Braided rivers: structure, types and hydrological effects

Sergey R. Chalov and Nikolay I. Alexeevsky

ABSTRACT

Braided rivers have been intensively analyzed mostly by geomorphologists. In the present study the approach to recognize braided channel types and effects with the special emphasis on flow partitioning has been applied. It is assumed that each braided channel represents the reach which is initiated with dividing of the single channel and completed below the confluence of the total multiplicity of channels. Proposed indices of braided channel structure and water discharges ratio which have been proposed and applied to 200 braided reaches of 40 rivers in Russia, China, and the USA enable the description of the origin and types of the observed rivers and further analysis of hydrological effects of braided channels. The latter represent physical, hydrochemical, and ecological conditions of stream along braided reaches caused by flow distribution among branches in relation to braiding intensity. Structure and braided channel pattern types impact on hydraulics, sediment transport, water temperatures, and stream communities are of primary interest in the present study.

Key words | braided channel, flow partitioning, river ecology, sediment load, water temperature

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INTRODUCTION

Braided rivers represent one of three main channel types. In Northern Eurasia up to 35% of total river length is characterized by this pattern (Chalov 2008; Alexeevsky *et al.* 2013). The total length of braided rivers in Russia accounts for 40% of the inland waterways and up to 57–62% of waterways in Siberia. Abundant studies describe braiding intensity (Howard *et al.* 1970; Germanoski & Schumm 1993; Egozi & Ahmore 2008), identify occurrence and development (Schumm 1977; Rhzanitcyn 1985; Chalov 2008) and variety of braided patterns (Rosgen 1994; Nanson & Knighton 1996; Chalov 2008). Yet significant uncertainty remains as to how to systematically describe the variety of river styles that arise wherever water and sediment conveyance is divided between multiple independent channels (Makaske 2001; Hundey & Ashmore 2009). In particular, there is an ongoing need to determine whether 'visually different' channel patterns can be discriminated consistently (Sapozhnikov & Foufoula-Georgiou 1996; Eaton *et al.* 2010; Carling *et al.* 2013); and whether these morphological sub-types do in fact differ in the processes governing their formation (Bertoldi & Tubino 2007; Carling *et al.* 2013),

persistence and hydrological or ecological characteristics (Van der Nat *et al.* 2003; Alexeevsky & Chalov 2009; Gostner *et al.* 2011).

The problem of discriminating channel patterns has been thoroughly analyzed recently (Downs 1995; Kaszowski & Krzemien 1999; Makaske 2001; Carling *et al.* 2013). Unfortunately, there is no consistent nomenclature but an overlapping and sometimes even conflicting usage of terms describing the pattern of multiple flow paths (Beechie *et al.* 2006; Alexeevsky *et al.* 2013). Original classifications of river channel pattern (Makkaveev 1955; Leopold & Wolman 1957) considered braided channels as one of three essential types of channel pattern: anastomosing, split, wandering; some other patterns were distinguished later to characterize forms of multiple flow paths. Although various fluvial classifications have been proposed to arrive at a rational and functional typology of rivers and channels (including braided patterns), none of them is universally accepted. The most elaborate classification schemes yet derived are those proposed by Rosgen (1994), Montgomery (Montgomery & Buffington 1997) and Schumm (Schumm

1977). None of the English language works deals with the results of the abundant studies of the fluvial processes in Russia (former USSR). Detailed classification of fluvial processes and channel patterns based on analysis of various rivers in the USSR was derived at Moscow State University on the work of Nikolay I. Makkaveev (Makkaveev 1955). It was in demand in many stream engineering projects in the former USSR and Russia (Chalov 2008). The Makkaveev–Chalov classification is based on observations in different environments in Russia – from mountains (Caucasus, Than-Shan, etc.) to flatlands (East European plain, West Siberian plain, etc.) and both at ephemeral and perennial nival belts.

The crucial problem in laboratory-derived and empirical data analyses concerning the discrimination of braided channel types has been connected with the absence of relevant quantitative descriptors. Application of structural indices to various forms of braided rivers (Riley 1975; Richard & Julien 2003; Foufoula-Georgiou & Sapozhnikov 1998; Egozi & Ashmore 2008) remains the only quantitative approach in understanding the variability of channel patterns and their maintenance. Although measurement of braided pattern morphology has been widely recognized as a key element for comparison of origin and evolution of braided rivers, application of braiding intensity indices was mostly associated with a geomorphological approach to describe channel morphology and bedforms (Kelly 2006). Measurement of braiding intensity is based on parameters of valley and channel morphology and channel count indices. It has been criticized recently to be not robust and even misleading (Carling et al. 2013) as far as it lacks process insight. Nevertheless, it is evident that a consistent, objective approach is needed to define planform and to determine any normative differences between river planforms (Luchi et al. 2010) and consideration of the braiding indices is probably a necessary first step (Kleinhans & van den Berg 2011). This partly could be solved by implementing consistent quantifying of flow partitioning in braided rivers as far as the origin of braided channels strongly depends on stream size and water regime. We argue that braided rivers exhibit kinds of numerous channels (flows) that split off and rejoin each other to give a braided appearance (Alexeevsky & Chalov 2009) and braided reaches represent the part of dendritic drainage networks, inverse to channel junctions. River

channel junctions as part of dendritic drainage networks represent longitudinal increase of water and sediment runoff, whereas bifurcations cause downstream partitioning of flow and water discharge decrease in separate channels. In this case, traditional views on stream size orders can be applied to discriminate channels of braided rivers and thus give process insight as far as it is evident that reach-scale planform processes are largely discharge driven (Bertoldi & Tubino 2007; Chalov 2008; Carling et al. 2013).

Based on this background we developed a robust approach to quantify braiding intensity. We contribute the recent approaches of braiding intensity (Egozi & Ashmore 2008) with a hydrological perspective through designing special tools for assessing flow partitioning which is regarded to follow the needs in process discrimination (Carling et al. 2013). This is also consistent with the objective to have an insight into special effects that braided channels have on the river hydromorphology, water and sediment transport, and river ecology. Flow partitioning among the multiple flow paths determines special impact on hydrological characteristics of rivers. Sediment (in suspended, bed, and dissolved form) transport and water temperatures strongly depend on channel morphology and are strongly affected by flow partitioning along braided reaches. Further benefits or constraints for development of navigation, within-channel alluvial gravel extractions, placer mining, river crosses, fisheries, etc. exist. All these phenomena are rarely investigated. Studies still lack analysis of braided channels effects on stream hydraulics. Few recent studies have been devoted to measurements of sediment transport in natural braided rivers (Ferguson 1987; Meunier et al. 2006; McNamara et al. 2008; Mao & Surian 2010; Chalov & Ermakova 2011) or in laboratory flumes and numerical models (Ashmore 1991; Métivier & Meunier 2003; Matti & Bezzola 2006; Bertoldi et al. 2009; Mouri et al. 2013), leaving a paucity of information on mass balance comparison between braided and parent channels (Schumm 1977; Alexeevsky & Chalov 2009) and related evolution of channel patterns. Only few works have been done to provide evidence on water temperature variability in the branches of braided rivers (Mosley 1983; Arscott et al. 2001; Stanford et al. 2005; Acuña & Tockner 2009; Gostner et al. 2011) and to study the ecological effects of braided rivers (Van der Nat et al. 2003; Tockner et al. 2006; Esin & Chalov 2011).

The aim of this paper is to provide a comprehensive comparison of braided patterns with braiding intensity indices, which further enables expansion of our understanding of braided rivers' diversity and determination of discrepancies. Application of the braided intensity estimation has certain links to water and sediment transport changes and water ecology. We were focused on understanding the spatial variability of the hydraulics parameters, sediment loads, temperatures, and habitat structures along braided channel patterns, which are discriminated by flow partitioning and morphological indices applied in the present study. These indices correlate with river stage and thus are regarded to be essential for progress in studies of braided morphology and dynamics at the scale of the channel network. They demonstrate familiarity and variety of river runoff changes along a braided channel. On this basis we contribute to linking variety of in-channel processes and braided patterns with physical and ecological processes according to their spatial and temporal scales. Flow partitioning influence on these phenomena and its role in longitudinal gradients of the associated parameters are of primary interest in the study.

The approach used in this paper is based on the following assumptions:

(1) Braided channels are a special type of channel pattern which are characterized by spatial and temporal dynamics.
(2) Each braided reach is recognized by the multiplicity of laterally mobile, intersecting channels, established by the dividing of the non-braided channel and ending where all channels join.
(3) Identification of the appropriate scales of the flow partitioning and related phenomena treatment is implied by the dynamic scaling (Foufoula-Georgiou & Sapozhnikov 1998). This scaling is regarded as a fundamental element of braided river morphology (Hundey & Ashmore 2009) and enables treating flow partitioning systems of various size (with a length from a few meters to hundreds of kilometers).

We address the following questions:

(1) How do we measure braided channels' structure and associated hydrological phenomena (flow partitioning)?
(2) How does it correspond to channel pattern types?

(3) What are the hydrological and environmental effects of braided channels?

In the present paper we used hydrological, topographic, and satellite data from more than 200 braided reaches from 40 Russian rivers and additional literature information. The main data were received from authors carrying out fieldwork where *in situ* measurements of water discharges, water surface slopes, sediment load, water temperatures, as far as investigations of stream communities were conducted.

DATA COLLECTION AND APPROACHES

Structure of braided channels and flow partitioning

Study of the types, origin and effects of braided channels is based on the quantitative description of braided channel structure. We address the issue of the measurement of braiding intensity mainly on the establishment of strict parameters and their application on natural rivers from various environments. The braided indices proposed below were partly based on the characteristics devised previously (Howard et al. 1970; Germanoski & Schumm 1993). In general, braiding intensity indices have been based on one of three characteristics: bar dimensions and frequency; the number of channels in the network; the total channel length in a given river length.

While it has been argued (Egozi & Ashmore 2008) that reach lengths of at least 10 times the average wetted width are needed to measure braid indices, we consider that calculation of the indices should be done for the entire braided reach (Figure 1). According to the definition and assumptions proposed above, each braided reach represents any river section consisting of multiple flow paths, which split off at the upper boundary and rejoin at the lower. Thus the measured reach is localized between the points of upstream single channel bifurcation and downstream confluence of all channels (distance from confluence to bifurcation). The length of braided reaches (L, km) varies in natural stream from a few meters to hundreds of kilometers. We aimed at applying both morphological ('visually different' planforms) and hydrological (water
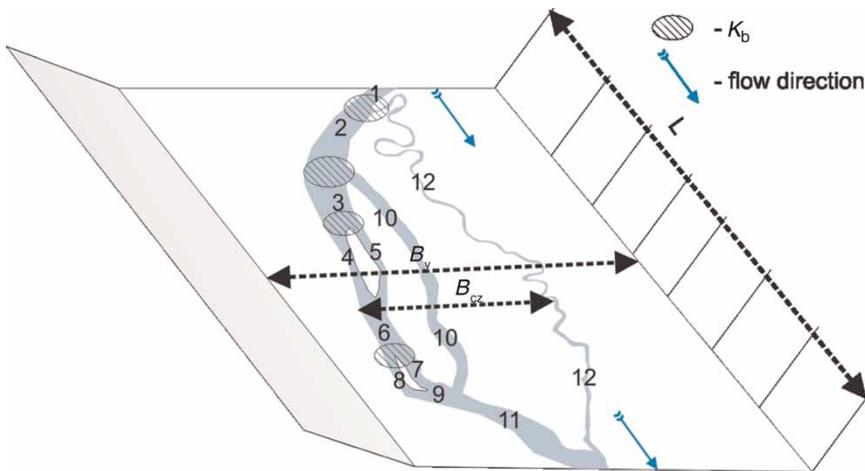
Figure 1 | Quantitative characteristics of braided channel. B_v, valley bottom width; B_{cz}, width of zone of channel migration; L, braided reach length (km); 1,2, … , K_a, number of channels; K_b, bifurcations.

discharge partitioning, processes insight) approaches for the braiding indices.

The variety of indices used in this work could be divided into the parameters of valley morphology, channel count indices, and water discharge partitioning indices. The first group of indices includes valley bottom width B_v and width of channel migration zone B_{cz}. For each valley cross-section the following equations represent channel width calculations (Figure 1):

$$\begin{cases} B_{ch} = B_2 + B_{12} \\ \qquad \cdots \\ B_{ch} = B_4 + B_5 + B_{10} + B_{12} \\ B_{ch} = B_6 + B_{10} + B_{12} \\ \qquad \cdots \\ B_{ch} = B_{11} + B_{12} \end{cases} \qquad (1)$$

The main are the B_v/B and B_{cz}/B ratio which give morphological variety of flow partitioning between channel branches. A similar index to describe spatial scale was proposed earlier by Riley (1975) who proposed length L_i to width B_i ratio. All of them are intended to discriminate channels which form a floodplain independent from the parent channel and those that form islands with width and length similar relative to channel width. Channel morphology along various parts of undivided individual reach and a channel divided around an island (group of islands) could be differentiated based on the relative water surface area F_{ws}/L value.

Braided channel structure is characterized by number of separate channels (branches, links, or segments) K_a and number of flow bifurcations K_b. Both parameters should be determined for the low-water stage as far as braiding intensity is sensitive to water levels (Egozi & Ashmore 2008). In the single braided reach formed by one island $K_a = 3$ including two segments and the parent channel. Relative ratio K_a/L (channels density) could be regarded as an evidence of flow partitioning. K_a/L increase is followed by a larger degree of flow partitioning.

Amount of bifurcations K_b characterizes frequency of longitudinal water discharge partitioning. It increases with successive dividing of the channel. Single (giving rise to two channels) and comprehensive (three or more channels) bifurcations could be found. Single bifurcations are related to number of channels according to the theoretical assumption that:

$$K_b = 1/3 K_a. \qquad (2)$$

Discrepancy of K_b and $1/3\ K_a$ could be used as evidence of braiding intensity. Also, we used maximal number of links $K_a^\perp$ intersected by cross-sections of the river in successive river lengths. Braided channels have $K_a^\perp \geq 2$ whereas single-thread channels $K_a^\perp = 1$.

Of special concern is the development of indices to characterize flow partitioning along rivers. The simplest way to describe flow partitioning along a channel is given

by relative discharge values $Q_{i(\%)} = Q_i/Q_0$, where Q_i is water discharge in separate branches and Q_0 is water discharge of a single-thread channel upstream from the braided reach (parent channel).

A new approach to assess branches' size and flow partitioning is provided through applying the stream orders concept to the braided channels. We applied so-called 'conventional orders' for individual branches of braided river. The governing idea is that conventional orders depend on stream order of parent channel N. According to Scheideggaer (1965), every junction along the river network is associated with an increase in channel order

$$N = 1 + \log_2 P_0 \qquad (3)$$

where P_0 is total amount of first order streams in the basin (streams with total length less than 10 km). It reflects the dependence between stream orders and annual water discharges Q_0

$$Q_0 = a\,e^{bN}, \qquad (4)$$

where a and b are empirical regional coefficients. Below the confluence of the two rivers the total amount of streams in the river basin is

$$P_0 = P_{01} + P_{02} \qquad (5)$$

additionally

$$Q_0 = Q_{01} + Q_{02}. \qquad (6)$$

The bifurcation process causes separation of the initially single channel into few independent channels; the latter could be regarded as analogues of channel in the dendritic channel network. Each segment is distinguished by certain water discharge Q_i which is less than water discharge of the single-thread channel above the braided reach Q_0. Equation (4) could be applied to each channel of the braided river assuming that conventional order N_y gives

$$Q_i = ae^{bN_{yi}} \qquad (7)$$

Following Equation (7), $N_{yi} = N$ if $Q_i \approx Q_0$. In that case Equations (5) and (6) could be applied to braided river:

$$\frac{P_1}{P} + \frac{P_2}{P} = 1, \qquad (8)$$

$$\frac{Q_1}{Q_0} + \frac{Q_2}{Q_0} = 1. \qquad (9)$$

Following Equations (4) and (7) and considering Equation (3):

$$Q_0 = ae^b P^{b/\ln 2}, \qquad (10)$$

$$Q_1 = ae^b P_1^{b/\ln 2}, \qquad (11)$$

$$Q_2 = ae^b P_2^{b/\ln 2}. \qquad (12)$$

Then taking into consideration that

$$\frac{Q_1}{Q_0} = \frac{ae^b P_1^{b/\ln 2}}{ae^b P^{b/\ln 2}} = \left(\frac{P_1}{P}\right)^{b/\ln 2}, \qquad (13)$$

Equation (8) could be transformed to

$$\left(\frac{P_1}{P}\right)^{b/\ln 2} + \left(\frac{P_2}{P}\right)^{b/\ln 2} = 1, \qquad (14)$$

where $b = \ln 2 \approx 0.69$. The final equation is then

$$\frac{P_{y1}}{P_0} = \frac{Q_1}{Q_0}. \qquad (15)$$

P_0 value is determined based on the river network structure according to Equation (1). Assessment of the conventional order of each channel gives the estimation of P_1 through Equation (15) which is input into Equation (3). Using this scheme, conventional orders could be defined for all channels of the braided reach.

Assessing conventional stream orders enables proposing special indices of flow partitioning degree of each braided

reach located between the bifurcation and confluence. One of them is

$$\Delta N_1 = N - N_{m,i}, \tag{16}$$

where $N_{m,i}$ is minimal conventional stream order of segment within the braided reach. Being the size-dependent value, ΔN_1 increases for larger rivers. In order to compare braided reaches of rivers of various sizes ($N \neq$ const) a special relative index was derived:

$$\Delta N_2 = \Delta N_1 / N. \tag{17}$$

Similar conditions of flow partitioning are characterized by $\Delta N_2 =$ const, e.g., following reaches ($\Delta N_2 = 0{,}667 =$ const): $N = 3$ ($N_{m,i} = 1$) and $N = 15$ ($N_{m,i} = 5$).

Proposed approaches require field *in situ* measurement of water discharges. The alternative method is associated with flow partitioning estimation on the basis of channel morphology data. A one-dimensional view on braided channels enable assessment of water discharges on the basis of hydraulic and morphological data (Grishanin 1969). The model includes water balance equations between upstream (up) and downstream (down) channel at each bifurcation:

$$\sum Q_{up} - \sum Q_{down} = 0. \tag{18}$$

and water surface equation ΔH around each island, dividing channels on left (l) and right segments (r):

$$\Delta H_r - \Delta H_1 = 0. \tag{19}$$

Water surface decreases along each i branch

$$\Delta H_i = F_i Q_i^2 \tag{20}$$

where F is hydraulic resistance

$$F_i = \frac{L_i n_i^2}{B_i^2 h_i^{10/3}} \tag{21}$$

where L_i is length, B_i is width, h_i is depth, and n_i is roughness coefficient of i segment. The model enables forming n

equations with n unknown variables and further to be solved (Figure 2)

$$\begin{cases} Q_0 - Q_1 - Q_2 = 0 \\ Q_2 - Q_3 - Q_4 = 0 \\ Q_5 - Q_1 - Q_3 = 0 \\ F_1 Q_1^2 - F_2 Q_2^2 - F_3 Q_3^2 = 0 \\ F_4 Q_4^2 - F_3 Q_3^2 - F_5 Q_5^2 = 0 \end{cases} \tag{22}$$

Field data

Channel patterns were surveyed and their structure quantitatively described for 40 rivers in Russia, China, the USA, and Italy. Most of the results arose from field work for the rivers in the Lena basin (Lena, Kirenga), Ob basin (Ob, Biya, Katun, Tom, Chylim), Volga basin (Volga, Oka, Protva), Severnaya Dvina basin (Vychegda, Sysola, Sukhona, Pinega), Enisey (Enisey and Angara Mezen), and Amur River and rivers of Kamchatka peninsula (Kamchatka, Avach, Vyvenka, etc.) and Caucasus mountains (Terek) (Figure 2). Field work was done from 2002 to 2009 under Federal programs for training of river channels and waterway maintenance and river status monitoring programs. Additional information was taken from the earlier (from 1970 to 2000) field reports of the Hydrology department and Makkaveev soil erosion and fluvial processes laboratory of Lomonosov Moscow State University. Some relevant field information was obtained from surveys on the Yangtze River jointly performed with Tongji University of China (Liu *et al.* 2001).

Field works included measurements of water discharge (Q, m³/s), water turbidity (T, NTU), suspended sediment concentration (SSC, mg/L), hydraulic geometry (w, d, and v), Froude number, stream power, and percent of suspended or bed load in relation to total load for cross-sections in all separate branches within a braided reach. Water discharges were calculated by multiplying the discharge flow velocities with cross-sectional areas of the rivers. Sediment discharges were calculated by multiplying sediment-load velocities with average SSC values and cross-sectional areas of the branches. Total water discharge of the entire river was usually found
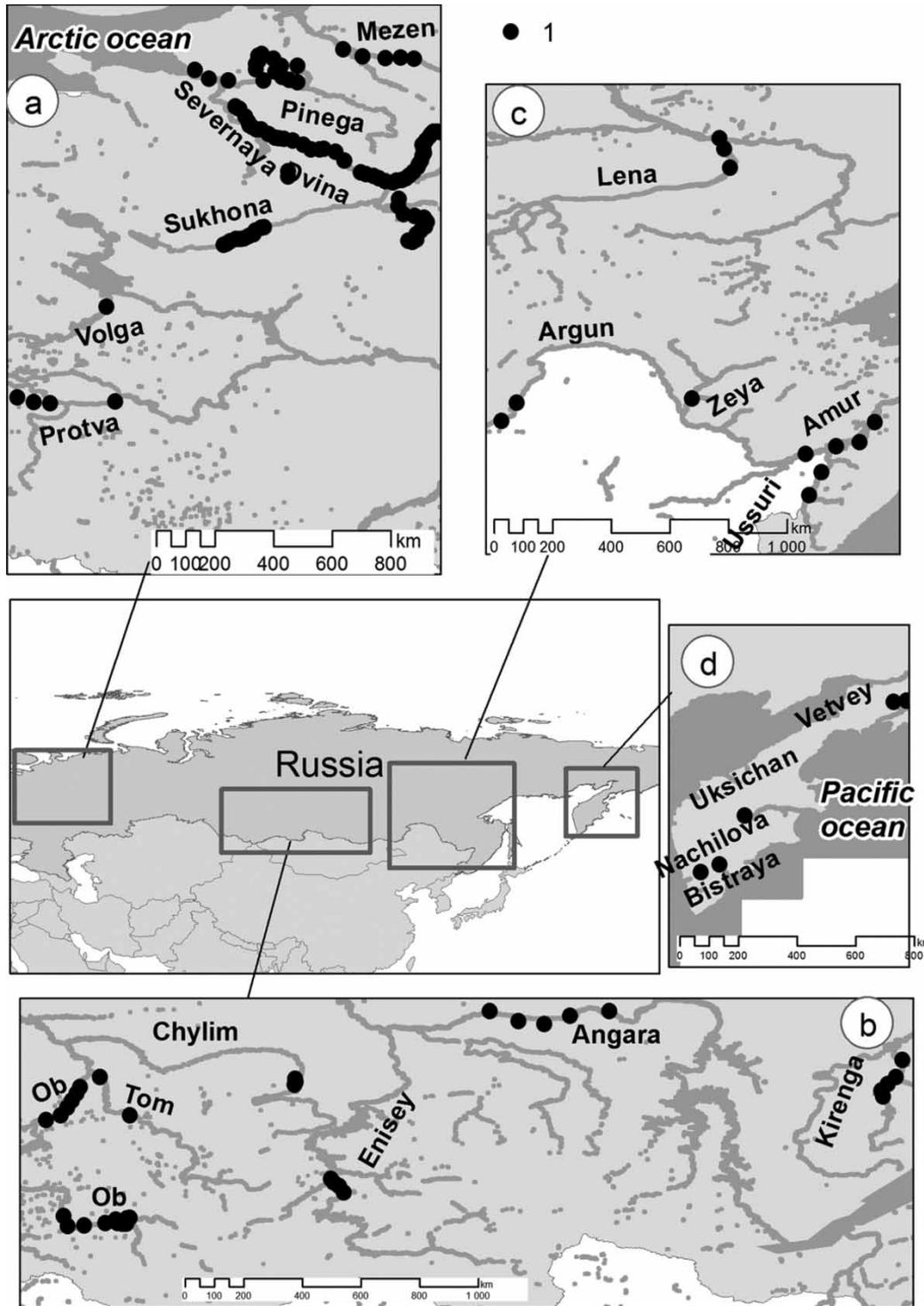
Figure 2 | Location of studied braided reaches (1): (a) rivers of European part of Russia (Volga, Severnaya Dvina, Mezen basins with the exception of the Terek River which is beyond the map borders); (b) rivers of Siberia (Ob and Enisey basins and Kirenga River); (c) rivers of far east (Lena and Amur basins); (d) Kamchatka peninsula rivers.

using a balance equation or by direct measurements on the cross-section located upstream from the braided reach. Where field information lacked measured water discharge, we used a one-dimensional model of water discharge estimation (Equations (18)–(22)). Based on bathymetric surveys, channel maps (scale 1:10,000) of the extended channel reaches, which included detailed morphology of predominant and subsidiary channel were prepared in ARCGIS 9.3. Information on valley morphology and channel count indices was additionally obtained from topographic maps and satellite imagery from several sources, including Landsat 5 TM and Landsat 7 ETM+ and Google Earth. As far as metrics are highly sensitive to river stage for some rivers (Luchi *et al.* 2010; Ashmore *et al.* 2011), planform analyses were done for the periods of average water discharge.

Field data were collected during the spring melt or summer water periods. In order to provide meaningful comparisons between rivers reaches, measured discharge values were then transformed to the annual average long-term conditions using ratio between Q_0 and Q_{00}, where Q_{00} is the annual average water discharge obtained from the nearest gauging station. These values of water discharge in separate branches ($Q_1 \ldots Q_n$) were then used to calculate conventional orders (Equations (3)–(15)).

The field data provide information on flow partitioning between branches and physical, hydrochemical and ecological characteristics of the diversity of long braided platforms. Some examples of braided channel patterns impacts on hydraulics, sediment transport, water temperatures, and stream communities were taken from the literature about the Horse River, USA (Leopold & Wolman 1957), Tagliamento River, Italy (Arscott *et al.* 2001; Van der Nat *et al.* 2003; Tockner *et al.* 2006; Acuña & Tockner 2009) and laboratory flumes (Schumm 1977; Ashmore 1991; Métivier & Meunier 2003; Matti & Bezzola 2006). Unfortunately, in most cases these data were not relevant for studying the role of braiding intensity due to lack of sufficient hydrological data or insufficient definition of how authors had derived their metrics.

RESULTS AND DISCUSSION

### Discriminating braided river types

Multiple flow paths separated by bars and islands are usually named as bar-braided, island-braided, anastomosing and anabranching channels (Leopold & Wolman 1957; Rust 1978; Ferguson 1987; Knighton & Nanson 1993). Special terms exist in the Russian language in literal translation meaning 'bar-braided', 'in-channel' and 'floodplain' multi-channels (Makkaveev 1955; Chalov 2008; Alexeevsky *et al.* 2013). Distributing and braiding systems were similarly proposed by Riley (1975) who refers to them as floodplains independent of the parent streams and systems which do not develop separate floodplains.

The special structural approach was applied using strict quantitative analyses on the basis of proposed indices (Alexeevsky & Chalov 2009). The approach summarizes braided patterns' morphology and origin. Various types of braided channels in different spatio-temporal scales are connected with structural levels of channel topography. Multiple flow paths separated by transient bars, relatively stable bars, islands, or floodplain segments correspond to bar-braided, island-braided (or in-channel), and anabranching (or flood-plain) channels. Bar-braided channels induce flow partitioning by submerged ripples and dunes which are in the form of sediment movement. Island-braided channels are separated by islands with the same width as parent non-braided stream width. Anabranching streams correspond to the size of river valleys. This approach incorporates both planform and process insight into discriminating braided river types.

The lowest level of multiple flow paths occurs where low water is divided by separate gravels and boulders – we propose to refer to it as 'local' multi-channels (distributaries). Width of zone of channel migration to channel width ratio B_{cz}/B is about 1 (Table 1), whereas small length of the channel is typically ($L < B$). Local multi-channels occur mostly in mountain and semi-mountain channels under low water stages when channel depths are the same order of magnitude as the bed particle dimensions. Flow partitioning could be observed only during low water period $0 \leq \tau_p \leq (365 - T_f)$, where T_f is duration (days) of floods (Figure 3).

Table 1 | Braided channel types and spatio-temporal levels

Braided channel types	Typical reach length	Cross-sectional size B_p/B	Longitudinal size of branches	Existence time τ_p
Spot	Particle	1–2	$L << B$	$0 \leq \tau_p \leq 365 - T_n$
Bar-braided	Riffle		$L < 10B$	$0 \leq \tau_p \leq 365 - T_n$
In-channel	River reach length	1–3	$L < 10B$	$365 - T_n \leq \tau_p$
Anabranching (floodplain)	Valley reach length	>3	$L > 40B$	$T_n \leq \tau_p$
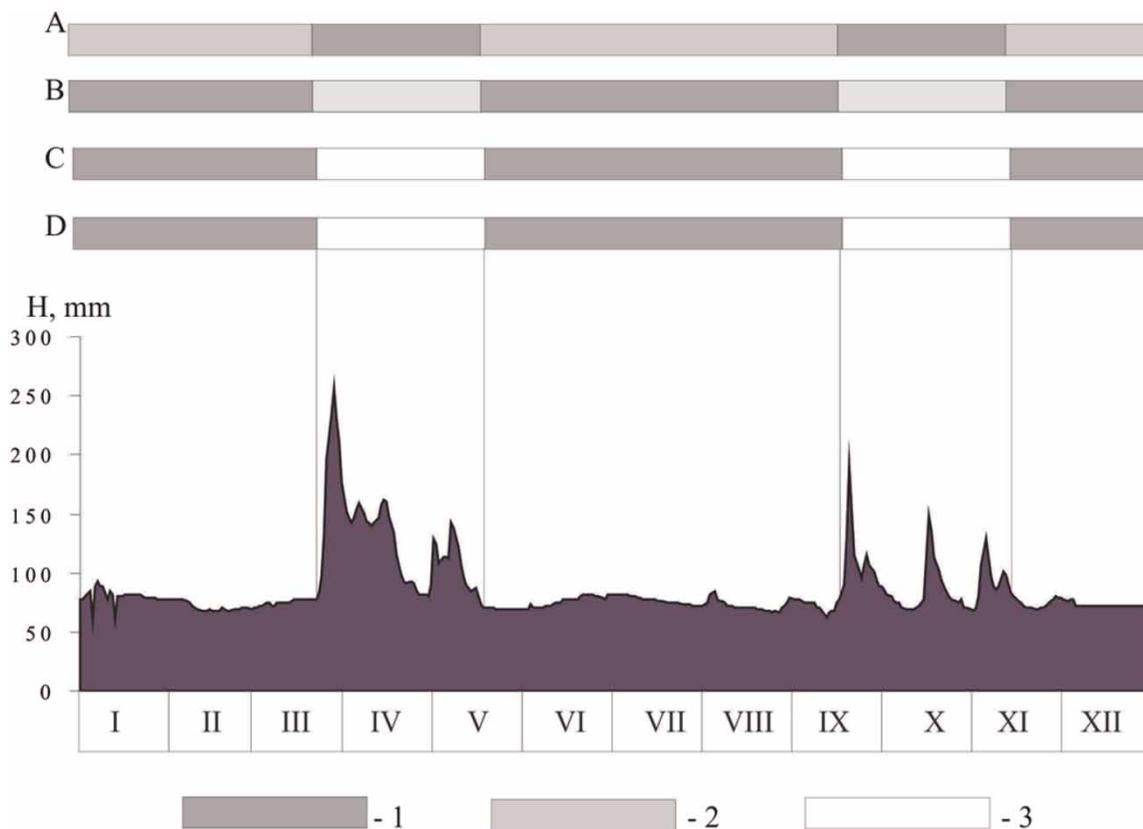
Figure 3 | Constant (1) and temporal (2) existence of anabranching (A), island-braided (B), bar-braided (C), and local (D) channels (3 – single channel).

Local distributaries vary in morphology and origin. On the small mountain rivers flow is separated by large boulders which are comparable to channel width B ($L \sim B$). Semi-mountain rivers usually correspond to the smaller length of the braided reach segments ($L < B$). Plains rivers due to the flow partitioning between single rocks form local braided channels which are many times shorter than the channel width ($L << B$).

Bar-braided channels are induced by emergence of mid-channel bars. They could be submerged under the highest water flow stages. Multiple paths in that case exist only during seasonal stages of water level decrease, i.e., $0 \leq \tau_p \leq 365 - T_f$. During this period $1 < B_p/B \leq 2$.

Island-braided channels (or split – which is traditionally used for the case of mid-channel island division (Ferguson 1987)) are separated by a vegetated island or group of islands. Islands are usually associated with the same spatial scale as meanders and thus represent types of channel patterns, whereas bars are associated with macroforms (Jackson 1975; Chalov 2008). The main type of island forming is bar

overgrowing. Island-braided channels distribute flow during the whole year. Islands submerged during high water stages cause the appearance of the single-thread channel ($\tau_p \geq 365 - T_n$). Channel length of the island-braided patterns has a length scale proportional to wave length of meandering channel and channel width (Makkaveev 1955; Hundey & Ashmore 2009).

Anabranching channel is defined as a special type, which may develop both from meandering when frequent neck cut-offs occur, and from braiding throughout vegetal colonization of bars and consequent island growth, accretion and avulsion. Anabranching channels are rather simple during low water periods when small distributaries usually dry off. Flow distribution increases during high water periods, $\tau_p \geq T_n$. Length of distributaries could be up to 50 times larger than the channel width.

Associated with different types of channel topography, each of the observed braided channel types requires an individual approach for classifying. Most challenging and contradictory is classifying of island-braided channels. The most elaborate scheme of island-braided and anabranching channel classification divided braided channels into solitary and conjugate, or simple and complicated. So-called 'single' and 'single-sided' braided reaches form the first group (Figure 4). Complicated channels include six types:

'conjugated' braided reaches where water flow crosses the river between banks (so-called 'figure of eight rule'); flow pattern at braided 'complex conjugated' and 'complex one-side' reaches where flow crosses the channel among large amounts of relatively small islands. All types of conjugated braided reaches are distinguished by discharge redistribution in the case of flow shifts among upper branches. Two or more general branches separated by long islands and connected by small streams form the essence of 'parallel-branching' reaches.

Existence of discrepant multi-channel patterns is proved by the statistical analyses. Thirty-two braided reaches of the Severnaya Dvina River basin were significantly discriminating using data sets (N, K_a, l, K_a/l, ΔN_1, ΔN_2). Through discriminant analysis island-braided (single; parallel-branch; single-sided; conjugated) and anabranching channels were separated. Further canonical analyses give discriminative roots R1, R2 … which were depicted by grouping values and their localizing in various parts of range (Figure 5) using linear function $X_1P + X_2P + X_3P + X_4P + X_5P$, where P is variable, $X_1 … X_5$ is canonical roots. Significant discrimination is observed for all channel patterns with the highest value through N and l coefficients (single Wilks' lambda defined as a measure of the class centers separation ranged between 0.66 and 0.68). The most
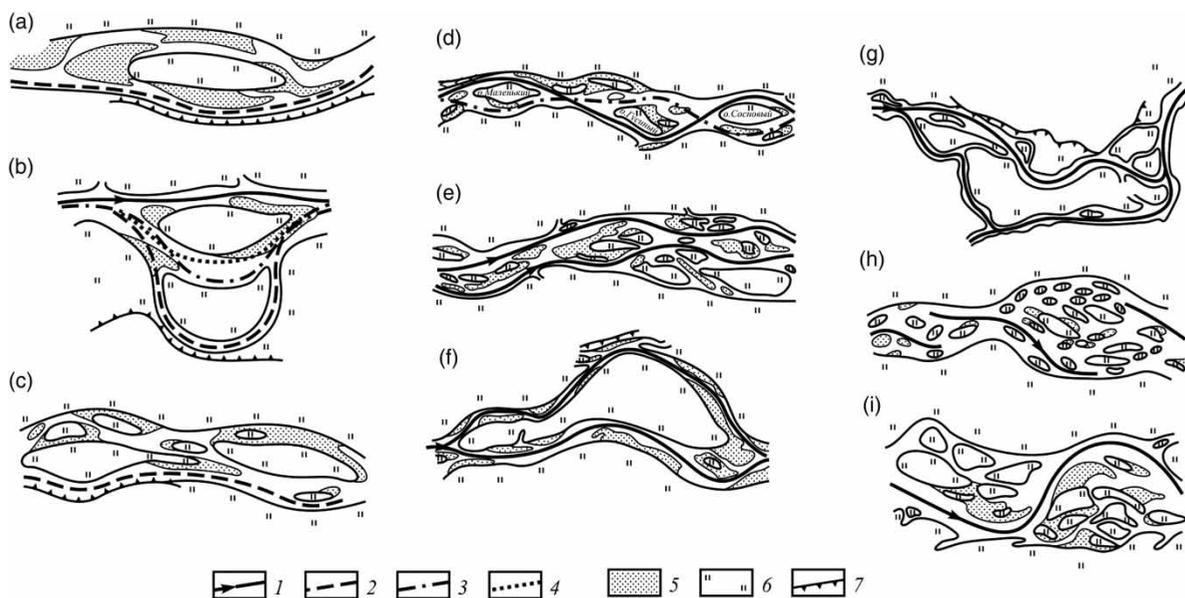

Figure 4 │ Island-braided and anabranching channels (Chalov et al. 2008). Simple: (a) single; (b) single-sided. Complex: (c) complex single; (d) conjugated; (e) parallel-branched; (f), (g) anabranching; (h) complex conjugated; (i) complex one-side. Dynamic axis of the flow: 1, modern; 2–4, previous; 5, side bars; 6, floodplain; 7, valley.
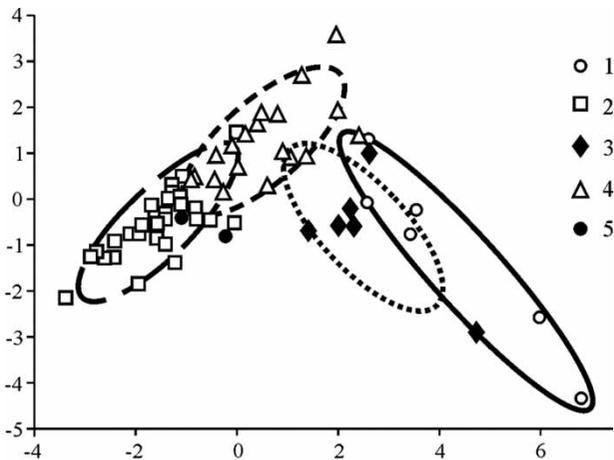
Figure 5 | Discriminant functions (roots) of braided patterns groups: anabranching (1) and types of island-braided channels (2, single; 3, parallel-branch; 4, one-side; 5, conjugated (Severnaya Dvina basin).

significant discrimination concerns anabranching channel in comparison with island-braided channels. Less discrepancy is demonstrated by indices of single and single-sided, as far as anabranching and parallel-braided channels are concerned. The same approach applied to the various hierarchical levels of distributaries (bar-braided, island-braided, and anabranching) demonstrated more significant discrimination between the reaches using quantitative data (B_{∂}, B_p, B, B_{∂}/B, B_p/B, K_a, $K_{a,\text{мх}}$, l, K_a/l).

The discrimination of braided channel types also have geographical scope. Bar and island-braided patterns are associated with various types of flow partitioning, which are dependent on stream size, sediments, and hydraulics regime (Table 2). We grouped braided reaches of large

plains sandy rivers; large and middle plains gravel-bed rivers; small mountain gravel-bed rivers; small plains rivers; large and middle semi-mountain gravel-bed rivers. The significant discrepancies are connected with channel density K_a/L. The smallest values of the observed variables are associated with large plains sandy rivers ($K_a/l \leq 1,3 \text{ km}^{-1}$; $\Delta N_2 = 0.06$–0.4). Gravel-bed rivers in a similar environment correspond to higher values of braiding intensity (up to 5 km^{-1}) with the fair values of flow partitioning ΔN_2. Smallest rivers where channel density increases demonstrate two-fold growth in flow partitioning ($\Delta N_2 = 0.3$–0.7). The largest values of K_a/l (up to 100 km^{-1}) are associated with semi-mountain gravel-bed rivers.

Hydrological effects of braided rivers

Hydrological effects of braided channels represent physical, hydrochemical, and ecological changes along braided reaches caused by flow partitioning among branches in relation to braiding intensity. We hypothesized that flow partitioning and braided channel types have an influence on the spatial patterns of sediment load, water temperature, and aquatic communities. The insight is provided by linear longitudinal gradient:

$$K = X_{nb}/X_b, \qquad (23)$$

where X is the studied variable (e.g., channel slope, sediment load, water temperature, and water species biomass and density), which is calculated as average for the parent channel (X_{nb}) and along the braided reach (X_b).

Hydraulics

Existence of additional hydraulic resistance is a distinguishing feature of braided river reaches. The most affected hydraulic parameter is channel slope. During low water stages the steepening of the slope in the divided reach is reported from classical analysis by Makkaveev (1955) and Leopold & Wolman (1957).

Local braided reaches demonstrate few changes in hydraulic parameters. Backwater profile upstream from the grains is characterized by $\partial h/\partial x > 0$ and $\partial v/\partial x < 0$, where h and v are average depth and flow velocity respectively. Along and

Table 2 | Braided channels types and flow partitioning indices

Braided channels types	Channel pattern	Flow partitioning indices		
		K_a/l	ΔN_1	ΔN_2
Large plain sandy rivers	1, 2, 3	≤ 1.3	0.8–6.5	0.06–0.4
Large and middle plain gravel-bed rivers	1, 2, 3	1.3–5	2.68–7.1	0.18–0.4
Small mountain gravel-bed rivers	2, 3	>5	1.1–2.8	0.3–0.7
Small plain rivers	2	>5	2–3.4	0.25–0.4
Large and middle semi-mountain gravel-bed rivers	2, 3	>100	3–3.9	0.3–0.5

Structural level of braided channel: 1, bar-braided; 2, island-braided; 3, anabranching.

downstream from grains usually a drawdown curve exists ($\partial h/\partial x < 0$ and $\partial v/\partial x > 0$), which causes turbulent flow. Data from laboratory flumes and natural rivers (Table 3) were investigated in order to compare undivided individual reaches and braided channels (bar-braided, island-braided, and anabranching channels). During low water stage flow partitioning determines increased water surface slope: $I_{nb} < I_{br}$. The observed phenomena could be explained by aggradation within the braided channel and associated increase of channel bed slopes. Another affected hydraulic parameter is water surface width B, which is increased both with a decrease in a mean depth h. Under constant discharges relative width B/h in the braided reach is larger, whereas hydraulic radius R decreases (Rhzanitcyn 1985). For small rivers I_b/I_{nb} is larger, e.g., during low water stage on the small mountain Uksichan River ($N = 6.7$) I_b/I_{nb} achieves 9.2, on the Bistraya River ($N = 9.5$) a value of 9.7 was observed. A less significant increase corresponds to bar-braided channels, e.g., on the semi-mountain Vetvey River ($N = 9.3$) $I_b/I_{nb} = 4.7$.

Less significant discrepancies in hydraulic parameters were observed during high water stages. At the Nachilova River anabranching reach ($N = 3.8$) I_b/I_{nb} declines from 8.1 during low water period to 2.0 during floods. Submerging of islands and floodplains by high water levels and associated transformation of flow pattern are regarded to be the main factor for the observed phenomena. At the braided reaches of the large plain, rivers (e.g., Vychegda

River, Table 3) this seasonal alteration is less evident than for the mountain rivers. This generally supports the findings that the behavior of a bifurcation is mainly related to the actual hydraulic conditions and geometry at the nodal point (Bolla *et al.* 2003).

Hydraulic changes have a certain impact on the morphodynamic discrimination of the channel pattern types as far as depends on floodplain area, channel width and water surface area F_{ws}. F_{ws}/L ratio achieves maximal values along anabranching and island-braided channels. Single-thread channels of the Middle Amur River are associated with $F_{ws}/L = 600$ m^2/km, whereas for single and single-sided island-braided channels $F_{ws}/L = 900$ m^2/km. Along anabranching channels $F_{ws}/L > 1{,}000$ m^2/km.

Sediment transport

Due to water partitioning along channels, sediment transport is affected significantly. Flow pattern alterations along a braided reach induce changes of amount and types of mobilizing sediments. In some braided rivers suspension has been reported as a dominating transport mode (Meunier *et al.* 2006), whereas generally abundant bed load transport is usually considered as the fundamental feature of braided channels (e.g., Ashmore 2001; Germanoski & Schumm 1993). As far as measurement and prediction of cross-section averaged bed load transport rate in braided rivers has been a

Table 3 | Average channel slopes upstream and downstream I_{nb} and along braided reaches I_b

Stream	Braided reach type	Water stage	I_{nb},‰	I_b,‰	I_b/I_{nb}	Data source
Mezen River (Russia)	2	Low water	0.18	0.3	1.7	Authors
Mezen River (Russia)	2	Low water	0.29	0.57	2.0	Authors
Nachilova River (Russia)	3	High water	2	16.2	8.1	Authors
		High water	7	13.9	2.0	
Vetvey River (Russia)	1	Low water	0,6	2.8	4.7	Authors
Uksichan River (Russia)	2	Low water	4	37	9.2	Authors
Bistraya River (Russia)	2	Low water	1	9.7	9.7	Authors
Enisey River (Russia)	2, 3	Low water	0.05	0.14–0.71	2.8–14.2	Bely *et al.* (2000)
Vichegda River (Russia)	3	Low water	0.15	0.286	1.9	Snischenko (1968)
		High water	0.69	1.02	1.5	Authors
Horse River (USA)	2	Low water	0.022	0.073	3.3	Leopold & Wolman (1957)
Laboratory flumes	1	–	<0.02	>0.02	>1	Schumm (1977)

Structural level of braided channel: 1, bar-braided; 2, island-braided; 3, anabranching.

long-standing problem due to technical complexity and instability of braided rivers (Bertoldi *et al.* 2009), in the present analyses we used surrogate measures of transport capacity in order to explain the transport description parameters. In the case of braided reach for each river cross-section transport capacity was determined as

$$R_{tr} = \sum_{i=1}^{K} (R_{tr,i}),$$ (24)

where $R_{tr,i}$ is transport capacity in the i-segment, k is number of segments intersected by cross-sections of the river. Degree of transport capacity change is characterized by the ratio between transport capacities in the parent channel and in the i-segment

$$\alpha_y = \frac{\sum_{i=1}^{K} (R_{tr,i}) - R_{tr}}{\sum_{i=1}^{K} R_{tri}}.$$ (25)

$\alpha_y > 0$ corresponds to increase of transport capacity along braided channel. For the R_{tr} assessment we used Rossinsky and Kuzmin's equation (Rossinsky & Kuzmin 1964)

$$R_{tr} = Qk\frac{v^3}{hu},$$ (26)

where $k = 0.024$. R_{tr} is associated with bed and suspended load which could be transported by the given flow.

Combined data (Table 4) illustrate the increase of transport capacity at low water levels (below bankfull discharges) along the braided reach in comparison with the undivided parent channel. Dependence on channel slope follows Equation (26): $R_{tr} \sim v^3$ and thus $R_{tr} \sim I^{3/2}$. Analysis of flow partitioning along braided channels of large plain rivers demonstrates the simultaneous increase of α_y and ΔN_2. The highest values of flow partitioning ($\Delta N_2 = 0.4$, braided reach at Ob and Lena rivers) correspond to highest values of α_y ($\alpha_y = 0.9$). During high water periods decrease of transport capacity along braided reach is observed due to hydraulic resistance increase and corresponding changes of flow pattern connected with island submerging (Table 4).

Corresponding seasonal changes of suspended and bed load depend on rates of channel erosion and deposition. During low water stages an increase of both suspended and bed load was observed along braided reaches of both plain and mountain rivers (Alexeevsky & Chalov 2009). This follows a general increase of transport capacity in comparison with undivided reaches. The reverse situation is observed during high water stages. Examples from Lena, Ob and small mountain rivers demonstrate a general decrease of suspended and bed load, whereas individual sediment load along separate segments could be either increasing or decreasing. For example, along a 30 km anabranching reach of the Lena River near Yakutsk city ($Q = 24,930$ m³/s) total suspended load R in various channel varied between 2,300 and 3,230 kg/s causing $R > R_{tr}$.

Table 4 | Results of transport capacity estimating for braided reaches at low water (l) and high water stages (h)

| River | Braided reach | | | | R_{tr} | | $\sum (R_{tr,i})$ | |
	Name	Type	N	ΔN_2	l	h	l	h
Severnaya Dvina	Holmogorskoe	3	16.5	0.24	11	85	49	24
Lena	Yakutskoe	3	17.8	0.4	300	2700	720	2000
Ob	Karposkoe	2	14.8	0.4	4	–	30	–
	Umrevinskoe	2	15.5	0.3	90	–	130	–
Enisey	Shushenskoe	3	14.6	0.3	47	–	160	–
	Altaiskoe	3	14.6	0.18	35	–	145	–
Kirenga	Bannoe	2	14.3	0.39	5	–	20	–
Protva	Satinskoe	2	8.3	0.25	0.03	–	0,07	–
Vetvey	Unnamed	1	9.3	0.12	0.6	–	4	–
Nachilova	Unnamed	3	3.8	0.29	18.6	–	21,7	–

Structural level of braided channel: 1, bar-braided; 2, island-braided; 3, anabranching. '–', no data.

Along the braided reach suspended load decreased up to 0.4%, whereas bed load was two times less in the low part of the reach than in the undivided reach upstream. This phenomenon is mostly connected with sediment deposition on the islands' surface. This has also important implications for the further understanding of the bed load transport along braided reaches (Mao & Surian 2010), in particular with the role of the active width temporal and spatial variability, which was reported recently to have a certain discharge threshold, below which active width is negligible and above which it increases monotonically with discharge (Ashmore et al. 2011).

Temperature

Hydrological variables influencing water temperature in rivers include the source of the water, relative contribution from groundwater, current velocity, and water depth (Arscott et al. 2001; Alexeevsky & Chalov 2009). The latter parameters are a function of channel form, water volume, and substrate type, and primarily depend on water discharges. Thus, in braided rivers flow partitioning plays the key role in water temperatures. Temperature regimes in the main channels and side braids are influenced by variations in channel discharge, and the relative contributions of groundwater and surface water runoff. Water temperatures at the same time in different branch channels of braided rivers may be distinctly different; commonly, backwaters and small side channels fed by seeps and springs are noticeably cooler than the main channel, but some side channels may also be markedly warmer (Mosley 1983).

Calculating average temperature θ of the segments intersected by cross-sections of the river enables an equation for assessing longitudinal changes of water temperature to be derived

$$\Delta\theta = \theta_2 - \theta_1, \tag{27}$$

where θ_1 is average water temperature in the upstream part of the braided reach, θ_2 is average water temperature in the lower part of the braided reach. The ratio of thermal transformation along the braided reach could be expressed as

$$K_{\theta i} = \theta_i / \theta_0, \tag{28}$$

where θ_0 is average water temperature of the undivided channel above the bifurcation. Thermal homogeneity occurs when longitudinal gradient along the braided reach is absent ($K_{\theta i} = 1$). If $K_{\theta i} > 1$ thermal heterogeneity increases and longitudinal growth of water temperatures along the braided reach is observed.

Stream temperature and its in-channel variability usually vary on seasonal and daily timescales. Previous empirical data evidenced (Mosley 1983) that during the summer period maximum temperatures are inversely proportional to discharge. A few studies (e.g., Stanford et al. 2005) reported that temperatures in small side-braids were lower than main channel temperatures because of the increased influence of groundwater. Both examples confirm the significant role of flow partitioning. During the winter season cooling of water causes warming of small channels by underflow seepage from the streambed (Arscott et al. 2001). At negative air temperatures, cooling could be reflected in heterogeneity of ice cover (Alexeevsky & Chalov 2009).

The assumption that water temperature depends on the net heat exchange at the water surface was used to design a theoretical equation to compare water temperatures of individual channels (1 and 2) in a braided reach during time duration Δt:

$$\theta_1 - \theta_2 = \frac{1}{c_\theta \rho \Delta t} B_R \left(\frac{h_2(l_1/v_{01}) - h_1(l_2/v_{02})}{h_1 h_2} \right) \tag{29}$$

where h, l, v are average depth, length, and average velocity; B_R is radiation balance, ρ is water density, c_θ is specific heat capacity. Numerical simulations using Equation (29) showed that along braided reaches of large rivers ($N > 15$) smaller channels should have a greater rate of temperature increase (and, therefore, higher temperatures) than larger braids. Even at relatively low flow partitioning ($\Delta N_2 < 0.2$) temperature differences achieve 0.2 °C ($B_R = 10$ MJ/m^2). Less significant changes of water temperature are expected at small rivers ($N = 9$) – under low flow partitioning ($\Delta N_2 < 0.1$) below 0.1 °C, and up to 0.25 °C if $\Delta N_2 = 0.4$.

Increased role of net heat exchange at the water surface at larger rivers (stream order increase N) was confirmed by temperature profile records in various braids of seven Russian rivers during summer days (air temperature $\theta_B >$

18 °C) (Table 5). Increases of river size N, braided reach length l and index of flow partitioning ΔN_2 cause temperature heterogeneity. Type of braided pattern (structural level of channel topography) also is of crucial importance: anabranching channels are associated with rather significant temperature discrepancies, whereas bar-braided channels represent a relatively homogeneous thermal pattern, even if flow partitioning is relatively high.

River type and associated hydraulic conditions of water flow have a special effect on temperatures of braided reaches Braided reaches of mountain and semi-mountain rivers, due to slow heat exchange at the water surface, are less dependent on flow partitioning ΔN_2. Usually water temperatures in adjacent channels are constant (if the groundwater impact is rather low). Under similar hydrological conditions (river size and flow partitioning) water temperatures at the different branch channels of several plains rivers may be distinctly different. For example, up to 2 °C differences between small branches and parent channel were observed at Severnaya Dvina braided river in midsummer days ($\theta_в = 25$ °C) (Table 5).

Ecology

Physical characteristics of aquatic habitats in the branches of braided rivers cause different combinations of water depth, water velocity and temperature and bed sediment type and have different suitabilities for species of water fauna. Braided rivers are distinguished by changes of fish and benthic habitats in comparison with single-thread channels (Tockner et al. 2006; Chalov & Esin 2007). They show a very high overall biodiversity, and are particularly important regionally. Tockner et al. (2006) focused on shoreline benthic communities and argued that braided rivers offer various categories of refugia such as shore areas, hypogeic and hyporheic habitats that are pivotal for maintaining diversity.

Effects of the hydrological processes of braided rivers on fish populations were studied in the rivers of the Kamchatka peninsula (Chalov & Esin 2007) where the largest world population of wild Pacific salmon reproduces. Juvenile fish habitats' density depends on refugia such as woody logjams, ponds, riverside scours, etc. Stream dividing usually induces the woody debris accumulation (four to five times more in comparison with non-braided reaches) (Esin & Chalov 2011). Benthic biomass and average juvenile salmon density was reported to increase up to two times from non-braided and braided reaches (e.g., from 8.2 up to 12.0 g/m², and 0.3 up to 0.7 specimen/m² in case study rivers). Fish population complexity and abundance differ between main and secondary streams of the anabranching channels. Usually, inside braided reaches, total benthic production grows sharply

Table 5 | Observed changes of water temperature along braided reaches during summer days ($\theta_в = 18$–26 °C)

River	N	Braided reach	Type of braided reach	ΔN_2	K_z/l, m^{-1}	$\theta_2-\theta_1$ °C	$K_{\theta i}$
Mountain rivers							
Nachilova	3.8	Unnamed	3	0.29	75	0	0
Levtyrinyvayam	4.5	Unnamed	1	0.34	47	0	0
Semi-mountain rivers							
Bistraya	9.8	Unnamed	3	0.31	200	0	0
Vetvey	9.3	Unnamed	1	0.14	15	0	0
Plains rivers							
Protva	8.3	Satinovsloe	2	0.25	68	0	0
Oka	13.5	Sosnovskoe	2	0.13	1	0.3	1.02
Severnaya Dvina	15.6	Payachnoe	3	0.2	0.9	1	1.03
	16	Kalkurskoe	2	0.17	1.1	0.7	1.04
	16	Orlovskoe	2	0.15	1	1.5	1.09
	16	Medvedok	2	0.25	0.5	2	1.12

Types of braided reaches: 1, bar-braided; 2, island-braided; 3, anabranching. '–', no data.

and the maximum density of juvenile salmon agglomerations is achieved. Braided reaches are characterized by the maximal specific juvenile fish abundance (12 to 13 species). Distinctions of juvenile salmon density between branches of anabranching and island-braided reaches increase in larger streams. In the large rivers fish prefer to live in small side-branches which play a role as a refugia.

With regard to adult salmonids, the role of braided reaches is connected with diverse heterogeneous conditions of in-channel morphology, flow hydraulics, sediments, and temperatures (Gostner et al. 2011). Maximal intensity of spawning and spawning area is observed along braided reaches in comparison with single-thread channels (Figure 6). Anabranching channels, due to hierarchy of structural levels and involvement of both bar-braided and island-braided reaches in their channels, usually represent the richest channel reaches. The sequence of deep (pools, riffle lee sides) and shallow (riffle ridges) sections along braided reaches induces the formation of most convenient and diverse life conditions. The high species richness and diversity in braided rivers can be explained by small-scale habitat mosaics encompassing aquatic habitats. The variability of hydrological conditions determines high density and biodiversity changes, which are primarily devoted to the structure of braided channels and degree of flow partitioning.

CONCLUSION

Braided channels exhibit many kinds of numerous channels (flows) that split off and rejoin each other. Braided reaches are part of dendritic drainage networks, inverse to channel junctions. River channel junctions as part of dendritic drainage networks represent longitudinal increases of water and sediment runoff, whereas bifurcations cause downstream partitioning of flow and longitudinal water discharge decrease. Flow partitioning is regarded to be the main hydrological phenomenon of braided channels. A new approach to assess branches' size and associated flow partitioning is given through applying the order numerical systems to the braided channels (so-called 'conventional stream orders').

Various types of braided channels in different spatio-temporal scales are connected with structural levels of channel topography and occur under scales of grains, bars (emerged riffles), islands, and floodplains. The distinction between braided patterns types is proved by braiding intensity and flow partitioning indices. Flow partitioning varies between braided reaches of large plains sandy rivers; large and middle plains gravel-bed rivers; small mountain gravel-bed rivers; small plains rivers; large and middle semi-mountain gravel-bed rivers. Existence of discrepant multi-channel patterns is a fundamental element of braided river morphology and
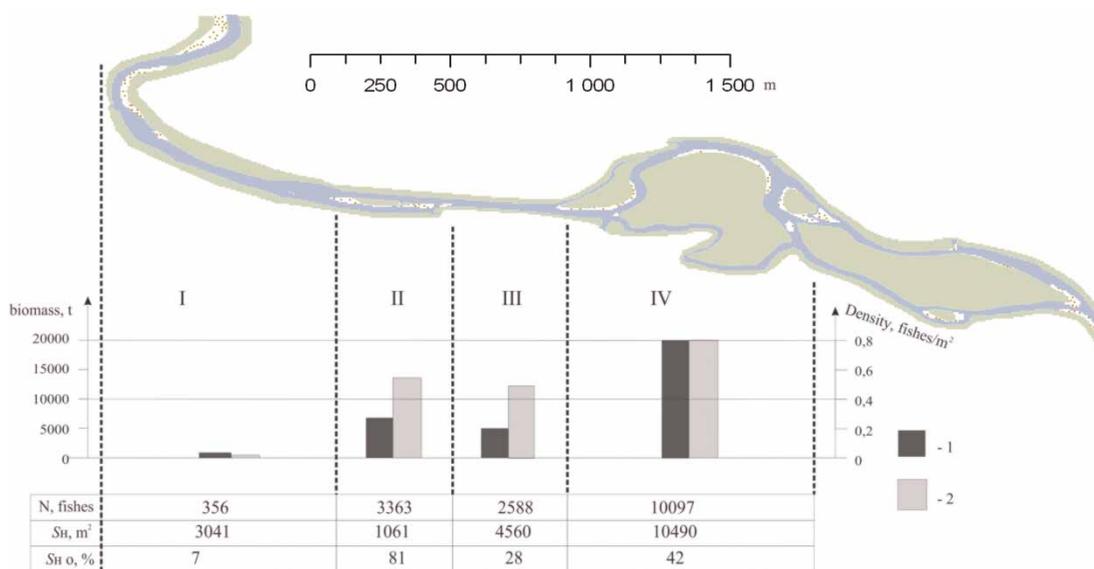

Figure 6 │ Changes of salmon spawning along straight single (II), meandering (I), bar-braided and anabranching reaches. N, number of specimens, ind.; S_H, spawning area; S_{Ho}, relative spawning area; 1 – biomass, t; 2 – spawning density, fishes/m².

suggests that braided patterns are created by processes that could be discriminated by the measures of the planforms and discharge partition in downstream branches.

Flow partitioning is crucial for hydrological effects of braided channels. Impacts on water and sediment discharge, water temperatures and stream communities could be studied on the basis of linear longitudinal gradient. Changes of water surface slope, sediment load, water temperatures in comparison with single-thread channel vary according to seasonal timescales. Due to these alterations braided rivers are spatially complex, temporally dynamic habitats with the highest biodiversity values along the river continuum. Most hydraulic, sediment transport, and ecological parameters of braided reaches are associated with the measure of the discharge partitioning.

ACKNOWLEDGMENTS

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