PRACE GEOGRAFICZNE, zeszyt 127

Instytut Geografii i Gospodarki Przestrzennej UJ
Kraków 2011, 61–70

Roman S. Chalov

FLUVIAL PROCESSES AS A REFLECTION OF RIVER SEDIMENT TRANSPORT

EXAMPLES FROM RUSSIA

Abstract: Sediment transport is one of the main elements of fluvial processes; and with it fluvial processes themselves are elements of sediment supply into rivers. The amount of sediment transported by a stream is determined by its carrying capacity, which changes in line with spatial and temporal changes in stream hydraulic characteristics. Correlations between them set the conditions for vertical channel deformation. When a riverbed is composed of heavy material, stream carrying capacity is realized due to horizontal channel deformations. The complexity of correlations between fluvial processes and sediment transport is determined by the transport of the latter in suspended and bed load forms, permanent conversions from one form to another in line with changes in stream hydraulic characteristics along and across the river channel, from the high-water to the low-water period versus the water flow in river branches.

Sediment load itself and its magnitude determine the development of channel relief forms and the transformation of straight channels to meandering or braided channels. The main role in channel development is played by bed load flow. The ratio of bed load to suspended load determines changes in morphometric channel characteristics and its stability as well as effects the development of channel meanders and river bifurcations. At the same time, it is important to take into account the proportion of suspended and bed load components and their proportion in channel-forming sediment.

Key words: river channel, fluvial processes, river sediment, river bed load

Introduction

Sediment transport is one of main components of fluvial processes; the latter being the system of phenomena appearing due to the interaction of stream flow and the river bed and further influx of sediment into a stream because of bank and bottom erosion. Therefore, fluvial processes themselves are the essential driver of sediment transport formation. However, only a part of the transported sediment is of in-channel origin. Ratio between wash load supplied from the watershes and bed load originated from in-channel sources and amount of sediment transported in suspension determine the various expressions of fluvial processes in rivers. Sediment transport patterns correspond to the dynamic of channel flow,, amount of transported sediments, intensity and type of channel shifts..

Methods

The entire volume of transported sediments consists of two types of sediments – in-channel and basin constituents, i.e. $W=W_{\mathrm{bas}}+W_{\mathrm{chan}}$. Sediments of channel origin consist of river bottom and bank erosion products; sediments of basin origin enter rivers due to erosion processes (slope erosion, soil erosion, gully erosion, linear erosion) and other denudation (gravitational) processes in river basins. These processes facilitate the transport of suspended sediments, which move in the water column and are measured via the determination of the suspended sediment concentration in water samples. Sediments of channel origin consist mainly of bed load, which is transported near the bottom or in the form of dynamic ridges of varying dimensions (a complex form of channel relief) or without ridge formation. Such unstructured sediment transport is typical of fast-moving mountain rivers (Froud number Fr>1) and plain rivers with fine channel forming sediments for which $V_{\mathrm{m}}>2.5V_{\mathrm{n}}$ (V_{m} – mean stream velocity, V_{n} – non-scouring velocity for sediment particles of definite size). Independently, the total sediment yield W is formed by total suspended load W_R and bed load W_G:

$$W=W_R+W_G$$

However, the boundary between sediments of channel and basin origin as well as between suspended load and bed load sediment is rather uncertain and even relative. It is possible to describe only the predominance of one of them in relation to river basin relief, lithology and resistance against the erosion of rocks and deposits present on river basin and river valley slopes, vegetation type (first of all: basin forest cover) and extent of human activity. The form of sediment transport (suspended or bed load) depends on the hydraulic characteristics of stream flow and is characterized by permanent spatial and temporal changes: sediments of the same grain size may possess suspended or bed load status during different water regime phases. Furthermore, they transform from one form to another in different parts of the channel due to the displacement of the main stream over the flow cross section.

This is why in the view of fluvial processes and sediment transport as a constituent thereof and vice versa, it is important to separate channel forming and fast-moving sediments and evaluate the correlation between sediment transport and sediment transport capacity, i.e. the maximum amount of sediment which may be transported by stream flow with certain hydraulic characteristics:

$$W_{\mathrm{tr}} \approx W_{R+G}$$

This also experiences spatial and temporal changes determining the direction and rate of channel deformation in different parts of the channel, along the river channel, in different water regime phases, due to long-term water flow changes. First, they determine the direction of vertical channel deformations – incision and sediment accumulation – which lead to the raising or lowering of the riverbed level: general – along the longitudinal profile, local – within morphologically common reaches, riffles and conjugated groups of them. In the first case, if $W_{R+G} < W_{\text{tr}}$ the river incises; degradation of the longitudinal profile curve occurs along the entire river or a considerable part of it during long-term and geological time periods reflecting general changes in water flow, the influx of erosion products into the river from the basin or tectonic changes in relief. In the other case, we mean local fluctuations in stream energy losses due to the straightening of meanders, development of more straight channel branches or their elongation, the formation of local sediment deficits in the case of their accumulation upstream or sediment abundance in the case of additional influx of erosion products. The seasonal riffle regime is closely associated with the aforesaid changes: the upstream riffle in the group becomes more shallow but the next riffle becomes eroded; during flood recession and low-water periods, the upper riffle becomes eroded and erosion products accumulate on the downstream riffle.

In the course of channel deformation, the river in certain cases begins to erode massifs of sand such as Tolokonnaya Mountain on the Severnaya Dvina River, Belaya Mountain on the Zeya River, Tulukoni on the Viluy River and Kilakhskiy Razboy on the Lena River. Tolokonnaya Mountain began to erode in the late 19th century, while in earlier times, it had been protected from the river by the local flood plain. A major influx of sediment into the river (the front of erosion is a few kilometers, the height of the “Mountain” is 30 m, the depth of the pool near it is 20 m, the rate of erosion – 15–20 m/year) led to the formation of a complex shallow reach downstream due to floodwaters backing up as the flood plain narrows from 15–20 km to 1.5–2 km and becomes replaced by an incised flood plain.

Sediment transport capacity W_{tr} in the case of a sediment yield deficit is realized first of all via bottom erosion. This is associated with water stream forces directed at the separation of particles from the bottom and with the much more stronger contact of the water stream with the channel bottom versus the channel banks as well as with bank protection from erosion by point-bars and vegetation. Only if $W_{\text{тр}} > W_{R+G}$ and in the case of the unwashed bottom of bedrock or cohesive material channels is $W_{\text{тр}}$ realized by horizontal channel deformations (bank erosion). It usually leads to channel widening and the formation of very complex morphodynamic channel types.

Sediment transport capacity is usually calculated only for suspended sediment. In the Russian research literature, methods described by K.I. Rossinskiy and I.A. Kuzmin (1964) are the most popular of methods. It is assumed that the water turbidity of a stream in the state of its maximum saturation corresponds to its sediment transport capacity. It is evaluated using the upper curve of the following mathematical relationship:

$$s_{\text{tr}} = k\frac{V^3}{hw}$$

where V – stream velocity, h – stream depth, w – hydraulic sediment particle size, k – coefficient.

This calculation method may be used in cases with a predominance of suspended sediment transport in total sediment transport. However, research in the last two decades has shown that the range of correlation between suspended sediment and bed load is rather broad. The latter prevail in many cases. Actually, W_{tr} may be realized due to the saturation of a water stream with suspended sediment with $w<V^*$, where V^* – vertical component of stream velocity. And with it, W_{tr} may be realized by the transport of bed load ranging from coarse sand to pebbles and cobbles. For example, in rivers in the Northern European part of Russia, the suspended sediment concentration during the low-water period is about several grams per m^3, while during the flood period, it is a few dozen grams per m^3, although channels are full of large sandy point-bars, riffles and spits, which move hundreds of meters during high-water periods and cause permanent deformations of the entire channel. This is why any calculation of W_{tr} must include an estimation of head losses related to the transport and suspension of sediments. This will then correspond to an integral estimate of sediment transport capacity as the limit of the annual sediment yield in light of the annual variability of water flow and the hydraulic characteristics of a water stream.

Results and discussion

The calculation of the correlation $W_{tr} \sim W_{R+G}$ becomes an estimation of the sediment transport balance along a river. For a stretch of river without any tributaries:

$$W_1 - W_2 = \Delta W_1,$$

where W_1 – amount of sediment influx measured at the upper cross-section of the given stretch of river, W_2 – amount of sediment outflow measured at the lower cross-section,

$$\Delta W \cong \left(W_{er} + \sum_{i=1}^{n} W_{er_i} + W_{den}\right) - W_{ac}$$

W_{er} – amount of sediment in the water stream due to channel erosion and with tributaries, n – number of tributaries, W_{ac} – amount of sediment deposited in the river channel due to accumulation processes, W_{den} – amount of sediment originating in gullies and associated with taluses and other denudation processes (Alekseevskiy 1998). A river's flow rate will either increase or decrease due to river incision or sediment accumulation. However, in this case, the real situation may be more complex. An increase in river water flow downstream of a point of confluence leads to a another increase in its transport capacity because $W_{tr} = f(Q^m)$ (Makkaveev 1955), where $m>1$, usually $m = 2–3$.

The complexity of correlations between fluvial processes and sediment transport is determined by the transport of the latter in suspended form and as bed load, permanent transitions from one form to another based on changes in stream hydraulic characteristics along and across the river channel, from the high-water to the low-water period versus the water flow of tributaries. The effect of stream hydraulic characteristics on its carrying capacity leads to the intermittence of sediment transport while the water flow is the same. On the one hand, riffles, riffle reaches and alluvial bars of different dimensions, and on the other hand, pools, pool reaches and the lowering of the riverbed bottom between alluvial bars take place. Meanwhile, the sediment balance in adjacent channel forms may be just the opposite. These peculiarities underlie the model of the seasonal development of pool-riffle systems: riffles are deposited during the flood-period and eroded during the low-water period (Fig. 1); on the contrary, pool-reaches accumulate sediments – products of erosion on upstream riffles – during the low-water period. In the case of conjugated development of adjacent riffles, accumulation and erosion processes take place during the anti-phase: while the upper riffle is eroded, the lower riffle is deposited and vice versa (Fig. 2). Riffle and pool reaches as a whole develop in the same manner. Meander cut-off and the development of a shallower channel branch are accompanied by an overflow of erosion products from the new branch (channel) downstream, where an increase in the size of shallows, the shoaling of riffles and meander shifting are observed.

Sediment transport itself and its magnitude determine the development of channel relief forms and the transformation of straight channels to meandering or braided channels. Meanwhile, the formation of initial channel meanders and water branch rounding over an island produce conditions for a local stream carrying capacity increase in spite of its elongation and increased energy loss in the first case and water flow spread over branches in the second case. This is associated with the peculiarities of the stream flow velocity regime at the meander or at the reach of channel bifurcation.

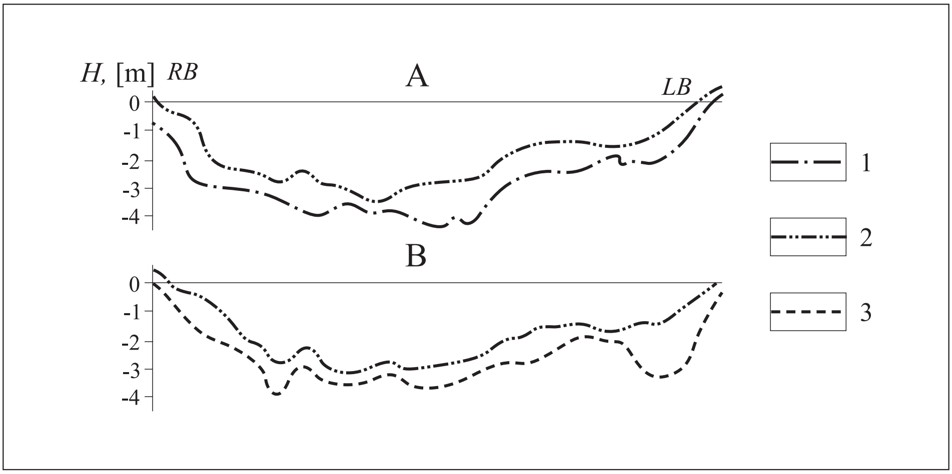

Fig. 1. Seasonal changes in bottom height marks on the riffle (deposition during flood-period – erosion during low-water period) – comparison of cross sections of the Orsko-Borskiy riffle on the Or' River (*Channel processes* … 2001)

A – flood-period, B – low-water period; 1 – May, 1988 (drawdown 201 cm), 2 – July, 1988 (drawdown 303 cm), 3 – September, 1988

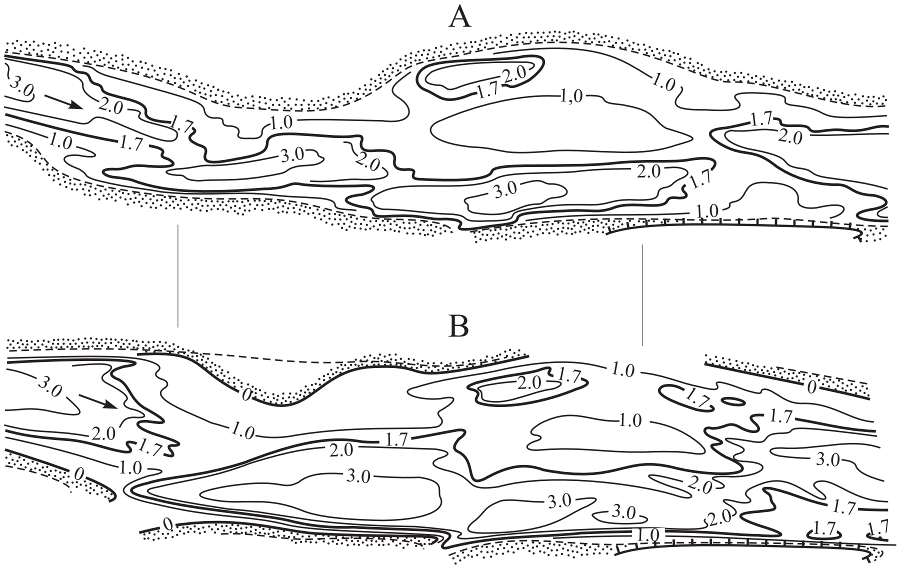

Fig. 2. Seasonal deformations on adjacent riffles (Sludskie riffles on the Severnaya Dvina River)

A – low-water period (20.08.1997, drawdown 30 cm): erosion processes at the upper riffle, sediment accumulation at the lower riffle; B – flood-period (August 18, 1998, drawdown 130 cm): shoaling of the upper riffle, erosion processes at the lower riffle

At the meander, there is an increase in stream kinetic energy $Э_{kin}$ which is proportional to the squared stream velocity and increase in the rate of flow, which is proportional to the cube of stream velocity (Makkaveev 1955). In real-world conditions, $Э_{kin}$ increases 50–80% at the channel bend. In a braided channel, the stream water distribution in general leads to local accumulation of sediment during flood-periods and the formation of riffles near the island head. However, downstream channel branch W_{tr} increases several-fold (Fig. 3) in comparison with the straight channel upstream of the bifurcation reach (Alekseevskiy, Chalov 2009). Riffles forming at bifurcations or at channel bends between adjacent meanders prompt a local increase in channel slope, which also leads to an increase in W_{tr}. This is why channel forms themselves (meanders and bifurcations) are not considered to be the result of systematic sediment accumulation or river incision. They reflect other processes occurring in the river channel and are associated with the peculiarities of sediment transport, water stream velocities (velocity field and circulation flow), channel width and the degree of stream flattening – for-

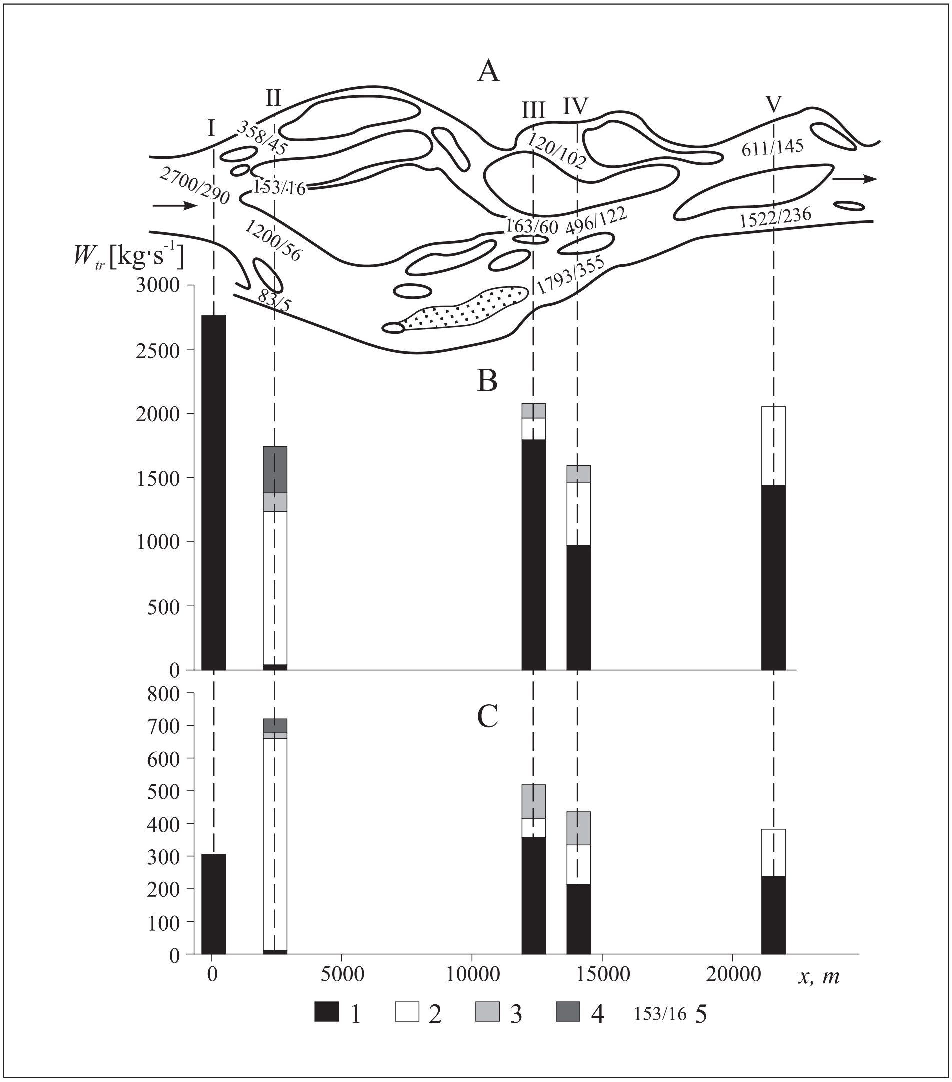

Fig. 3. Sediment transport capacity changes (with respect to suspended sediment) W_{tr} along the Yakutskoe bifurcation on the Lena River (Alexeevskiy, Chalov 2004)

A – channel map; diagrams of W_{tr} values in channel branches: B – during flood-period, C – during low-water period, 1, 2, 3 – in the first, second and third channel branches (from the right bank); 4 – value of W_{tr}: in the numerator – during flood-period, in the denominator – during low-water period

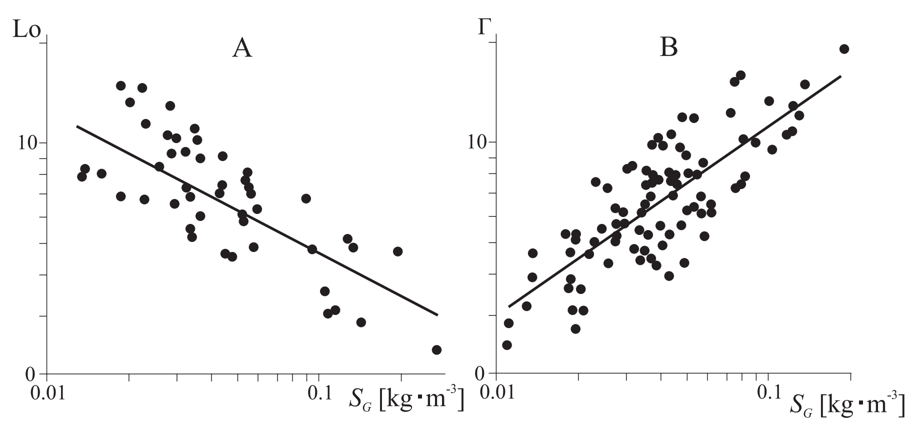

Fig. 4. Relationship between the channel stability coefficient – the Lokhtin number *Lo* (A) – and Glushkov's morphometric parameter Γ (B) with the average annual bed load concentration S_G (Reznikov 2006)

mation of several dynamic axes of a watercourse. Moreover, channel forms (meanders and bifurcations) and forms of channel relief (riffles, point-bars, alternate-bars and middle-bars) are considered to be a result of sediment transport on the one hand, and regulators of sediment transport on the other hand. Local increases in kinetic energy and the rate of flow along a river determine certain conditions that favor significant transport of material, as opposed to a case with no channel forms. In a rather straight unbraided channel, this is equalized by the arrangement of side-bars in a staggered order and associated with the tortuosity of the dynamic axis of a watercourse or the formation of a one-sided flood plain and the occurrence of a specific circulation flow pattern, which results in lateral sediment transport and its absence near non-flooded bedrock-based banks.

The main role in channel development is played by bed load including all bed load itself and a part of suspended sediment, all of which transitions into the form of bed load or bottom sediments, where a reduction in stream velocity and stream transport capacity occurs. This is why, under the same conditions, rivers with little bed load possess straight unbraided channels. Examples include rivers flowing out of bogs or lakes or through areas featuring non-eroded hard rocks. Large river channels become meandering or braided downstream due to an influx of sediments from their basin, tributaries, gullies and thanks to bank erosion. The same processes occur at the river valley bottom and channel while W_{tr} increases and a part of the bed load passes into the category of suspended load. At the same time, the predominance of suspended load in total sediment load in the case of high suspended sediment load and $W_R > W_{\mathrm{tr}}$ prompts the rapid destruction of meanders (at the stage of the initial bend of a watercourse dynamic axis) and filling in of channel branches with sediments. This is why straight unbraided channels are predominant along such rivers (Yellow river, Amudariya, Terek) but remain distinct in terms of major changes of riffles and other forms of channel relief. These channels can be usually classified as unstable (wandering) channels.

In order to estimate the effect of bed load on river channel morphology and dynamics, it is suggested to use its average annual specific value S_G [kg·m^{-3}] – the relationship between average annual sediment discharge G and average annual water discharge Q, i.e. $S_G = G/Q$ (Reznikov 2007). The displacement rate for riffles, side-bars and middle-bars is inversely proportional to channel stability characteristics such as the Lokhtin number Lo=d/I (d – average size of bottom sediment particles along a stretch of river, mm; I – river slope ‰) (Makkaveev 1955; Chalov 1979; Berkovich 2003) which reflects the rate of bed load transport. There exists an inverse relationship between S_G and Lo (Fig. 4A) for the Severnaya Dvina, Volga, Ob, Lena and Yana river basins. An increase in channel stability corresponds to a decrease in the transportability of channel-forming sediments as well as a decrease in bed load discharge and average annual concentration S_G. At the same time, the larger the S_G value, the larger the channel width and water stream flattening, i.e. the value of the Glushkov parameter

$$\Gamma = \frac{b_{\mathrm{ch}}^{0.5}}{h}$$

(reflects relationship between channel width b_{ch} and channel depth h) is directly proportional to the concentration of bed load in a water stream (Fig. 4 B). On meandering rivers, an increase in S_G is accompanied by an increase in developed meanders (development ratio l/L=1.4–1.7, where l – meander length, L – meander step), while the part with flat meanders (l/L<1.4) decreases. This is evidence of rapid development and transformation of smooth meanders due to an increase in bed load. However, the part of steep meanders with a more complex form (l/L>1.7) does not depend on the value of S_G because hydraulic factors play the more important role in its formation (Reznikov 2007).

Recapitulation

Sediment yield, bed load/suspended load ratio and its interseasonal variability is significant driver of fluvial processes in rivers. It causes implication to channel evolution description. Detailed analysis of interactions between sediment transport and fluvial processes determines the accuracy and reliability of channel deformation predictions, especially in the case of natural and anthropogenic changes to the natural environment and climate. Bed load which is the most difficult to measure and thus which is still insufficiently investigated is of crucial concern for fluvial processes. Its proper estimation underlies channel stability, channel pattern and adjustment of channel form predictions.

Acknowledgements

The study reported in this paper was undertaken with financial support from the Russian Fund for Basic Research (Project No. 09-05-00221-a).

References

Alekseevskiy N.I., 1998, *Formation and transport of river sediment*, MSU Publishers, Moscow. 203 pp. (in Russian).

Alekseevskiy N.I., Chalov S.R., 2009, *Hydrologic functions of a bifurcated channel*, Faculty of Geography at MSU, Moscow, 240 pp. (In Russian).

Berkovich K.M., Zlotina L.V., 2003, *Account of river channel stability in the case of an anthropogenic load*, Geography and Natural Resources, 4, 117-123 (in Russian).

Chalov R.S., 1979, *Geographic studies of fluvial processes*, MSU Publishers, Moscow, 232 pp. (in Russian)

Channel processes and waterways in the Ob' River Basin, 2001, RIPEL plus, Novosibirsk, 300 pp. (in Russian)

Makkaveev N.I., 1955, *The river channel and erosion in its basin*. The Academy of Sciences of the USSR Publishers, Moscow, 347 pp. (in Russian)

Reznikov P.N., 2006, *Effect of sediment load on the hydrological and morphological characteristics of river channels*, [In:] *General and applied aspects of erosion and fluvial processes*, MSU Publishers, Moscow, 194-201 (in Russian).

Rossinskiy K.I., Kuzmin I.A., 1964, *Balance method of channel bottom deformation estimation*, Proceedings of the Hydroproject, Sankt Petersburg, 2, 265-271 (in Russian).

Roman S. Chalov
Faculty of Geography,
Lomonosov Moscow State University,
Moscow, Russia
e-mail: rschalov@mail.ru