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ScienceDirect
Geomorphology 98 (2008) 262–274
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Predicting changes in alluvial channel patterns in North-European Russia under conditions of global warming

Oleg Anisimov [a,*], Jef Vandenberghe [b], Vladimir Lobanov [a], Alexander Kondratiev [a]

[a] State Hydrological Institute, Second Line V.O., 23, 199053 St. Petersburg, Russia
[b] Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

Accepted 27 December 2006
Available online 18 May 2007

Abstract

Global climate change may have a noticeable impact on the northern environment, leading to changes in permafrost, vegetation and fluvial morphology. In this paper we compare the results from three geomorphological models and study the potential effects of changing climatic factors on the river channel types in North-European Russia. Two of the selected models by Romashin [Romashin, V.V., 1968. Variations of the river channel types under governing factors, Annals of the Hydrological Institute, vol. 155. Hydrometeoizdat, Leningrad, pp. 56–63.] and Leopold and Wolman [Leopold, L.B., Wolman, M.G., 1957. River channel pattern: braided, meandering and straight, Physiographic and hydraulic studies of rivers. USA Geological Survey Professional Paper 252, pp. 85–98.] are conventional QS-type models, which predict the existence of either multi-thread or single-tread channel types using data on discharge and channel slope. The more advanced model by Van den Berg [Van den Berg, J.H., 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology 12, 259–270.] takes into account the size of the sediment material.

We used data from 16 runoff gauges to validate the models and predict the channel types at selected locations under modern and predicted for the future climatic conditions. Two of the three models successfully replicated the currently existing channel types in all but one of the studied sites. Predictive calculations under the hypothetical scenarios of 10%, 15%, 20% and 35% runoff increase gave different results. Van den Berg's model predicted potential transformation of the channel types, from single- to multi-thread, at 4 of 16 selected locations in the next few decades, and at 5 locations by the middle of the 21st century. Each of the QS-type models predicted such transformation at one site only.

Results of the study indicate that climatic warming in combination with other environmental changes may lead to transformation of the river channel types at selected locations in north-western Russia. Further efforts are needed to improve the performance of the fluvial geomorphological models and their ability to predict such changes.
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Keywords: Climate change; Fluvial morphology; Modeling

1. Introduction

Climatic change in the 20th century has led to a 0.6 °C global temperature rise and slight to moderate increase in precipitation in many northern regions (Houghton et al., 2001). Results from general circulation models and analysis of weather records indicate that future warming and changes in precipitation are likely to be more pronounced in the high latitudes than in other parts of the world, and significant environmental impacts may be expected. In this paper we discuss the potential effects of climatic change on river patterns.

* Corresponding author. Tel.: +7 812 234 58 94; fax: +7 812 323 10 28.
E-mail addresses: oleg@oa7661.spb.edu (O. Anisimov), jef.vandenberghe@falw.vu.nl (J. Vandenberghe).

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doi:10.1016/j.geomorph.2006.12.029

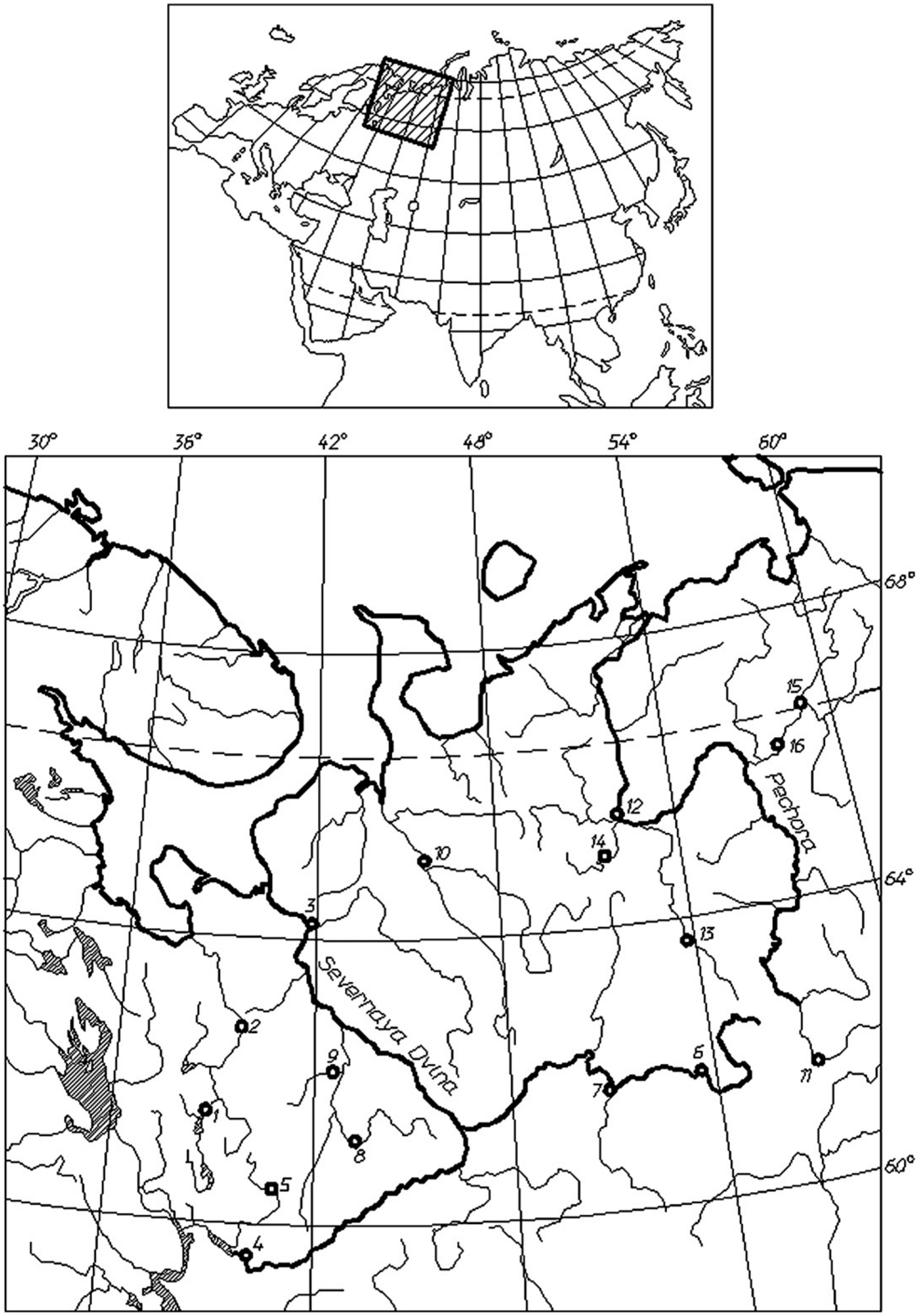

Fig. 1. Location of the study region in North European Russia.

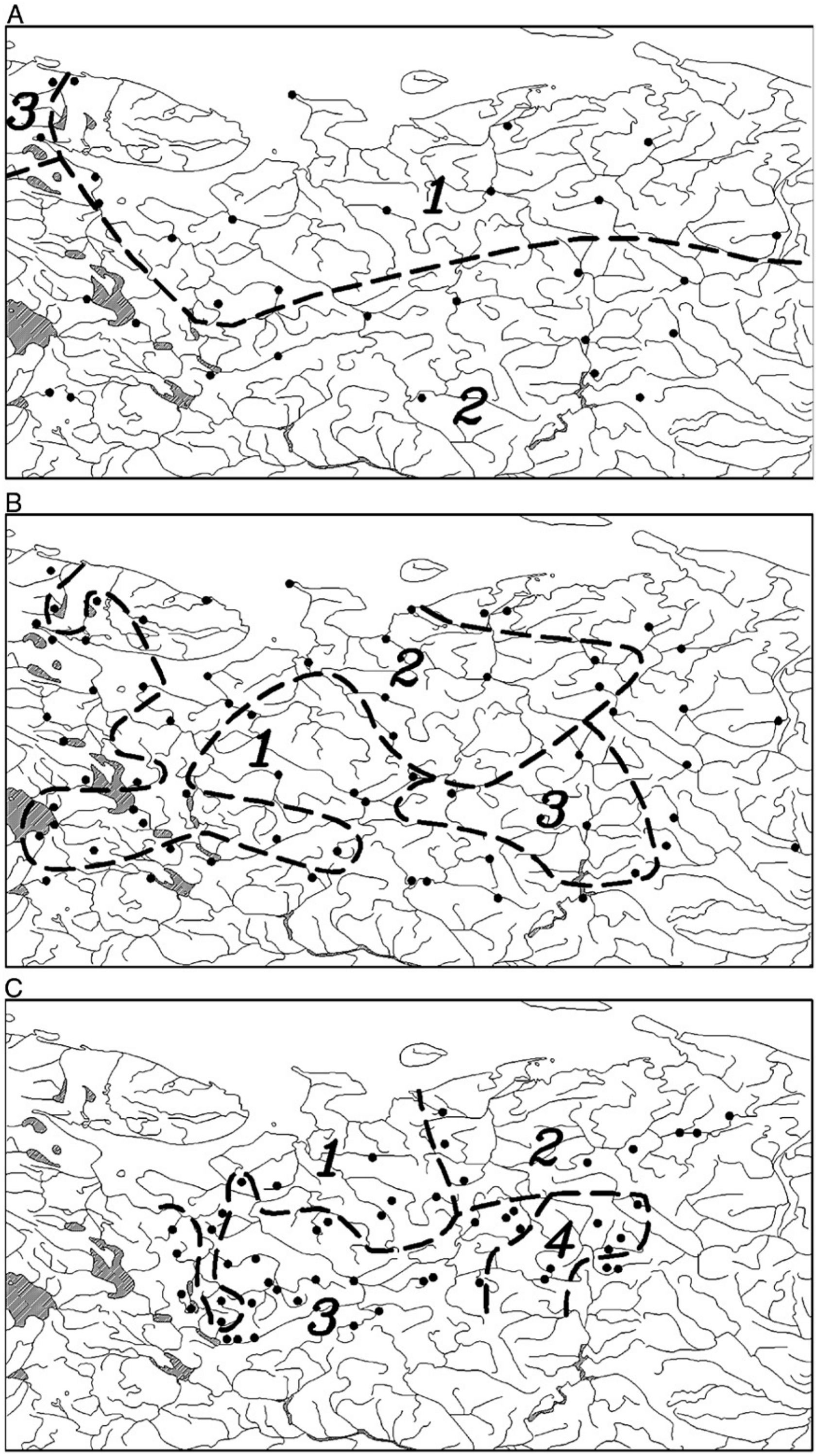

Fig. 2. Regionalization of the study area with respect to changes in the air temperature (A), precipitation (B), and runoff (C) in the 20th century. Circles indicate locations of weather stations and runoff gauges used in this study. See text for further explanation.

Therefore, we use quantitative basin and channel characteristics to evaluate the effectiveness of categorizing river channel types into a prescribed number of classes. Finally, we want to compare the potential future changes of the river channel patterns in northern Russia as predicted by different geomorphological approaches.

The European Russian North is crossed by several large rivers that show a wide variety of channel patterns ranging from meandering and anabranching to braided rivers, and rivers that are annually shifting between meandering and braided styles. The study region (Fig. 1) falls into several bio-physiographic zones, from boreal forest in the south to tundra underlain by permafrost in the north, and is characterized by a distinct gradient of climatic and environmental conditions.

Fig. 2 illustrates the regionalisation of North-European Russia with respect to temperature (Fig. 2a), precipitation (Fig. 2b), and runoff (Fig. 2c) changes that took place in the 20th century and are likely to continue into the future. The method that we used to develop this regionalisation is detailed by Lobanov and Anisimov (2003). The data presented in Fig. 2 indicate that the changes of climate and runoff were not uniform. In the century-scale retrospective the air temperature was relatively stable in the northernmost locations of the study area (region 1), was characterized by an increasing trend in the last decades in the southern part (region 2) and a decreasing trend in the Kola Peninsula (region 3). Annual precipitation shows no change in almost the half of the study area (region 1), a decreasing trend in the northern part (region 2) and a small increase in the south-eastern part (region 3). As concerns river runoff, the Severnaya Dvina river basin shows cyclic fluctuations (region 3), the Pechora basin has a stable runoff (region 2), while two other regions are characterized by reduced (region 1) and increased annual runoff (region 4) largely corresponding with their precipitation regimes.

Results of an earlier study conducted in the Usa catchment indicated that phases of incision and subsequent changes in the river channel patterns during the Holocene often coincided with climatic and environmental

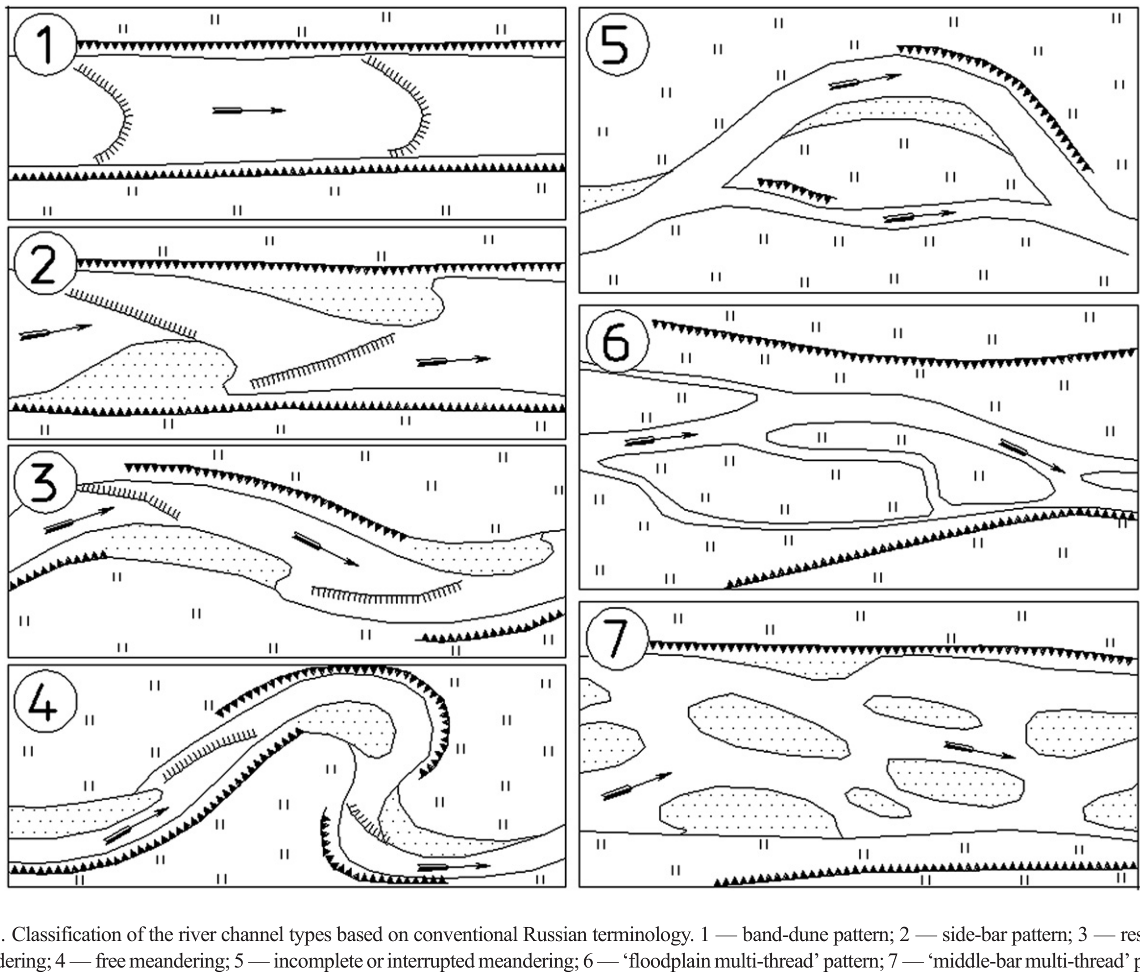

Fig. 3. Classification of the river channel types based on conventional Russian terminology. 1 — band-dune pattern; 2 — side-bar pattern; 3 — restricted meandering; 4 — free meandering; 5 — incomplete or interrupted meandering; 6 — ‘floodplain multi-thread’ pattern; 7 — ‘middle-bar multi-thread’ pattern.

(i.e. vegetation, permafrost) changes (Vandenberghe and Huisink, 2003). These data provide empirical evidence of the impacts that climatic warming and associated environmental changes may have on the fluvial morphology ultimately leading to transitions between different river channel types. To get insight into such potential processes under projected climatic conditions and runoff, we applied several scenarios to hydro-geomorphological approaches that may predict river pattern evolution.

2. Fluvial geomorphological models and channel classifications

There are several computational methods that are used to predict alluvial channel patterns under prescribed environmental conditions. They are typically based on the assumption that the transitions between the different channel types are threshold-governed processes. Alluvial channel patterns form a continuum rather than discrete types (Bledsoe and Watson, 2001), but threshold-based approaches imply the distinction between a finite number of morphologic classes with somewhat fuzzy boundaries. Classifications that have been developed so far delineate different numbers of river channel types, which complicates the comparison of results from different models.

Russian fluvial geomorphology traditionally employs classifications that operate with relatively large numbers of channel types. A typical example is given by the classification developed at the Russian State Hydrological Institute that has 7 classes. For modelling purposes, however, it is more appropriate to use a reduced number of river types. The hierarchy of such classifications is illustrated in Fig. 3.

Theoretically, the complexity of classification depends on the availability of information about the features that

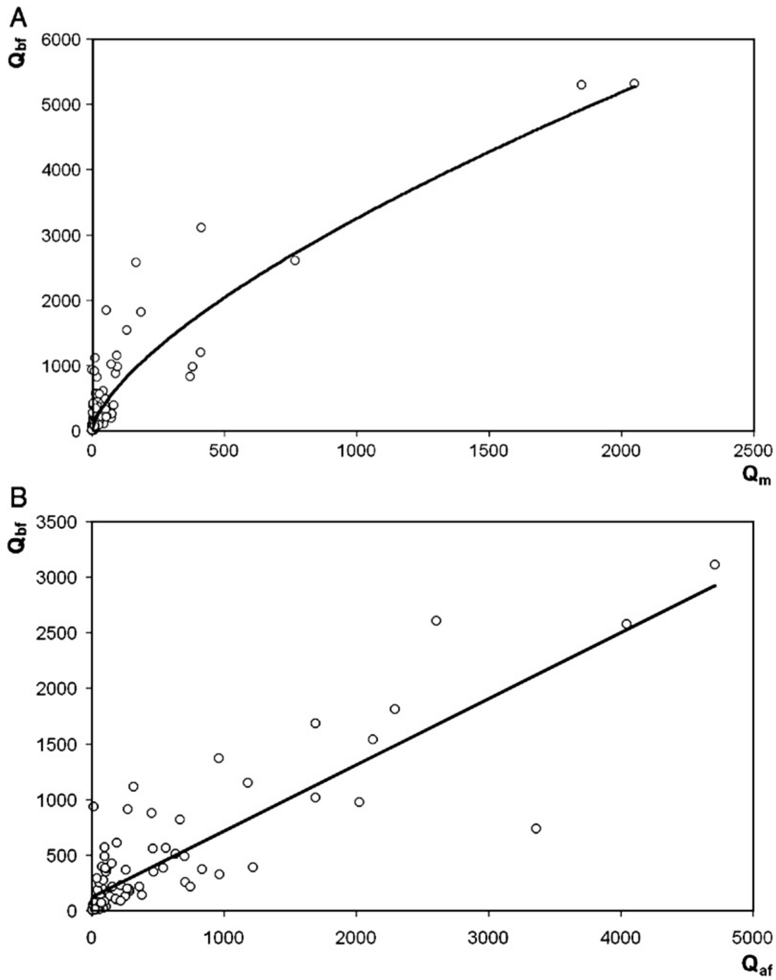

Fig. 4. Empirical approximation of bankfull discharge (Q_{bf}) through mean annual discharge (Q_m) (A) and maximum annual flood (Q_{af}) (B), derived from data from Russian rivers.

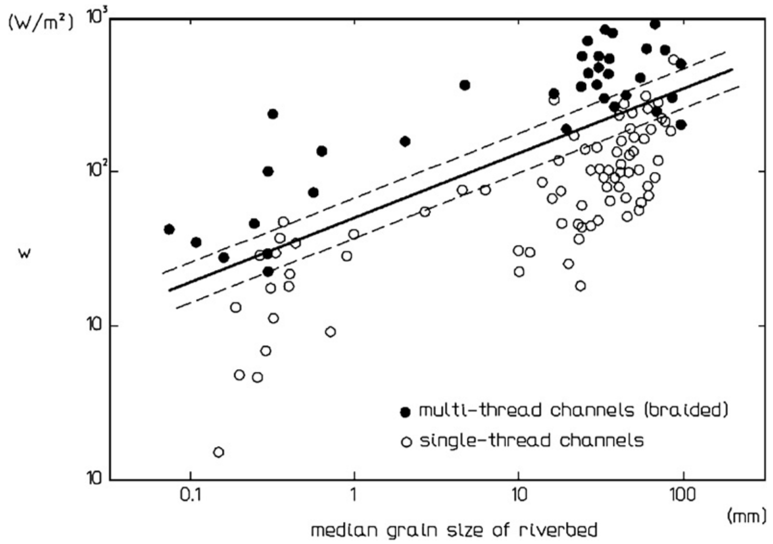

Fig. 5. Transition zone between the single-and multi-thread channels in as a function of $\acute{\omega}$ and D_{50}. The solid line designates the hard divide introduced by Van den Berg (1995), dashed lines designate the boundaries of a ±35% transition zone. The plot is based on the data by Van den Berg (1995).

essentially distinguish one class from the other. Ideally, a classification might be developed that would reflect the differences in morphological features, alluvium, channel geometry, intensity of sediment transport, etc. In reality, however, such a detailed information is rarely available, which is especially true in the case of predictive modelling.

The majority of classification models in fluvial geomorphology use either the relation between discharge and slope of the river (QS-type models; e.g. Leopold and Wolman, 1957; Schumm, 1977), or the combination of both these values and the average grain size (Van den Berg, 1995). Ratios between these variables are compared with the different channel types. It implies that in the modelling studies the number of channel types to be considered is limited by the ability of the specific model to resolve the differences between them. The better the model resolves the features that are essentially different between classes, the more classes may be distinguished in a model-based predictive assessment.

While most of the QS-type models distinguish between the two major channel classes, meandering (single-thread) and braided (multi-thread), Russian fluvial geomorphology often employs the model that considers three channel types. QS-thresholds for that model have been derived on the basis of the analysis of data from 250 observational points on the rivers of the

Table 1
Baseline characteristics of 16 Russian rivers under contemporary climate

No.	River/site	Q_m, (m^3/s)	Q_{af}, (m^3/s)	S_r, (‰)	D_{50}, (mm)	Channel type
1	Onega — Nadporogsky Pogost	117	366	0.32	0.70	S
2	Onega — Zmiyevo	386	2220	0.36	0.60	S
3	Severnaya Dvina — Ust-Pinega	3330	21700	0.30	0.69	M
4	Sukhona — Raban'ga	135	489	0.27	0.20	S
5	Kubena — Troitsko-Enal'skoe	11.2	160	0.65	0.69	S
6	Vichegda — Malaya Kuz'ba	250	1880	0.31	0.66	S
7	Vichegda — Syktuvkar	622	4180	0.30	0.66	SM
8	Ustja — Shangali	87.6	1040	0.49	0.90	S
9	Ledj – Zeleninskaya	17.1	177	1.34	0.70	S
10	Mezenj — Malonisogorskaja	644	5760	0.48	0.61	M
11	Pechora — Yaksha	154	1450	1.75	0.70	S
12	Pechora — Ust-Tzilma	3440	23700	1.00	0.62	M
13	Ukhta — Ukhta	46.8	501	0.83	1.18	S
14	Pizdma — Borovaja	48.7	565	0.62	0.69	S
15	Usa (site Adzva)	931	9380	0.06	0.40	S
16	Usa (site Makarikha)	1100	11300	0.15	0.30	M

former USSR (Romashin, 1968). According to the conventional Russian approach, free meandering rivers have a QS < 350 m^3/s; the so-called non-complete meandering (type 5 of the Russian classification in Fig. 3) is characterized by 350 m^3/s < QS < 1400 m^3/s, whereas the braided rivers have QS > 1400 m^3/s (Romashin, 1968).

Many authors recognized the limitations of the simple QS models in neglecting the bed material. Various QS-thresholds suggested by different researchers are based on the analysis of data coming from the rivers with different bed materials, and as such represent hypothetical "average" conditions with respect to sediment size. The "average" values of the critical stream power appear to be too high for sand bed rivers and too low for gravel bed rivers (Carson, 1984). More advanced models define the slope of the transition lines between braided and meandering also as a function of the bedload grain-size (Henderson, 1966; Carson, 1984; Ferguson, 1987; Van den Berg, 1995).

Emphasizing the complexity of river processes that underlie the patterning of river planforms, e.g. Lewin and Brewer (2001, 2003) deny the possibility of using simple hydraulic parameters to explain the channel planform (Van den Berg, 1995). Lewin and Brewer (2001, 2003) question especially the reliability of the river width and stress the need for including other important parameters as bedform development, leading to a separation of relationships for sand-bed and gravel-bed rivers. In their reaction to the latter comments Van den Berg and Bledsoe (2003) agree with most theoretical considerations by those authors, but stress the distinction between a theoretical approach and practical applicability. For instance, bedform distribution is difficult to use, given the very limited amount of available observational data for natural rivers. The 'stability diagram' of Van den Berg (1995) is aimed to provide 'a rough indication of the channel pattern that will develop when conditions change', as has been done for instance by Vandenberghe (2001) in the case of climatic

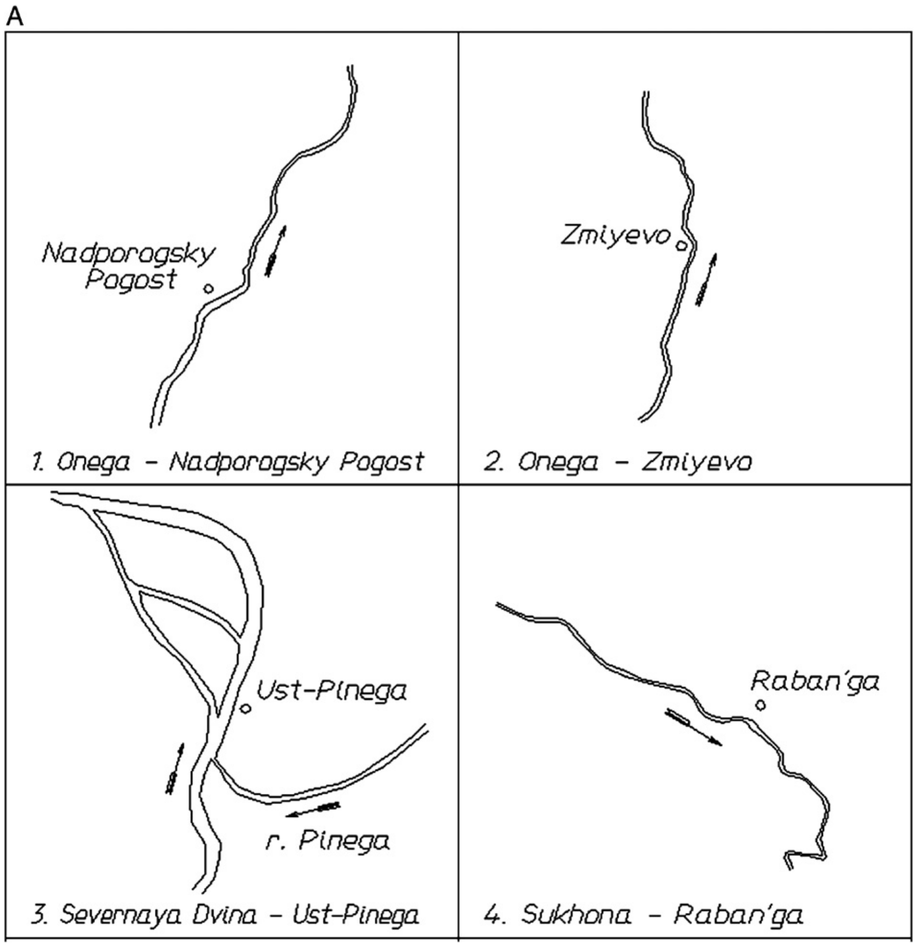

Fig. 6. River channel types at 16 selected locations in the study region.

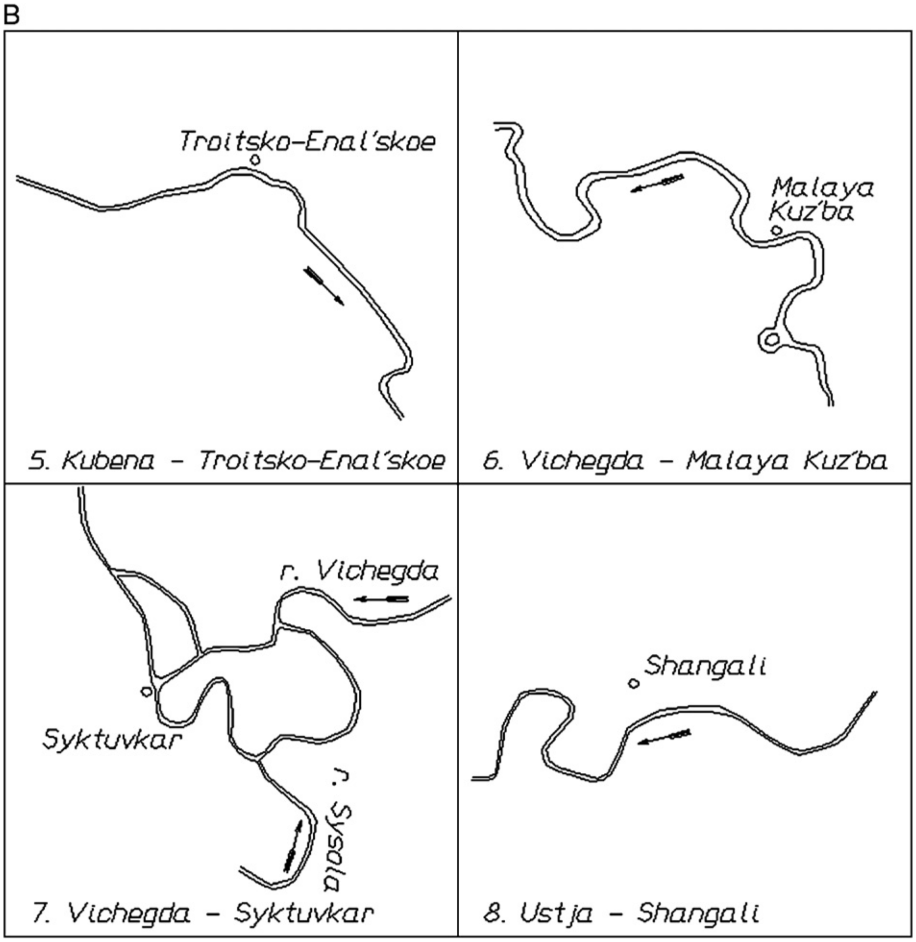

Fig. 6 (*continued*).

change (Van den Berg and Bledsoe, 2003). Pattern dependant geometric or hydraulic parameters are not useful to be incorporated in such diagrams.

3. Modeling potential channel transformations under predicted future climate conditions

We focus our further analysis on the potential impact that changes of climate and runoff may have on the fluvial channel patterns in North-European Russia. In this study we use three different fluvial geomorphological models illustrative for Russian and western studies. Two of them are the QS-type models by Leopold and Wolman (1957) and Romashin (1968). Although Romashin's model considers three different river channel types, we use the aggregated 2-grade classification that distinguishes between meandering (single thread) and braided (multi-thread) rivers. The third model is more advanced, explicitly takes into account the size of the sediments, and is detailed in the publication by Van den Berg (1995). We reassessed the data from 228 rivers presented by Van den Berg (1995) and made two modifications to his model, which are the following:

Firstly, because the data on the bankfull discharge (Q_{bf}) for the study region is not available, we derived empirical equations that express Q_{bf} through the maximum annual flood (Q_{af}) and mean annual discharge (Q_{m}). Observational data for those empirical equations are obtained from Russian rivers (Fig. 4):

$$Q_{\mathrm{bf}} = 0.594Q_{\mathrm{af}} + 126.9, \qquad (1)$$

$$Q_{\mathrm{bf}} = 31.26Q_{\mathrm{m}}^{0.67}, \qquad (2)$$

Correlation coefficients between the discharge characteristics in Eqs. (1) and (2) are 0.86 and 0.81 respectively, indicating similar coherence in both equations. The reason for this modification is a practical one: it is more convenient to measure the maximum annual flood than the bankfull discharge, and thus a

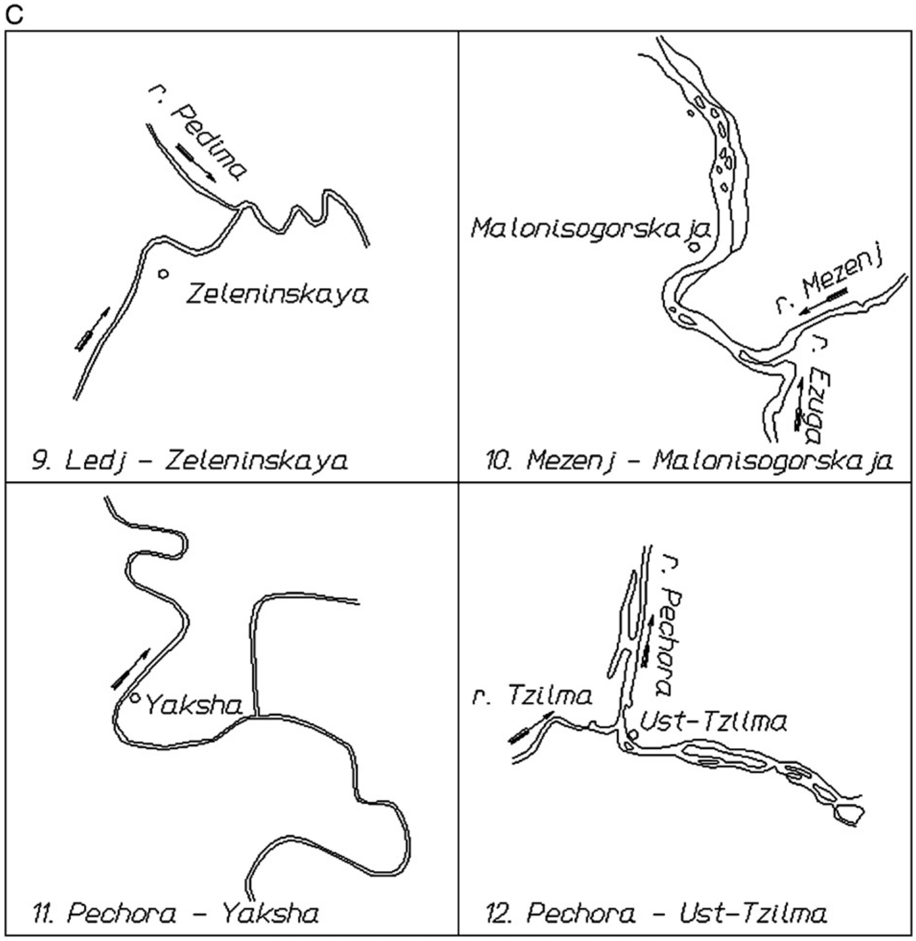

Fig. 6 (*continued*).

higher number (and more reliable) data are available for Q_{af} than for Q_{bf}. In addition, width (used to calculate the stream power) may be better measured during maximum annual flood than estimated from bankfull discharge as did Van den Berg (1995). This partly avoids the criticism of Lewin and Brewer (2003) of 'an unjustifiable regime-based relation between bankfull discharge and bankfull width in the van den Berg method'.

Secondly, we made a re-analysis in order to estimate the mean error, of the empirical equation that was derived by van den Berg (1995) to express the critical unit stream power $\acute{\omega}_c$ through the median grain size of the sediments, D_{50}:

$$\acute{\omega}_c = 900_{50}^{0.42}. \tag{3}$$

This equation plays a key role in the model, defining a boundary line in the logarithmic $\acute{\omega}-D_{50}$ diagram between rivers with single and multi-thread channels. In our re-analysis we assume $\varepsilon=0$ if the model predicts the presently existing type of the river channel. In the opposite situation we attribute the discrepancy to the effect of statistical errors in Eq. (3), which may be expressed as $\varepsilon=|\acute{\omega}-\acute{\omega}_c|$. Here þ is the unit stream power that is calculated using the equation in the Van den Berg (1995) model through bankfull discharge, which is calculated through measured parameters in Eqs. (1) or (2). According to our results, the standard error may be as high as 70% of calculated $\acute{\omega}$. In contrast to Van den Berg (1995), we consider a transitional zone surrounding the "hard" divide between channel types as has been done also for instance by Lane in 1957. In our study for any $\acute{\omega}_c$ given by Eq. (3) we defined the lower and upper bounds of the transition zone as þ$_c$±35%. The transition zone is represented in Fig. 5, which was constructed using data from the publication of Van den Berg (1995). This transition zone may account for the statistical bias mentioned by Lewin and Brewer (2001, 2003) caused by the data quality and the complexity of the processes that underlie the patterning of channel planforms.

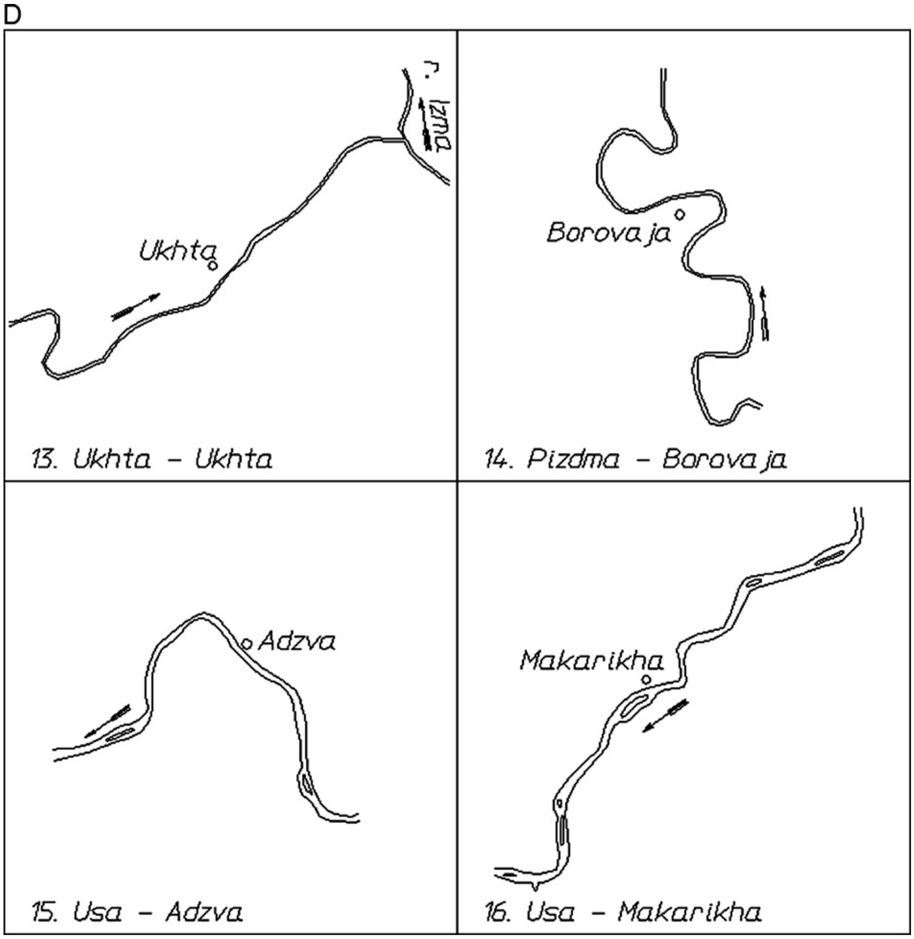

Fig. 6 (*continued*).

All three models were validated using data for the rivers in the North-European part of Russia. Of 54 runoff gauge sites shown in Fig. 1 only 16 have the full set of input data for the Van den Berg (1995) model. These data for the contemporary baseline climatic conditions are presented in Table 1. Single-and multi-thread channel types in the last column are designated as S, and M, respectively. The channel type of the river Vichegda changes from single- to multi-thread near the city of Syktuvkar (gauge 7), this is indicated in the table as SM. River channels at the locations selected for our study are shown in Fig. 6.

These data have been used to test the three selected models. Bankfull discharge (Q_{bf}) was calculated through the maximum annual flood (Q_{af}) and the mean annual discharge (Q_m) using Eq. (1) and (2) and averaged. All other parameters, i.e. the critical stream power and the unit stream power were calculated using conventional equations presented in the paper by Van den Berg (1995). The models by Van den Berg (1995) and by Romashin (1968) replicate the observed channel types in all but one gauge (No 12, Pechora-Yaksha); Leopold and Wolman's (1957) model gives wrong results at gauges 9, 11, and 16. Interestingly, while Romashin's model was formulated specifically for Russia using data from more than 250 rivers, van den Berg derived the semi-empirical equations in his model using data from 228 rivers elsewhere in the World. However, the results from both models for Russia were equally accurate, i.e. fifteen positive out of sixteen tests.

4. Potential fluvial development

Our main goal was to study potential transformations of the river channels under projected future environmental conditions. Such transformations may occur largely due to changes of runoff, but also due to variations of other factors, such as the grain size of the riverbed material, permafrost occurrence and vegetation changes in the river valley.

Table 2
Projections of future changes in annual runoff

Author, year	Climate scenario	River basin	Discharge change (%)	
			Annual discharge	Winter discharge
Miller and Russell (1992)	Canadian, GISS $2xCO_2$	Yenisey, Lena, Ob, Kolyma	from +10 to +45	
Georgievsky et al. (1996)	GFDL $2xCO_2$ UKMO $2xCO_2$	Inflow into the Barents Sea	+14–35	+25–46
Arnell (1999)	HadCM2 HadCM3 6 scenarios by 2050.	Yenisey Lena Ob Kolyma Mackenzie Yukon	+6–14 +12–25 +3–10 +30–40 +12–20 +20–30	
Miller and Russell (2000)	GISS CO2: +0.5%/yr to 2100	Arctic total Eurasian rivers N. American rivers	+12 +9 +23	
Mokhov et al. (2003)	HadCM3	Yenisey Lena Ob	+8 +24 +4	
Mokhov et al. (2003)	ECHAM4	Yenisey Lena Ob	+8 +22 +3	

A survey of the scientific literature indicates that constructing a scenario of future changes in river runoff is a difficult task. Available estimates have been obtained using specially developed hydrological models that were forced with scenarios of climate change. These scenarios were based on various general circulation models (GCMs)-run with doubled CO_2 concentrations and transient increases of CO_2, and on paleoclimatic reconstructions. Selected projections in Table 2 (Hassol, 2005) fall into a wide range indicating that robust scenarios for changes in runoff are not available. Future changes of other factors that may lead to transformation of the channel types may also be predicted only on a qualitative basis.

Under these circumstances we limit our further analysis to sensitivity tests targeting them to the response of the fluvial regime to gradual increases in annual runoff by 10%, 15%, 20%, and 35% compared to the modern norms. This range corresponds with the changes projected for the mid-21st century by different authors (Hassol, 2005).

Results from three geomorphological models forced with the described runoff data and with the other data as for the modern conditions unchanged are presented in Table 3. Data in this table are presented only for those sites, where the changes of the annual runoff according to the model's results should lead to transformation of the channel type.

5. Discussion and conclusions

The results of this study indicate that two of the three selected geomorphological models, while being equally accurate in predicting the modern fluvial regime, give significantly different projections under the potential changes of river runoff. According to the van den Berg model, river channels at sites 2, 7, 9, and 13 are potentially unstable even under the current conditions, although the critical stream power is not yet reached. They are situated in the transition zone defined by þ$_c$± 35%. In the conventional model, even a slight increase of the annual runoff by 10% leads to the situation that the critical stream power should be exceeded to transform the channel from the single-to the multi-thread type. The more advanced probabilistic approach, however, indicates that the unit stream power in this case will still be in the transition zone around the critical threshold where both single-and multi-thread type channels may be expected.

A further open question is what will be the changes of other environmental factors, such as vegetation in the

Table 3
Potential changes of river channel types predicted by three geomorphological models under gradual increase of annual runoff

No of site	Channel type at present			Potential changes of channel type under projected increase of annual runoff (%from modern)											
				10%			15%			20%			35%		
	VB	LW	RM	VB	LW	RM	VB	LW	RM	VB	LW	RM	VB	LW	RM
2	S	S	S	M			M			M			M		
7	S	S	S	M			M		M	M		M	M		M
9	S	M	S	M			M			M			M		
13	S	S	S	M			M			M			M	M	
14	S	S	S										M		

Designations in the table: VB—model by Van den berg; LW—model by Leopold and Wolman; RM—model by Romashin; S = single channel, M = multi-channel. For the other sites no pattern change is predicted.

river valley and permafrost that largely control the input of sediments to the river and the stability of the banks. It has to be kept in mind that in these scenario experiments all other factors than runoff remain constant. But warmer climatic conditions will favor vegetation growth and permafrost retreat. An earlier and longer transition from winter to spring will lead to more protracted snowmelt, with less intense peak runoff. Deeper seasonal thawing and loss of permafrost will increase the water storage capacity of the ground, leading to an increase in summer base flow. Ultimately, under warmer climatic conditions there will be less seasonal fluctuation in runoff throughout the year (Anisimov and Fitzharris, 2001). Given that the transformations of the river channels under appropriate conditions like those projected for our selected sites should normally be initiated by the significant disturbances of the fluvial regime, seasonal redistribution of runoff may somewhat offset the effect of increased annual discharge.

In a hydrological model study of the Usa basin Van der Linden (2002) found that GCM-simulation scenarios for the near future lead to increases in annual discharge at the end of the twenty-first century by 25%–38% and evapotranspiration up to 44%. However, discharges depend on the balance between both temperature and precipitation: changes in evapotranspiration (as a result of temperature changes) may be counterbalanced by changes in precipitation. In addition, model results may differ largely as a function of the hydrological model used and the climate scenario. Also the possible feedback effects related to, for instance, snow and vegetation should be taken into account (Koster et al., 2005). In contrast to the considerable effects of climate change on discharges, indirect effects –for instance on vegetation–are minor according to Van der Linden et al. (2003).

On a Holocene time scale Vandenberghe and Huisink (2003) show obvious effects of vegetation density changes on sediment supply in the same Usa basin. Thus it seems that the combination of changes in both discharge regime (possibly induced by permafrost degradation) and vegetation density (of climatic or anthropogenic origin) may have the largest effects on river activity and morphology, as they define both transport capacity and sediment supply. It confirms that the functionality between fluvial morphology and hydrology, and climate change, water balance and vegetation is—in the long term—a complex one, as described by Woo (1990), Woo et al. (1992) and Vandenberghe and Woo (2002).

According to Lewin and Brewer (2003) the chosen approach, more particularly the simplicity of the parameters used, is only useful when the channels are far from the designated threshold line. However, we feel that the bias that is induced by this 'simplicity' is largely overcome by the introduction of a 'diffuse transitional zone' rather than a sharp line in the original van den Berg model. In fact, the 'stability diagram' in Fig. 5 appears to be a very useful and well performing assessment tool in scenario studies, more particularly in the discrimination of the classic channel patterns.

Acknowledgements

Support for this research comes from the National Science Foundation of the Netherlands, NWO grant 047.011.2001.003, and the Russian Foundation for Basic Research, grant 04-05-64488. The paper benefits from the useful comments made by T. Coulthard and L. Starkel.

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