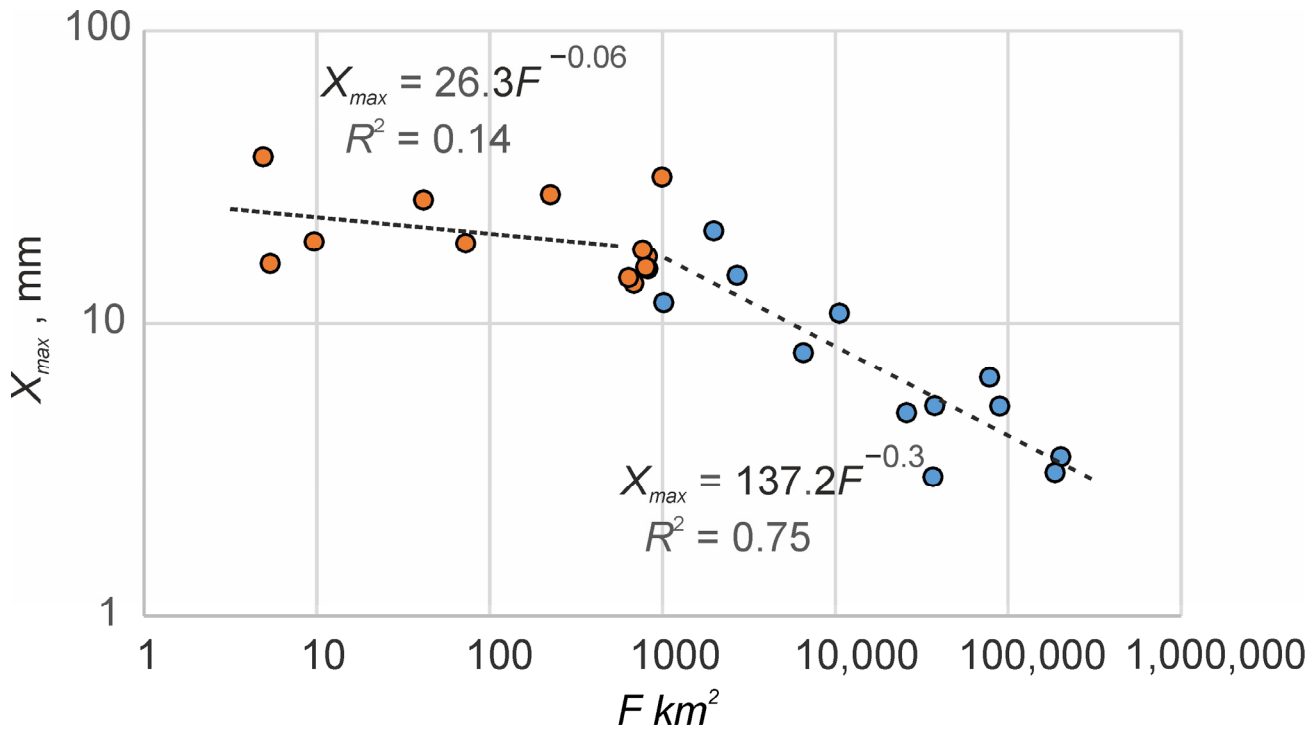

Figure 5. The relationship between effective maximum daily surface runoff depth and the contributing basin area for the Vilyui River basin (East Siberia), with taiga landscapes and deep permafrost. Red circles—basins with areas ≤1000 km², blue circles—>1000 km².

Empirical regime equations are usually derived from a set of measurements for some river basin or territory. Therefore, the exponents b_0 and b_2 in these power law morphometric relationships are regional, averaged for a certain river basin or area. The coefficients a_0 and a_2 in the equations can also be regarded as regional. At the same time, it is possible to estimate these coefficients for each local point of measurements of *Qmax*, *W* and *F* with the regional exponent. Such local coefficients show spatial variability of hydrologic characteristics within a region or a river basin.

3. Results

3.1. The Regime Equation between River Channel Width and Discharge

3.1.1. General Assumptions

The main hypothesis of paleohydrology, already implicitly used in the first works on this topic [5,7], can be formulated as follows: the values of the coefficients and exponents in regime equations derived from measurements for the modern rivers are constants also valid for the ancient rivers. This hypothesis was never proved but is broadly used [23], especially in the case of Equation (2). For the further reasoning, there is a need to investigate this hypothesis. For this purpose, we used three datasets of river channel morphology and hydrology.

The fragments of large paleochannels were formed by the rivers draining periglacial landscapes [23]. Therefore, the first dataset chosen to estimate a coefficient and exponent in Equation (2) contains 40 sections of the modern rivers of East Siberia (the Lena River basin, Table S3) existing in the coldest modern environment with deep permafrost, with tundra and open forest landscapes [26,28]. The exponent b_0 is 1.46 for these rivers, and the coefficient a_0 is 0.8 (open circles in Figure 6).

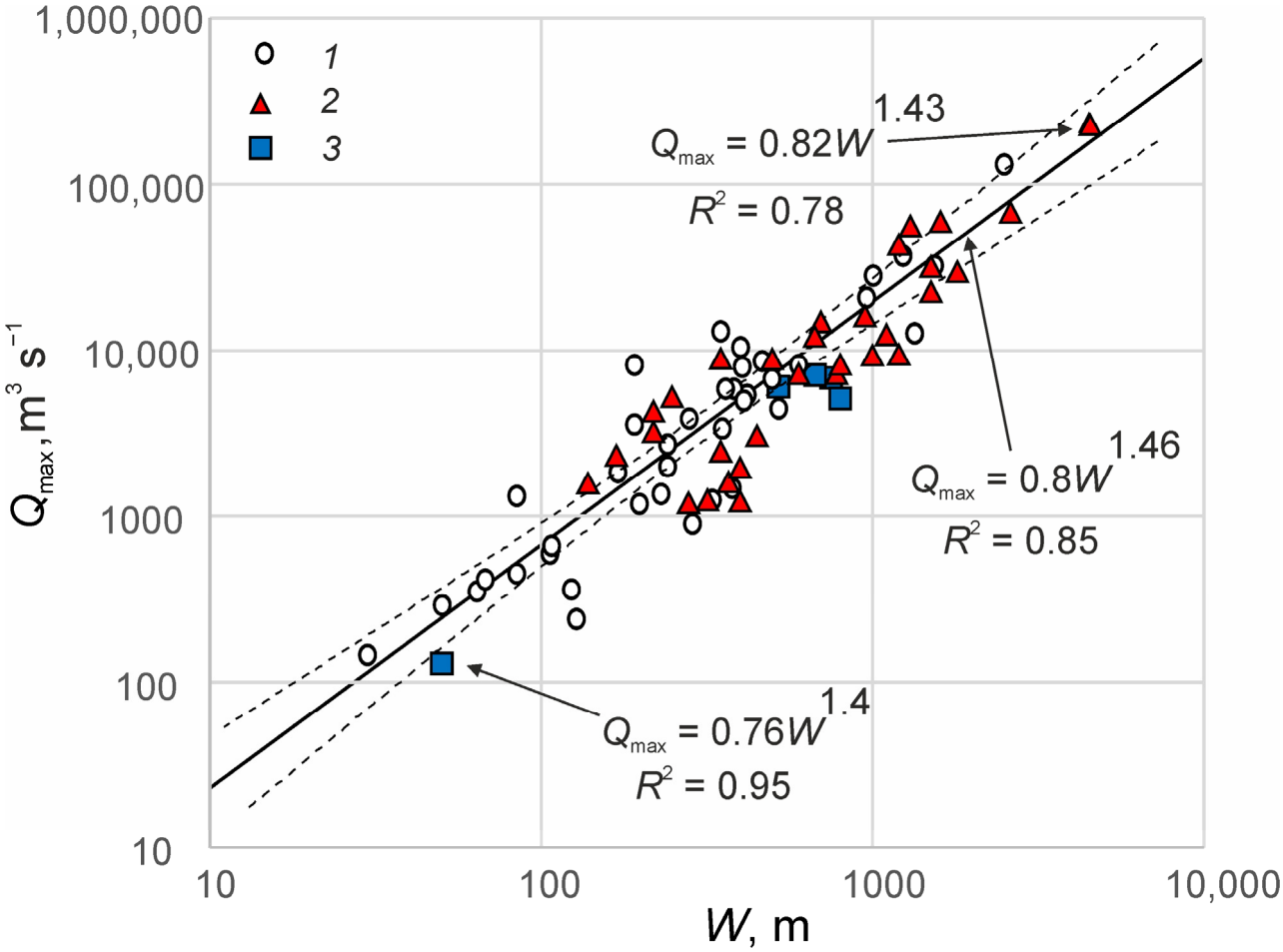

Figure 6. The relationship between the channel bankfull width *W* and mean maximum discharge Q_{max} for the rivers: (1) of the Lena River basin (Table S3), (2) of equatorial zone river basins (Table S4) and (3) of ancient rivers of the Late Pleniglacial age [12,35].

The intra-annual variability of discharges in the rivers of modern periglacial landscapes is very large. For example, the mean maximum discharge of the Lena River at the top of its delta is about 130,000 m^3/s, and the mean annual discharge is about 16,500 m^3/s. The rivers of the second dataset belong to completely different environment: 31 sections of rivers situated in the equatorial zone (mostly of Southern America and Africa) with basin areas >100,000 km^2 (Table S4) [28]. Here, the flow regime is much steadier, and intra-annual variability of discharges is small. For example, the mean maximum discharge of the Amazon River at Obidos–Porto is about 234,000 m^3/s, and mean annual discharge is about 170,000 m^3/s. The exponent b_0 is 1.43 for these rivers, and the coefficient a_0 is 0.83. The data points of the second dataset are mostly within the scatter for the first dataset (red triangles in Figure 6).

These two datasets show the necessity to use the mean flood discharge in Equations (1) and (2). When the mean flood discharge is used (Figure 6), its relationships with the channel width for the rivers of East Siberia and Brazil are similar despite significantly different intra-annual hydrological regime. If the mean annual discharge is used, its relationship with the channel width differs significantly for these two regions (Figure 7), as well as coefficient a_0 and exponent b_0 in Equation (2). Figure 7 shows that channel width is not controlled by mean annual discharge, and close statistical correlation between these variables reflects only the relationship between the mean annual and mean maximum discharges.

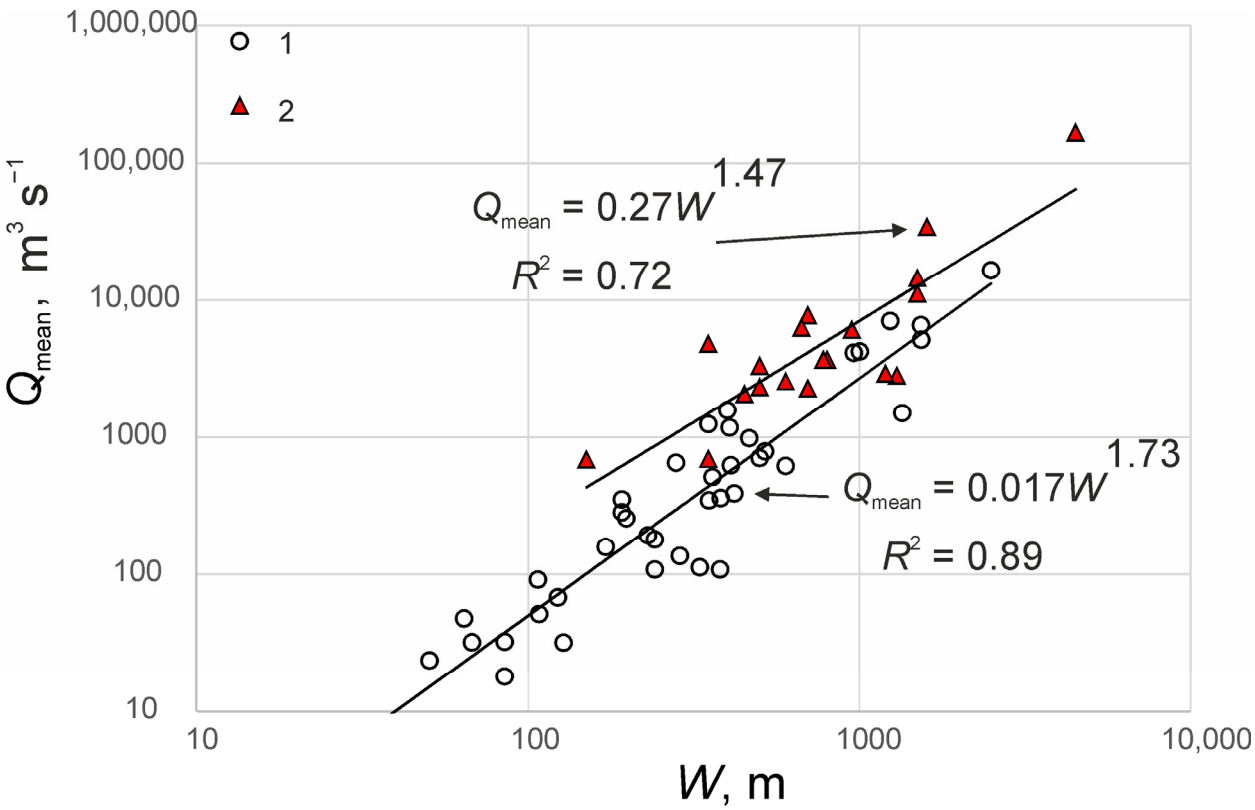

Figure 7. Relationship between bankfull width W and mean annual discharge Q_{mean} for the rivers of the Lena River basin (1) and the Amazon River basin (2).

The coring of paleochannel cross-sections allowed us to measure bankfull width and to calculate bankfull discharge with the Chezy–Manning formula for a few paleorivers of different ages [12,35]. For these rivers, exponent b_0 is 1.4, and a_0 is 0.76, and the data points are also mostly within the scatter for the first dataset (blue squares in Figure 6).

An analysis of these empirical data helps to clarify the main hypothesis: Exponent b_0 and coefficient a_0 in Equation (2) vary in a relatively narrow range for the rivers with different hydrologic regime and of different ages, both modern and ancient. Nonetheless, these parameters have regional values and may vary slightly in different river basins and in different territories.

From this conclusion follows the possibility to estimate the mean maximum discharges of the ancient rivers using their bankfull widths (index "old") along with the coefficient and exponent from Equation (2) for modern rivers (index "mod"):

$$Q_{\max\_old} = a_{0\_mod} W_{old}^{b_{0\_mod}} \quad (5)$$

3.1.2. Equation (2) for the West Siberian Plain

Parameters in Equation (2) were derived using the data on the modern rivers of the West Siberian Plain (Figure 8): a_{0_mod} = 1.14, b_{0_mod} = 1.29. These values differ statistically significantly from those on the Lena River basin (gray lines in Figure 8), showing regional differences in the relationship described by Equation (2). In the Lena River basin, river channels with the same mean maximum discharges are narrower than in West Siberia.

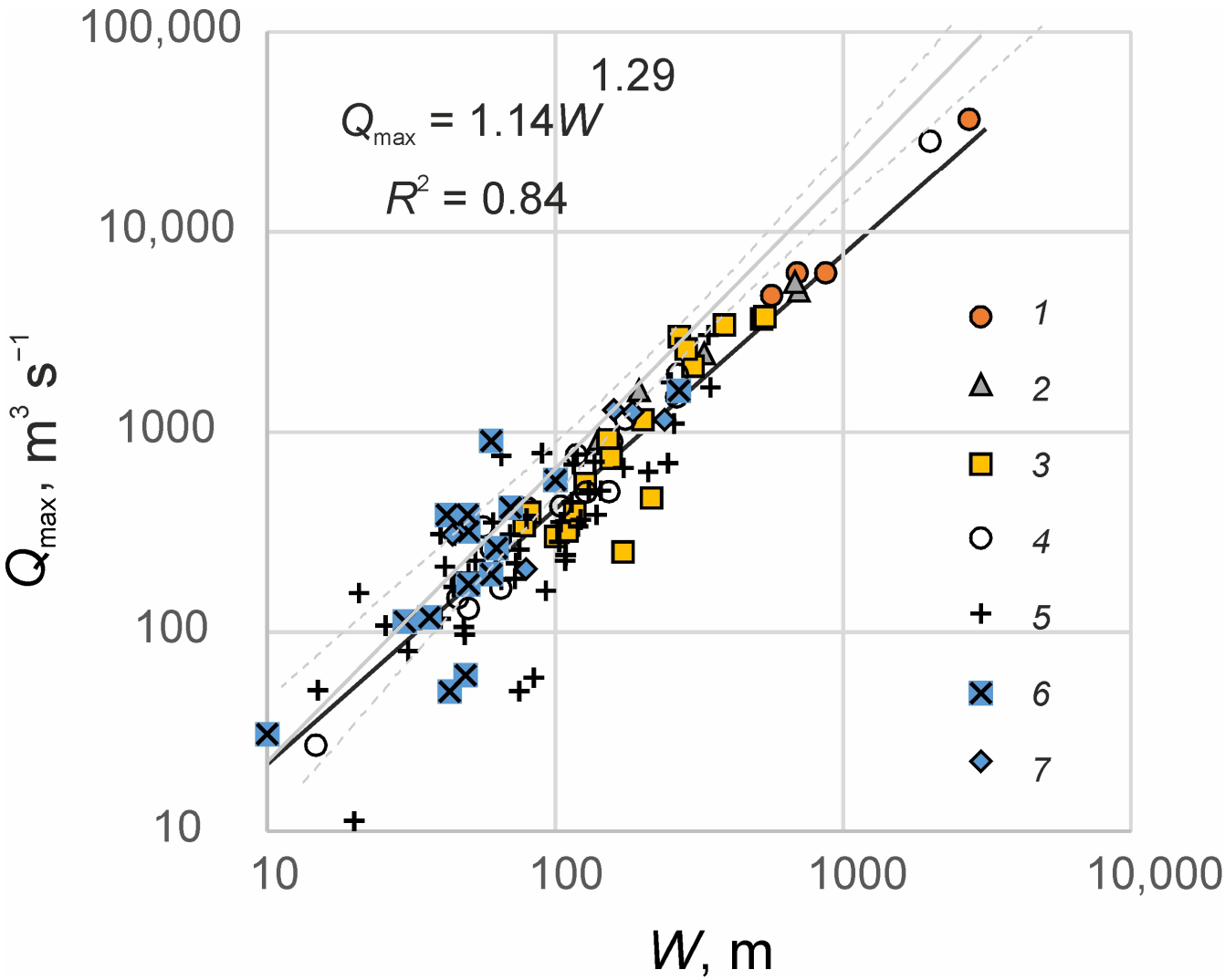

Figure 8. The relationship between channel bankfull width *W* and mean maximum discharge Q_{max} for the rivers of West Siberia. Landscape zones: 1—tundra with continuous permafrost; 2—sparse forest (forest–tundra) with continuous permafrost; 3—northern taiga with discontinuous permafrost; 4—middle taiga with discontinuous permafrost; 5—middle and southern taiga; permafrost-free; 6—forest–steppe; 7—steppe. Gray solid line shows the relationship for the Lena River basin; dashed lines—95% confidence interval (see Figure 6).

Equation (2) can be derived from the formula for the discharge calculation as the product of flow velocity *U*, depth *d* and width *W*:

$$Q = UDW = U\beta W^2 \quad (6)$$

Here, β is the depth/width ratio *d*/*W*. Equation (6) shows that the exponent in Equation (2) is controlled by the change in flow velocity and depth-to-width ratio as flow changes along the river. Flow velocity is nearly constant along large rivers, while the exponent in Equation (2) is mostly controlled by the depth/width ratio decrease with discharge. The ratio of depth to width for the rivers of the Ob basin decreases with discharge according to a power law with an exponent of −0.46 (Figure 9). Such a relationship will give an exponent of 1.3 in Equation (2). This is consistent with the parameters of Equation (2) for the rivers of Western Siberia (Figure 8). The relationship $\beta \sim Q_{max}$ for the rivers of the Lena River basin decrease according to a power law with an exponent of −0.38, which gives an exponent of 1.45 in Equation (2). Therefore, differences in regional values of exponent b_0 in Equation (2) are caused by regional differences in the shapes of cross-sections of river channels and their changes along the river.

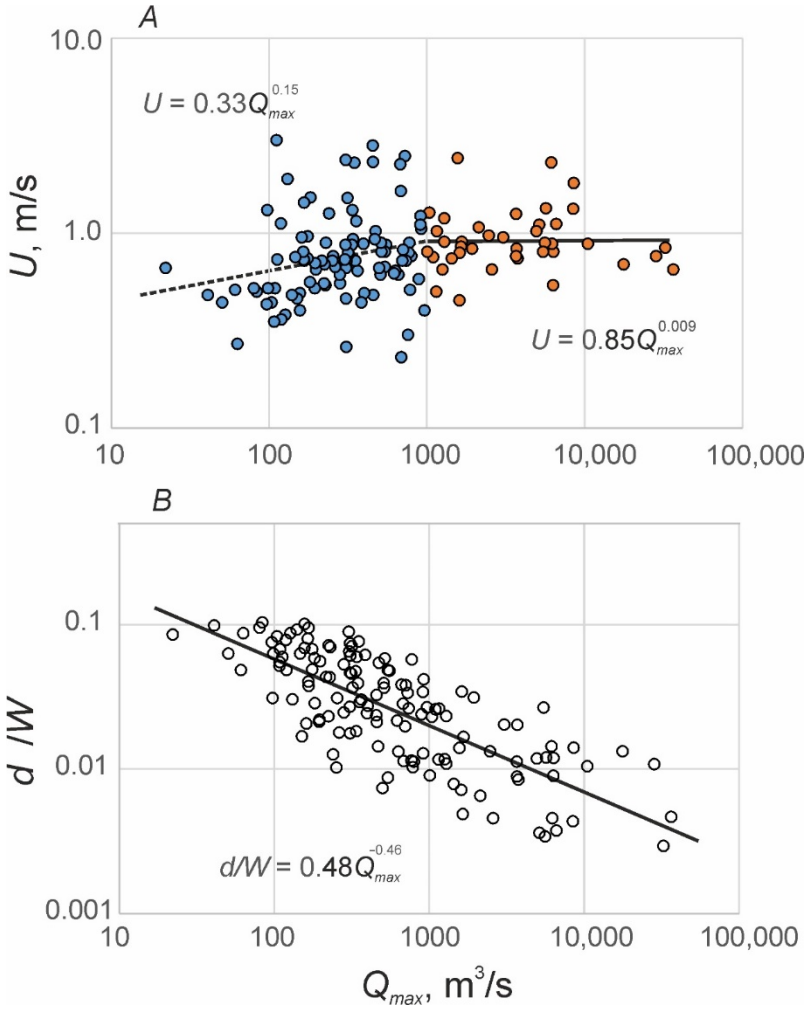

Figure 9. Downstream changes of hydraulic geometry of the rivers of West Siberia with mean maximum discharge Q_{max}: (**A**)—of flow velocity U for the rivers with Q_{max} < 1000 m³/s (blue circles) and Q_{max} > 1000 m³/s (red circles); (**B**)—of depth to width ratio d/W.

Within West Siberia, the measurements on the modern rivers in different landscape zones generally follow the same relationship, with scatter increasing from the north to the south. Therefore, we can assume that these parameters are stable for the entirety of West Siberia. Following the main hypothesis of paleohydrology, regional parameters for the modern rivers of the West Siberian Plain were used for calculating the mean maximum discharges of the ancient rivers for all locations with the measured ancient bankfull widths.

3.2. Relationships between River Channel Width and Contributing Basin Area for West Siberia

3.2.1. The Modern Rivers

Regional relationships between the maximum discharge and contributing basin area (Equation (3)) were derived using information on the modern rivers of West Siberia. The geographically weighted regression (GWR) technic [36] was applied. Landscape zones were taken into account for spatial differentiation between measurement points. Due to the different number of hydrological stations within different landscapes (see Figure 4), some of these zones were combined into larger regions. The resulting global relationships were obtained for two regions, (1) tundra and sparse forest (forest–tundra) with continuous permafrost; (2) taiga, both with permafrost and permafrost-free, followed by forest–steppe and Altai piedmont (Figure 10). Further spatial differentiation in the second region did not lead to statistically significant changes in exponent b_2 in Equation (3).

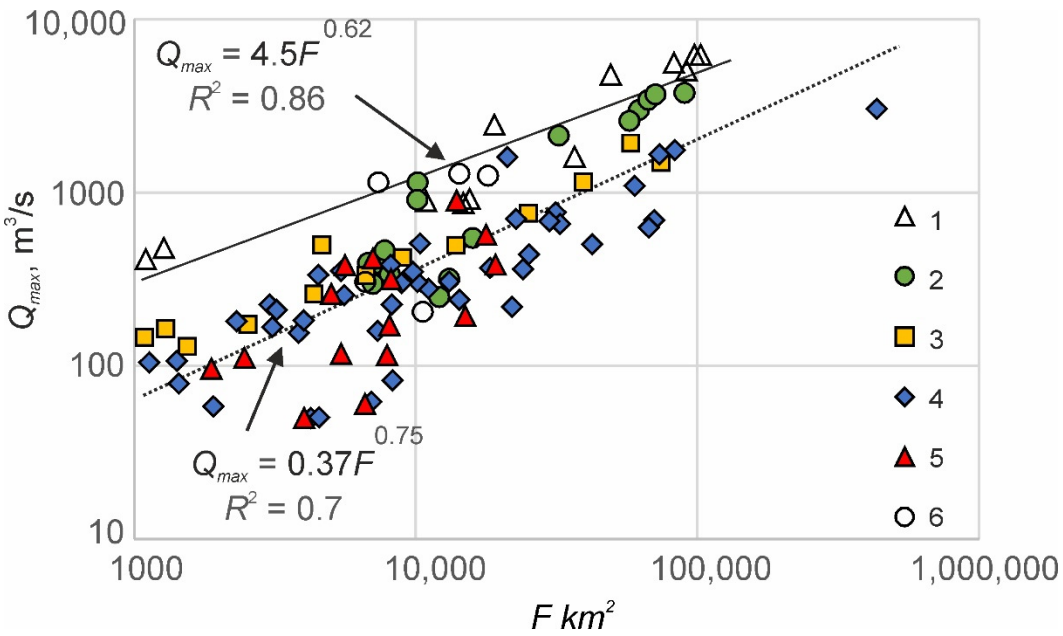

Figure 10. Regional relationships between mean flood discharge Q_{max} and contributing basin area F for the modern rivers of West Siberia. Landscapes: 1—tundra, 2—sparse forest (forest–tundra), 3—northern and middle taiga with permafrost, 4—middle and southern taiga, permafrost-free; 5—forest–steppe and steppe, 6—Altai piedmont.

The mean value of coefficient a_2 in Equation (3) (expressed in m³ s⁻¹ km⁻² in Figure 10), which shows the effective maximum daily surface runoff depth, is lower in the southern region than in the northern one. The exponent b_2, which shows the losses of flood runoff and transformation of the shape of flood wave, increases in the opposite direction. It shows a greater degree of flood wave transformation in the northern (tundra and sparse forest) region.

The scatter around the regional values of a_2 is due to spatial differences in surface runoff formation in different river basins. Being recalculated with Equation (4) for the basin area 1000 km² for each hydrological station

$$X_{\max\_1000} = ka_2 1000^{(b_2-1)} \quad (7)$$

it shows spatial distribution of water input intensity, which forms mostly due to snow thaw processes (Figure 11). Coefficient k=86.4 transfers the units from m³ s⁻¹ km⁻² to mm per day. A noticeable decrease in the effective maximum daily surface runoff depth for a unit basin from north (15–20 mm/day) to south (1–5 mm/day) corresponds to a decrease in its regional values showing more details. The mean value for the entire West Siberian Plain is 8.5 mm per day. As Figure 5 shows, this value of X_{max_1000} for the basin area 1000 km² is also valid for smaller unit basins.

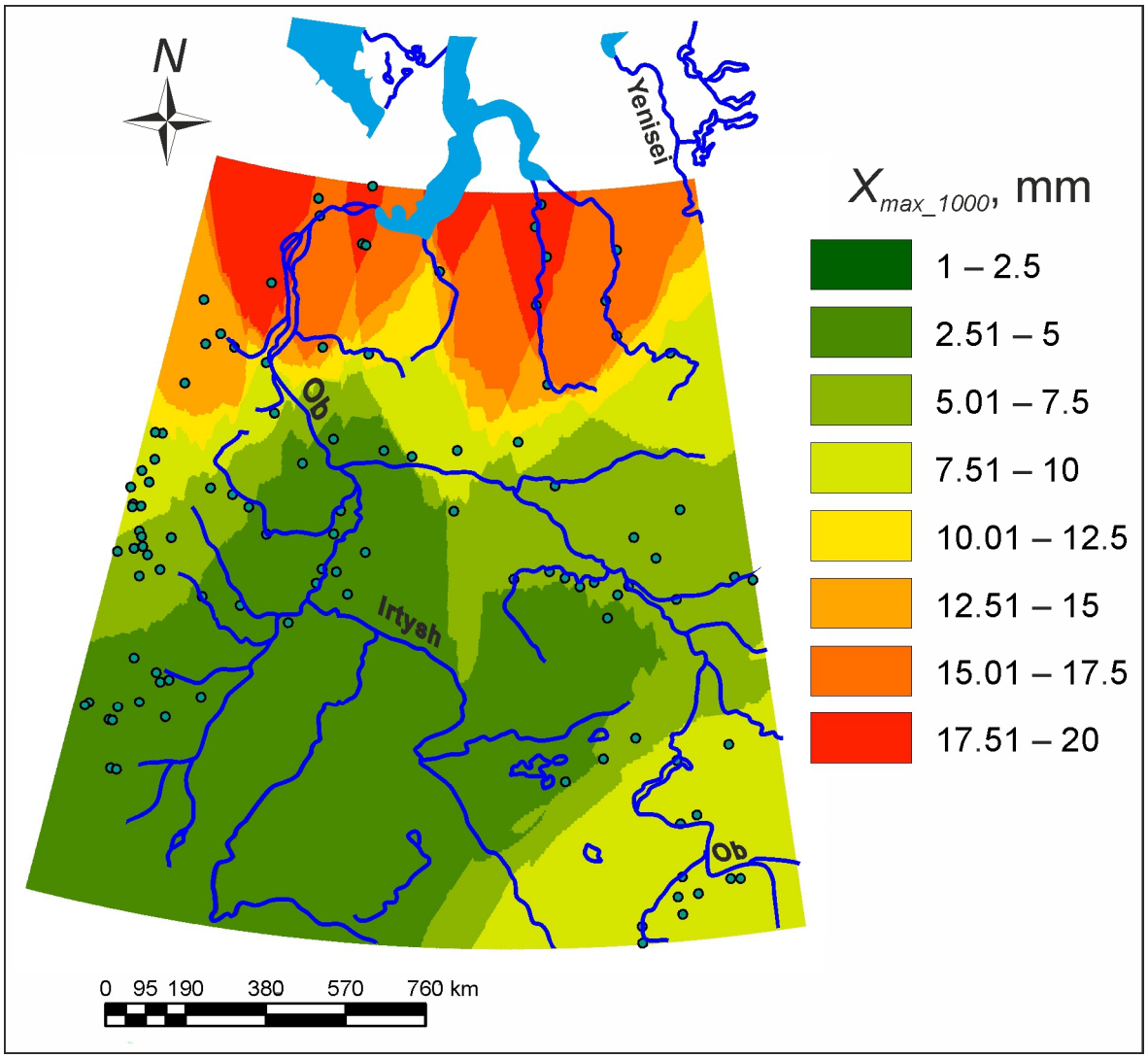

Figure 11. Distribution of the modern effective maximum daily surface runoff depth X_{max_1000} for a unit basin.

3.2.2. The Ancient Rivers

It is possible to derive Equations (3) and (4) for mean maximum discharges of the ancient rivers Q_{max_old} calculated with Equation (2) and their measured modern contributing basin areas F. As for the modern rivers, landscape zones of the Late Pleniglacial (see Figure 1) were taken into account for spatial differentiation between sites. Due to different numbers of ancient channel fragments in different zones, the zones with similar landscapes were combined into larger regions. The resulting relationships were obtained for two regions (Figure 12): (1) tundra–steppe (periglacial tundra and open woodlands) (numbers 1–3 in Figure 12) and (2) periglacial steppe (meadow and dry steppe) (number 4 in Figure 12).

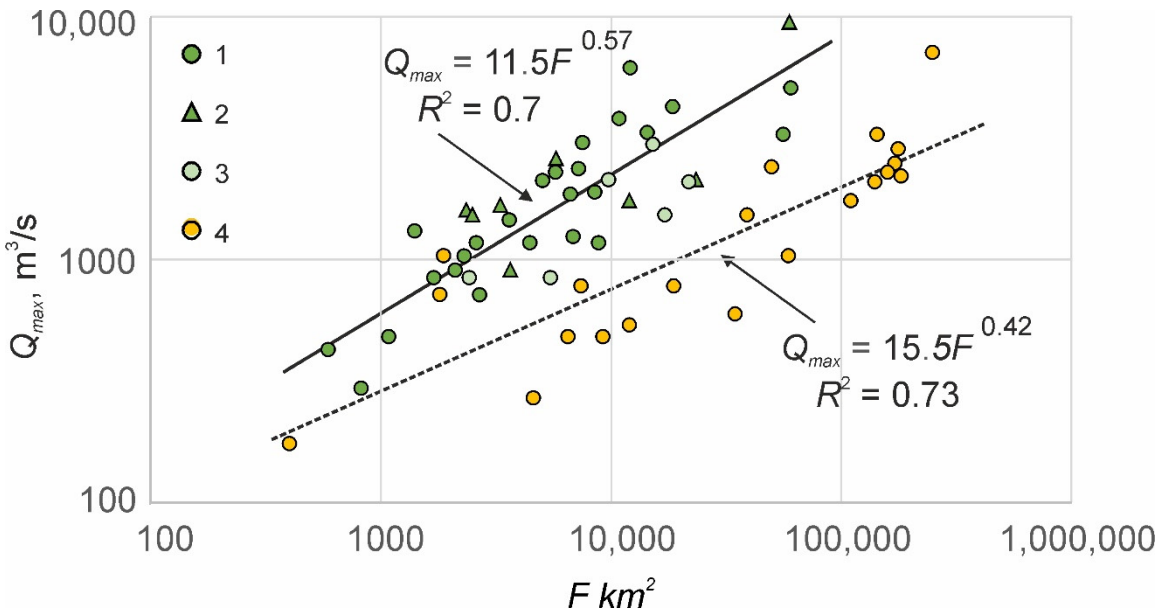

Figure 12. Regional relationships between maximum flood discharges Q_{max} calculated with Equation (2) and contributing basin areas F for the ancient rivers of the western Siberia. Regions: 1—moss and dwarf shrub tundra, locally with birch and spruce open woodlands; 2—spruce and birch open woodlands; 3—meadow steppe with birch and spruce forests and some tundra communities; 4—meadow and sagebrush–herb and sagebrush–saltwort steppes.

The exponent b_{2_old} in Equations (3) and (7) for the ancient rivers, which shows losses of river runoff and transformation of the shape of the flood wave down the river, decreases from the north to the south. It shows a very high degree of flood wave transformation for the southern periglacial steppes, which contrasts with the same relationship for the modern rivers. As the losses on evaporation and infiltration were low in the conditions of cold periglacial climate, the rapid decrease in maximum runoff depth, calculated with Equation (2) from the widths of paleochannels, can be explained by high storage capacity of the large ancient river channels and floodplains. The rate of transformation of the flood wave is lower in the northern region and is more similar to that of the modern rivers. Nonetheless, the height of the flood wave in the northern region decreased down the river more rapidly than that in the modern rivers of this region, presumably also due to higher storage capacity of river channels and floodplains.

The mean values of coefficient a_{2_old} for the ancient rivers (expressed in Figure 12 in $m^3\ s^{-1}\ km^{-2}$) also show a tendency opposite to the modern rivers and increase from the northern region to the southern one. Nevertheless, flood discharges and runoff depths in the unit basins are still higher in the northern region than in the southern one.

3.3. The Ancient Maximum Surface Runoff in West Siberia

The effective maximum daily surface runoff depth X_{max_old} calculated with Equation (7) for a unit basin area of each ancient river shows spatial distribution generally similar to that of the modern rivers (Figure 13). X_{max_old}, forming presumably due to spring snow thaw, also decreases from north to south.

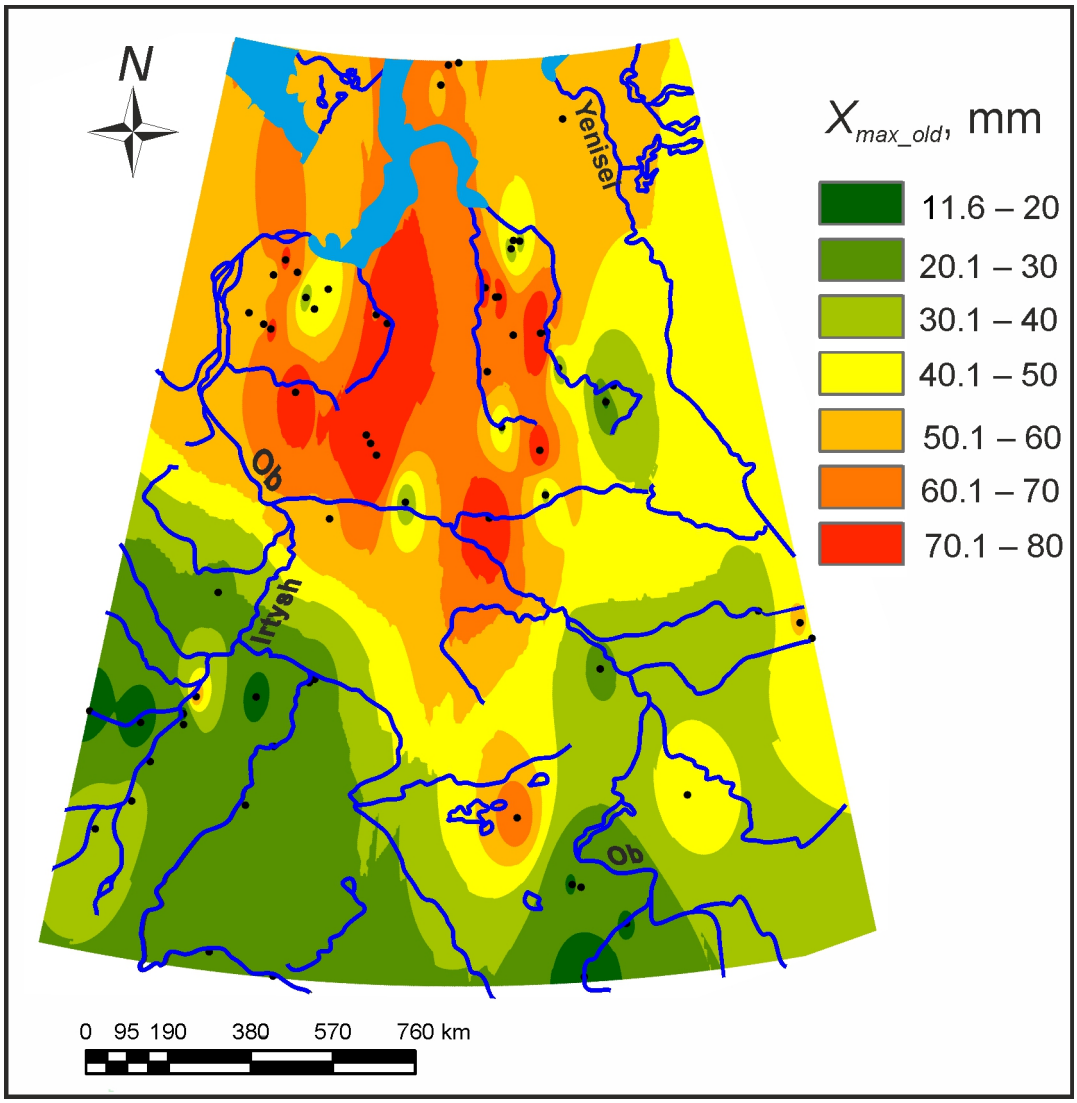

Figure 13. Distribution of reconstructed ancient effective maximum daily surface runoff depth X_{max_old} for unit basins on the West Siberian Plain.

The main difference between the daily maximum surface runoff depth X_{max_old} during the Late Pleniglacial/Late Glacial and at the present time is the much higher values. Daily water input during snow thaw was 60–75 mm in the northern region (tundra and sparse forest) and 20–40 mm in the south (periglacial steppe). In a vast relatively homogeneous periglacial hyperzone [37], a spatial differentiation of X_{max_old} was lower than in the modern conditions. The mean daily maximum surface runoff depth for the entirety of West Siberia was about 46 mm, which is more than five times larger than the modern value.

3.4. The Possibility to Estimate Mean Annual Flow Characteristics

As it is not possible to determine mean annual discharges of the ancient rivers directly from their morphology, for this purpose, the method of paleohydrological analogue was proposed [38]: the runoff characteristics for the ancient and present-day river basins are similar if these basins have similar landscapes. The modern landscapes, which can be considered the closest analogues for periglacial landscapes of the East European Plain 18 cal ka BP, were determined from paleofloristic data on ancient alluvial deposits derived mainly from pollen analyses [17,18]. The most probable landscape analogues are intermountain basins of Altai and Sayan mountains. A similar climate on the plains exists in the open forest areas of Central Yakutian Plain (the Vilyui River basin) and

in tundra on the plains of the northeastern European Russia and the Yamal Peninsula. The climatic conditions of these territories are characterized by long and severe winters with considerable snow accumulation. The spring is relatively short with low evaporation and infiltration rates. Therefore, surface runoff during the spring is high. During the rest of the year, surface and groundwater runoff are negligible due to low precipitation and continuous permafrost. For example, the channels of the rivers in the western Yamal Peninsula are nearly dry during the summer [16]. Therefore, the ratio between mean annual and flood discharges is low, and intra-annual discharge variability is high.

The periglacial climate was geographically more homogeneous than the modern one [37]. The same ecosystem analogues in the Altai Mountains are determined for the periglacial landscapes of West Europe [39] and of West Siberia [40]. Therefore, it is possible to use the hydrological data on climatic analogues, estimated for the East European Plain and for the West Siberian Plain. The relationship of the ratio between the mean annual and mean maximum runoff depths with the contributing basin area

$$y = \frac{X_{mean}}{X_{max}} = f(F) \tag{8}$$

is quite similar for the rivers of the Vilyui River basin, northeastern European Russia and the Yamal Peninsula (Figure 14). A few estimates of this ratio for the ancient rivers of the East European Plain [35] also confirm this relationship. For the river basins with the area less than 1000 km^2, the ratio between the mean annual and mean maximum runoff depths y_{old}, which vary in the range 0.02–0.04, is assumed to be constant and equal to 0.029. This value was used to calculate the mean annual river runoff over the territory of West Siberia:

$$X_{mean\_old} = k y_{old} a_{2\_\mathrm{old}} 1000^{(b_{2\_\mathrm{old}}-1)} \tag{9}$$

Calculated total mean annual runoff from the Ob River basin was about 1000 km^3. The Altai mountainous area, about 16,900 km^2, and broad floodplains of the Late Pleniglacial time with a total estimated area of 257,000 km^2 were excluded from the calculations.

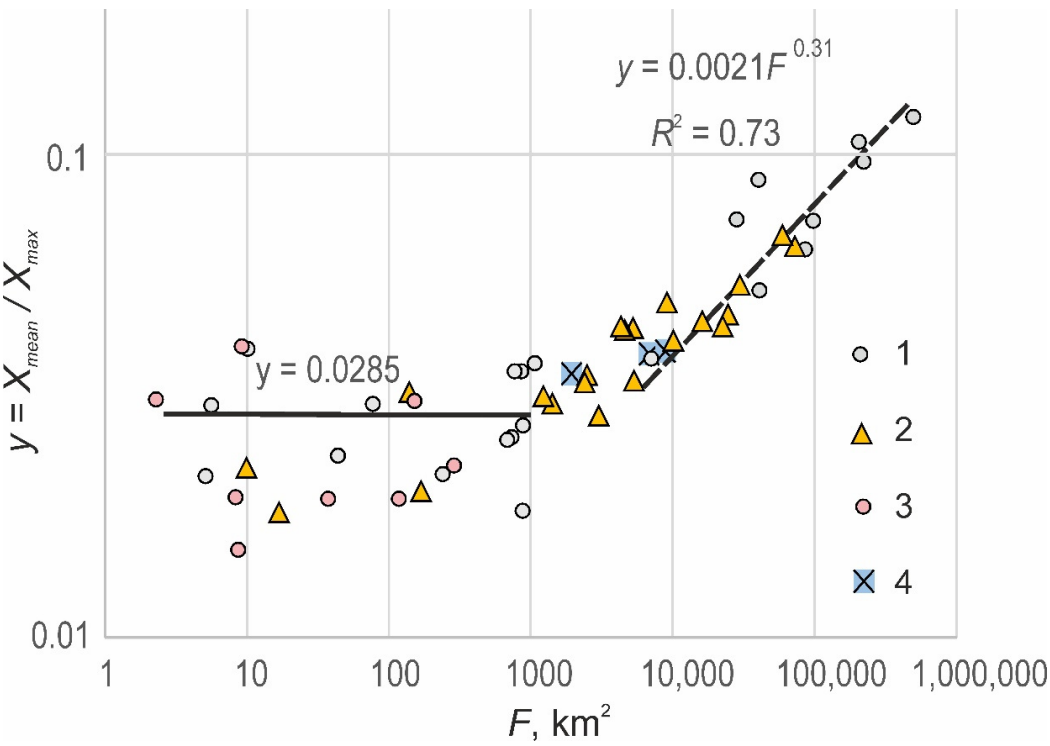

Figure 14. The relationship between the ratio of mean annual and mean maximum runoff depths y and contributing basin area F for the rivers of Vilyui River basin (1), of the northeastern European Russia (2), of the Yamal Peninsula [34] (3) and for the ancient rivers of the East European Plain [35] (4).

The modern mean annual runoff from the Ob River basin (without Altai) is 345 km^3. About a three-fold difference between the ancient and modern river runoff does not contradict the reconstructions for the rivers of the East European Plain [14–18]: the ancient Volga River runoff was two times higher than the modern one, and that of the ancient Don River was four times higher. This huge amount of water runoff was formed in the basins of the Ob River tributaries and in the basins of the Taz and Pur Rivers and other rivers draining into the Ob Gulf. An additional significant volume of water supply to the ocean through the main trunk of this drainage system was formed by catastrophic floods from large proglacial lakes in the Altai Mountains [41,42].

4. Discussion

There are two interrelated problems to discuss: (1) differences in parameters of the relationship between channel bankfull width W and mean maximum discharge Q_{max}; (2) the ways to estimate mean annual flow characteristics.

4.1. Parameters of the Relationship between Channel Width and Discharge in Downstream Direction

This relationship for alluvial rivers was estimated by Inglis [43] in the 1940s in the form as follows:

$$W \sim Q^{0.5} \tag{10}$$

The exponent value 0.5 was confirmed by empirical data in the papers of Leopold and Maddock [29] and Leopold and Wolman [44]. The value of 0.55 was determined by the theoretical findings of Leopold and Langbein [45]. Using the meander wavelength L instead of the width, Dury [5] reversed Equation (10) with the same exponent for the purposes of paleohydrology:

$$Q \sim L^2 \tag{11}$$

Our empirical data (Figures 6 and 8) show that an exponent in Equation (2) (or in its version, Equation (10)) is in the range of 1.3–1.5. It means that an exponent in Equation (10) is in the range 0.67–0.77. Careful examination of Figure 45 in the classic paper by Leopold and Wolman [44] shows that the exponent in the Equation (10) is about 0.7 for the rivers with bankfull discharge >100 cubic feet per second.

The exponents in Equations (10) and (2) are controlled by the change in flow velocity and depth-to-width ratio as flow changes along the river (see Equation (6)). For small streams, flow velocity usually increases downstream with discharge, therefore increasing the exponent in Equation (2) and decreasing it in Equation (10). Nachtergaele et al. [46] showed that for the rills on the slopes, the exponent in Equation (10) is 0.3, and in the gullies, it is 0.4. Its value is 0.5 for small rivers. This means that in small rivers the influence of velocity increase is compensated by downstream decrease in the depth-to-width ratio. Flow velocity is nearly constant along large rivers, while the exponents in Equations (10) and (2) are mostly controlled by the depth/width ratio decrease with discharge. Therefore, diagram 10 in [46] can be extended to the field of large rivers, for which the exponent in Equation (10) is about 0.7.

Schumm [47] showed that the channel width/depth ratio is correlated with the sediment composing the perimeter of river channel (a weighted mean percent silt–clay) M (in percent):

$$M = \frac{S_c W + S_b 2d}{W + 2d} \tag{12}$$

Here, S_c is the percentage of silt and clay in the channel alluvium, and S_b is the percentage of silt and clay in the bank alluvium. Recalculation of the data from Table 1 in [42] to the depth/width ratio β gives the relationship

$$\beta = 0.0054M^{0.93} \tag{13}$$

with $R^2 = 0.82$, or, simply

$$\beta = 0.0052M \tag{14}$$

Differences in M values for modern and ancient rivers cause differences in the b_0 exponents in Equation (2) and make it difficult to use the main hypothesis of paleohydrology in its current form: the values of the coefficients and exponents in regime equations derived from measurements for the modern rivers are constants valid for the ancient rivers. Unfortunately, M values for the ancient rivers are scarce. Even special investigation by Schumm [7] of M for the ancient channels on the Riverine Plain (Australia) did not allow finding the corresponding exponent b_0, so Schumm had to use the classic value of 2.

Schumm [48] also showed that channel sinuosity is correlated with β and M. This observation makes it possible to compare the sinuosity of modern and ancient rivers in order to decide whether the main hypothesis is correct. The modern and ancient rivers in West Siberia are meandering (the Ob River being an exception), and their meanders are well developed with sinuosity of 1.5–1.7 (see Figure 3B,C). Therefore, we can assume that it is possible to use the hydraulic geometry of the modern rivers for calculations of paleohydrological characteristics of West Siberia.

4.2. Estimations of the Mean Annual Flow Characteristics

The main cause of the formation of large ancient rivers was a significant increase in flood discharges. The correlation between the mean maximum discharge and the channel bankfull width is high (see Figures 6 and 8). Therefore, using the main hypothesis of paleohydrology (with the clarifications described in Sections 3.1.1 and 4.1), it is possible to estimate the main characteristics of the floods on the ancient rivers, particularly in the basin of the paleo-Ob River. The next step is estimating mean annual discharges of the ancient rivers. For this purpose, the principle of paleohydrological analogue was proposed [44], and the closest analogues for periglacial landscapes were determined from paleofloristic data [17,18].

In our previous papers [14–18], we used purely empirical approach to calculate the former mean annual discharges. We used about 700 sections of rivers in the northern Eurasia with annual discharges Q_{mean} from 1 to 13,000 m^3 s^{-1} and channel bankfull widths W from 20 up to 8000 m, with the drainage basins situated in a variety of landscapes from steppe to tundra. Based on these data, the following empirical relationship was derived (the last approximation in [49]):

$$Q_{mean} = 0.019y^{0.64}W^{1.34} \tag{15}$$

Coefficient y here is the ratio of annual to mean maximum discharge

$$= 100\, Q_{mean}/Q_{max} \tag{16}$$

representing intra-annual discharge variability. It depends on the river basin area F:

$$y = aF^N \tag{17}$$

The mean maximum discharge was calculated from Equations (16) and (17):

$$Q_{max} = \frac{100Q_{mean}}{aF^N} \tag{18}$$

Coefficient a and exponent N vary with the river basin landscape. The principle of paleohydrological analogue was used to estimate these parameters for the ancient rivers.

It is obvious that the new approach applied in the current paper uses the opposite sequence of calculations compared to the one in our previous reconstructions. We now first estimate the mean maximum discharge Q_{max} directly from the paleochannel bankfull width using empirical Equation (5), following the proven assertion that the main cause of

the formation of large ancient rivers was a significant increase in flood discharges. Then we transform Q_{max} into the maximum surface runoff depth in the unit basin with Equation (7). The last operation is the estimation of the mean annual surface runoff depth with Equation (9), using the principle of the paleohydrological analogue and finally calculate the mean annual discharge.

The procedure of estimating the maximum discharge of an ancient flood is explicit in the new approach. The most hypothetical principle of paleohydrological analogue is used only at the last stage of mean annual discharge calculation. The previous purely empirical approach includes all these procedures, but in an implicit form, and the paleohydrological analogue is already contained in the very first formula of the method (Equation (15)). In [16], we determined the error of the estimate in paleohydrological reconstructions as ±20% of the mean value, based on statistical formulas for the error of the mean. The difference in the values of annual runoff volume V_{old} calculated with both of the methods for the same river basin is close to this error. For the Volga River basin, the previous estimate was V_{old} = 500 km^3 [16]; using the new approach, it is estimated at −420 km^3 [50]. For the Ob River basin, the previous estimate of V_{old} was 800 km^3 [16]; in the current paper, it is 1000 km^3. We assume that although the results of the calculations are close, the explicit methodology is still preferable to the implicit one.

Both methods include the main hypothesis of paleohydrology and the concept of paleoanalogues. The errors arising from the application of these two hypotheses are difficult to assess. We can only assume that they are not too large, based on the studies of modern analogues [38] and the analysis of the main method of paleohydrology carried out in this article. Therefore, paleohydrological reconstructions are valid only for the case when the difference in sizes between modern and ancient rivers is obvious and large, while the difference in environmental conditions is not critical. The environment in the Late Pleniglacial–Late Glacial was not so different from the modern situation that it would be impossible to find its sufficiently close modern analogues. At the same time, a five-fold difference in maximum runoff and three-fold in mean annual runoff are large enough to override possible errors in the calculations.

5. Conclusions

1. The West Siberian Plain is the territory with numerous remnants of large meandering paleochannels formed during the Late Pleniglacial/Late Glacial time. Their widths are 2–16 times greater than those of the modern rivers with the same basins.
2. The relationship between river bankfull width and mean maximum discharge is relatively close for the rivers with very different regimes of water runoff and different ages. This observation allows for the use of the main hypothesis of the paleohydrology: the hydraulic geometry equations, designed for the modern rivers, are valid for the ancient rivers. The main limitation of this approach is the possible change in the morphological type of the river channel in time.
3. The hydraulic geometry of the modern rivers of West Siberia was used to reconstruct the mean maximum discharges of the ancient rivers based on their ancient bankfull widths. Mean maximum discharges were recalculated to the mean flood surface runoff depth from a unit basin. The ancient daily water input intensity during snow thaw was 60–75 mm/day in the north of the plain occupied by tundra and sparse forest and 20–40 mm/day in the south (so-called periglacial steppe with sparse forest), with the mean value for the entire plain of 46 mm. This is more than five times larger than the modern value.
4. Maximum daily water input intensity during snow thaw was recalculated into mean annual river runoff using assumptions of the paleohydrological analogy. The average annual depth of the river runoff was 430 mm for the Ob basin, except for floodplains and mountains. The total annual flow of the Ob into the ocean was about 1000 km^3. This is three times the current flow from the same basin, so the river was a significant source of fresh water to the Arctic Ocean during the last period of deglaciation.

5. Almost all factors listed by Dury [5] (further in italics) were important for the changes in hydrologic regime and flood runoff increase in West Siberia in the Late Pleniglacial. Data from analogous regions show that the winter *air temperature reduced* by 8–10 °C, but that of the snowmelt period (June–July) was approximately the same as the current one. *Total precipitation increased*, and the *regimen of precipitation changed*, with a shift to the winter months. The *extent of frozen ground increased* dramatically: the southern boundary of the continuous permafrost was then at about 50° northern latitude instead of the modern 66°N. The *regimen of runoff changed* along with the regime of precipitation, with high floods during the snow thaw period and nearly empty channels during all the rest of the year. *Increased size of individual rains, increased frequency of storms* and *increased wetness of soil* were probable but not proved. *Vegetation cover changed* within the area of boreal forest (taiga), largely replaced by sparse forest and tundra–steppe landscapes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15020258/s1, Table S1: The morphological data for the ancient rivers in West Siberia; Table S2: The hydro-morphological data for the modern rivers in West Siberia; Table S3: The hydro-morphology of the meandering and winding rivers of the Lena River basin (East Siberia); Table S4: The hydro-morphology of the meandering and winding rivers situated in the equatorial zone (South America, Southern Asia and Africa).

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