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Methodology for Assessing the Potential Danger of Horizontal Deformations of River Channels

Victor M. Katolikov, Nataliya I. Katolikova, Olga A. Petrovskaya

v.katolikov@mail.ru

State Hydrological Institute, Saint-Petersburg, Russia

ABSTRACT:

Relevance. In this paper, a methodology for expert assessing the danger of horizontal deformations of riverbed banks near settlements caused by natural channel processes unrelated to the influence of any hydraulic structures is proposed. **Methods.** The methodology is based on the postulates of the hydromorphological theory of the channel process, the improved hydromorphological classification of riverbeds and types of riverbed process, and the long-term experience of using this theory. It makes it possible to assess the degree of danger of riverbank erosion at a qualitative level based on the type of riverbed process determined by satellite images and morphological affiliation of the deformation site. **Results.** The method is designed to be used by specialists of authorities of the constituent entities of the Russian Federation making managerial decisions to protect the population from the effects of dangerous hydrological phenomena and take necessary measures for timely prevention of errors when making the above decisions.

KEYWORDS: potential deformations of channel, bank stability, type of channel process, hydromorphological type of channel, orographic channel, floodplain channel, concave bank.

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INTRODUCTION

The paper considers dangerous hydrological phenomena on rivers caused by the negative impact of channel processes and associated with natural potential riverside outwash within settlements. At the same time, local bank deformations associated with hydraulic structures should be identified in designs of these structures. In order to prevent destructive consequences of natural channel processes and organize appropriate protection, it is necessary to assess the condition of river channels using a certain system of hazard criteria for horizontal river deformations.

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At present, the hazard criteria for planned deformations of water body banks are stipulated by two regulatory documents: SP 482.1325800.2020 and SP 115.13330.2016. SP 482.1325800.2020[1] recognizes as dangerous deformations of riverbanks at the water edge line and abrasion step edge rate of more than 1.0 m per year. SP115.13330.2016[2] assesses the danger of deformations quantitatively (Table 1). However, both documents lack information on the causes of bank deformations making it difficult to predict their development.

Table 1. Hazard categories of channel deformations according to SP 115.13330.2016

Indicators used in assessing natural process hazard	Hazard categories of processes			
	Extremely dangerous (catastrophic)	Very dangerous	Dangerous	Moderately dangerous
Affected region, per cent	–	8–10	6–8	5–6
Volume of relatively simultaneous deformations of land sediments, mln м^3 per year	–	0,2–0,3	< 0,04	< 0,08
Rate of development, m per year	–	> 3	1–3	0,1–1

In domestic science literature, the hazard of horizontal bank deformations is not singled out from the hazard of general deformations of river channels. Detailed complex ideas about the hazard of channel deformations on rivers under undisturbed conditions are presented in works [1, 2] suggesting the danger of channel processes should be assessed on a 6-point scale on the basis of channel stability indicators:

Lokhtin number:

$$\Lambda = \frac{d}{H}$$

Makkaveev stability coefficient:

$$K_C = \frac{d}{b_p I},$$

where d is the average coarseness of bottom sediments, I is the river slope, b_p is the width of the river channel.

[1] SP 482.1325800.2020. Engineering-hydrometeorological surveys for the construction industry. General rules of work. Official edition. M., Standardinform. 2020. 49 p.
[2] SPP 115.13330.2016. Geophysics of hazardous natural impacts. Updated edition of SNiP 22-01-95. M., Standardinform. 2018. 43 p.

In each selected hazard degree indicators of channel stability correspond to the rate of potential channel deformations, displacement of channel relief forms, the extent of erosion zones, periodicity of developing and straightening of bends, deepening and shoaling of river horns [2]. Table 2 presents classification of river sections according to the hazard of channel processes in terms of potential deformations and the level of channel stability.

Table 2. Hazard level of channel processes depending on channel stability and rate of potential deformations

Hazard level of channel processes depending on the stability of the channel and the rate of horizontal deformations (channel stability)	Intensity scale	Indicators of channel stability		Rates of outwash (inwash) of bank sediments, m per year		Maximum possible bank erosion, m/year
		Λ	Kc	Small rivers	Average and large rivers	
Very high (totally unstable)	5	< 0,5	< 2	> 5	> 50	> 100
High (unstable)	4	0,5–2	2–6	2–5	> 10	> 50
Elevated (weakly stable)	3	2–5	6–15	0,5–2	5–10	> 20
Moderate (relatively stable)	2	5–10	15–20	0,1–0,5	2–5	> 10
Weak (stable channels)	1	10–50	20–100	< 0,1	< 2	> 5
No danger (absolutely stable)	0	> 50	> 100	No erosion		

The methodology developed by scientists of the Moscow State University (MSU) provides for assessing the danger of anthropogenic channel alteration ranked in values depending on the size of the river and the length of altered sections.

In addition to special and local hazard indicators, the MSU methodology also introduces an integral territorial feature - the region ecological tension characterizing the living conditions determined by channel processes. The integrated criterion of ecological tension is obtained by adding special hazard intensity values to a weighting factor that takes into account the contribution of each factor. This criterion ranks regions on a 6-point scale (from 0 to 5).

Foreign scientific literature (developed mainly in the USA) often uses a similarly comprehensive geomorphological method for assessing the impact of land use on river channel dynamics. Two riverside erosion hazard indices are most often used [3-11]:

– Bank Erosion Hazard Index (BEHI)
– Near-Bank Stress (NBS).

Both parameters were proposed by D. Rosgen as components of his Watershed Assessment of River Stability and Sediment Supply (WARSSS) Model [3, 8, 10], which is a quantitative method for determining the influence of land use on river channel and sediment dynamics.

The BEHI index focuses on bank characteristics affecting bank erosion, among which there being morphometric characteristics of the channel (ratio of bank height to flow depth at bankfull discharge and bank slope angle), bedrock composition, its stratification and filtration properties, density and depth of the riverside vegetation root system, and the degree of bank littering with its remains.

All of them are determined in a specific way and do not coincide with the characteristics accepted in Russia [9]. For each of these parameters, relationships with the corresponding special BEHI index are constructed (the BEHI index identifies six hazard categories from very low to extreme with values from 1 to 10) [10]. The total riverbank hazard index is defined as the sum of special indices and all five parameters.

The BEHI index is adjusted depending on the bedrock composition and layering of the bank. Banks composed of bedrock and boulders correspond to the lowest erosion hazard. If the bank is composed of coarse pebbles and small boulders, 10 points are deducted from the total BEHI index, and 10 points are added if the sand fraction predominates. Depending on the stratification of the bank, 5 to 10 points are added.

The NBS index operates with in-channel characteristics that estimate the degree of hydraulic loading on the bank due to the shape of the channel. One third of the total stream cross-section adjacent to the eroding bank is assumed to affect the riverside, and bank erosion depends on the location of the stream cross-section (Fig. 1) [4]. Depending on this feature, morphometric and hydraulic characteristics of the channel in the cross-section at the bankfull discharge, different methods of NBS estimation have been proposed [9, 11].

In addition, in the USA there is used classification of bank erosion hazard operating with six hazard categories, bank soils and their fixation by vegetation [5] taken into account. All these indices are difficult and labor-intensive to determine.

Thus, the proposed methods of riverbank erosion hazard assessment are extremely costly, which makes their use difficult. They require detailed field surveys and participation of highly qualified specialists in geomorphology. As a result, in practice, preliminary hydromorphologically based assessment of riverbank deformation hazard is not carried out at all leading to an irregular struggle against the consequences of destructive deformations.

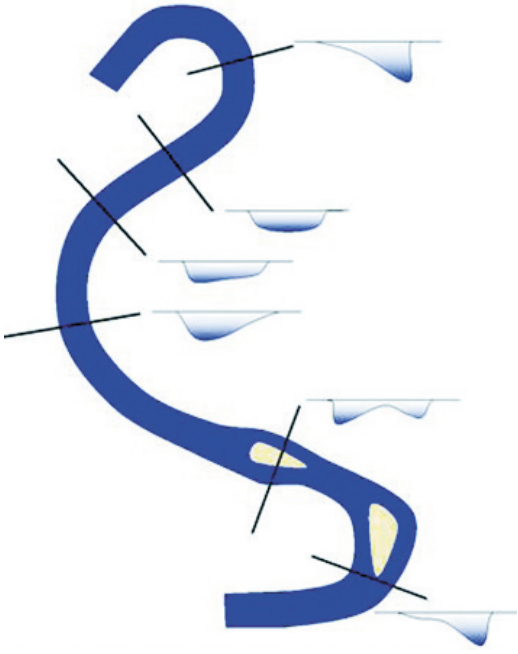


Fig. 1. Cross-sections of the riverbed that determine the hydraulic load on the shore.

In this regard, there is an obvious need to develop a methodology for preventive determination of the danger of estimated deformations of river channels near settlements taking into account the morphological features of the deformation site; simplicity and accessibility of such a methodology for users, its orientation on the use of publicly available space images and topographic maps and plans, and the absence of the need for special hydromorphological field surveys being very important requirements.

RESEARCH METHODS

The proposed methodology was developed at the State Hydrological Institute (SHI) within the framework of the budget theme on the basis of the hydromorphological theory of channel process. The methodology key point is the dynamics of discrete channel forms manifested in deformations of river channels (types of channel process). It should be identified when interpreting space images and topomaps, previously developed methods of interpreting morphological characteristics of river channels and floodplains identified within the hydromorphological theory of channel[3] taken into account.

[3] Methodical instructions of the HMSD. Issue 71 / SHI / Application of aerial photography materials for studying channel processes and deformations of reservoir banks. L.: Gidrometeoizdat, 1966.

The following hydrological classifications are used in methodology:

– river channels[4],

– types of river channels [5],

– intensity of planned deformations and their hazard degree.

The first two classifications concisely schematize and describe hydromorphological types of channels, channel processes, corresponding channel deformation patterns and external classification features of each type, while the third classification qualitatively ranks channel deformations according to the intensity of potential bank deformations within the morphological elements of river channels.

The proposed methodology requires initial skills in working with cartographic material and space images (from available interactive programs such as Google Earth), i.e. knowledge of visual interpretation of morphological structure of river channels and floodplains. In this case we mean a special type of interpretation – hydromorphological interpretation of river channel types and channel forms.

There are distinguished direct and indirect interpretation features. Direct features play the main role in recognizing objects. They include:

– shape and size of the watercourse;

– image tone;

– image colour (certain colour shades are used to recognize the following: shades of green – features of floodplain relief; shades of gray, brown, red – bedrock banks of the channel; green color of vegetation cover – islands in the channel; gray-yellow shades of sand and gravel surfaces and absence of vegetation – braid bars and sidelines);

– image structure (the characteristic flake pattern of the river bottom surface under a transparent water layer indicates the presence of ridges and mesoforms).

Vegetation on in-channel formations can serve as a natural indirect sign. By the nature and degree of its development (or absence) one can distinguish a channel island from a braid bar and assess the floodability of a morphological formation.

The following examples demonstrate simplicity of using visual information for expert assessment of channel development. In this case, hydromorphological interpretation is aimed at recognizing objects of different structural level – from a long morphologically homogeneous river section to underwater intra-channel formations. For this purpose interactive programs allow to change easily the im-

[4] SP 493.1325800.2020. Engineering surveys for construction in areas of perennially frozen ground distribution. General requirements. Official edition. Moscow: Ministry of Construction of the Russian Federation, 2020. 131 p.

[5] STO GUGI 08.29-2009. Accounting of channel process at the sections of underwater pipeline crossing rivers. SPb: Nestor-History, 2009. 184 p. ISBN 978-59818-7393-5.

age scale creating different image generalization, images of late years available making it possible to compare them and even trace the dynamics of estimated changes in river channels.

Obviously, the quality of visual interpretation is determined by the level of qualification of interpreters, their professional erudition and intuition, knowledge and understanding of classification features of hydromorphological types of river channels and types of channel process.

The proposed methodology is based on the following postulates of the hydromorphological theory:

1. The essence of the channel process is transporting channel-forming sediments, which takes place in the form of spatially isolated discrete (integral and indivisible) morphological forms (micro-, meso- and macro-forms) of the river channel under conditions of dynamic channel equilibrium.

2. All natural deformations of river channels and floodplains are an external form of manifestation of dynamics of these discrete morphological elements of river channels (forms of movement of channel-forming bottom sediments).

3. The processes of channel formation, and consequently the parameters and dynamics of morphological elements of the river channel, develop under the influence of limiting factors of the channel process, which is reflected in the hydromorphological typification of river channels.

The initial stage of the methodology for assessing the potential hazard of river channel deformations is to assess the degree of influence of the limiting factor on channel reformation at a particular river section, i.e. identification of the watercourse with one of the identified river channel types according to the typification given in Table 3, the detailed version of which is published in SP 493.1325800.2020 (Annex L). The channel type and sub-type are determined with the help of maps and satellite images directly based on direct interpretation features and using descriptions from Table 4.

Table 3 proves that deformations of all Type I channels are irreversible and have no cyclic regular course, i.e. the state of dynamic equilibrium is not characteristic for them. It can be stated that they are the most stable with respect to potential deformations as they are subject to significant and sometimes absolute influence of limiting conditions.

River channels of types II and III are in a state of dynamic equilibrium, so the SHI classification of channel process types is applicable to them [14].

The basis of the proposed methodology for assessing the degree of bank deformation hazard is the following distribution of deformation intensity:

– by morphological elements of the river channel (the highest intensity is observed in concave banks of bends, the second – at their inflection points, the third- on concave banks of weakly sinuous channels);

Table 3. Hydromorphological classification of river channels

Types and their characteristics	Subtypes and their characteristics
I. Orographic low-water channel (single channel or multi-channel). Slopes, valleys, and rocks that fill its bed determine the size and shape of both the flood and low water channels.	Ia. The bed and bank slopes of the channel are composed of rocks difficult to erode. There is no floodplain and the channel is orographic (single or multiple channels). Local irreversible deformations occur in the channel due to erosion processes on the valley slopes and mechanical erosion of the banks. Displacement of debris by the stream occurs in suspension, as well as in a structureless or ridged form making accumulative formations (beaches and rolls), the estimated position of which is determined by the channel configuration.
	Ib. The characteristics of the low-water channel of the river are determined by inherited coarse fractional alluvial deposits formed by the ancient flow of high water content. The orography of these sediments defines potential outlines of the weakly embedded low-water channel. Channel deformations are manifested in the movement of separate fractions of alluvium in an unstructured form making accumulative formations, the potential position of which is determined by the channel configuration, all channel deformations being local, irreversible. They are not manifestations of transporting channel-forming sediments
	Ic. Channel sections with waterlogged floodplains or waterlogged valley bottoms. These are embedded channels running in peat areas overlying loams. The processes of bog formation in regularly flooded areas prevail over the processes of channel formation. Channel sinuosity is irregular, determined by the local structure of the bog area. Transporting of sediments (more often sandy) is of low-intensity and takes place in structureless and ridge forms. Bank deformation is insignificant
II. Orographic flood channel (narrow valley). Valley slopes determine the size and shape of the river channel at high water levels	II. The river floodplain is absent or only slightly and locally developed. During periods of high water and floods there is active transporting of channel-forming sediments in the form of mesoforms of the flood river channel, which determine the size and shape of the low-water channel. Channel processes are of the band-dune type, side-bar type, middle-bar type and valley wandering types on mountain rivers.
III. Floodplain channels in their own sediments, with morphological homogeneity and cyclical development of potentially-stationary floodplain areas and with transporting bedload in the form of microforms with the development of underwater morphological elements of floodplain areas (beaches, spits, rolls).	IIIa. Valley slopes have a limiting effect on the flow and formation of floodplain areas during floods. Channel-forming sediments are transported as microforms and ribbon ridges with the formation of underwater elements of floodplain areas (beaches, spits and rolls). Channel-forming processes develop as restricted meandering and multi-armed channel.
	IIIb. Valley slopes have practically no influence on the potential development of bends and formation of floodplain areas (minimal manifestation of the limiting factor of the channel process). Channel-forming sediments are transported as microforms and ribbon ridges with the formation of underwater elements of floodplain areas (beaches, spits and rolls). Channel-forming processes develop as free and incomplete meandering, floodplain multi-armed channel and mountain floodplain multi-armed channel.

– the genesis of eroded banks (bedrock or floodplain) considered;

– the type of channel process and hydromorphologic type of channel considered.

In this regard, the second stage of the hazard assessment methodology is to establish the type of channel process in the area under study using satellite images and topomaps based on the classification features of all types of channel process given in the revised classification of SP 493.1325800.2020 (Annex L).

At the third stage of the assessment, first of all, it is necessary to perform morphological classification of riverside territories (water protection zones) in accordance with the Methodological Guidelines NRM[6], the morphological position of the eroded area defined:

– within the bedrock slopes of the valley,

– within floodplain areas,

– within inherited floodplains,

– as the boundary of the flood channel,

– within the flood channel.

On the basis of the long-term experience of research conducted in the Department of Channel Processes of the State Hydrological Institute allowing to assess on a qualitative level the intensity of potential bank deformations for each type of channel and type of channel process, there has been defined the sequence of increasing degree of stability of eroded banks of both meandering channels with floodplains and weakly sinuous floodplain free channels, as well as orographic ones. The greatest intensity of erosion is typical of concave banks:

– at the top of free and limited meandering bends;

– at the top of bends of incomplete meandering and floodplain horns;

– near inflection points of any type of meandering bend;

– the most stable banks of meandering channel bends are those with outcrops in the geological structure that are resistant to rock erosion and break the typical patterns of bend development;

– the banks of floodplain free and flood river channels;

– the most resistant to erosion are the inherited and bedrock banks of orographic embedded channels.

Fig. 2. shows typical channel sections in the sequence of increasing relative stability of their eroded banks. In Table 4, this sequence (column 1) is supplemented with a qualitative assessment of the degree of potential bank erosion hazard (column 4).

[6] Methodological guidelines of the NRM for the implementation of state monitoring of water bodies in terms of observations of the state of the bottom, banks, the state and regime of use of water protection zones and changes in the morphometric features of water bodies or their parts, approved by NRM Order No. 432 of October 8, 2014

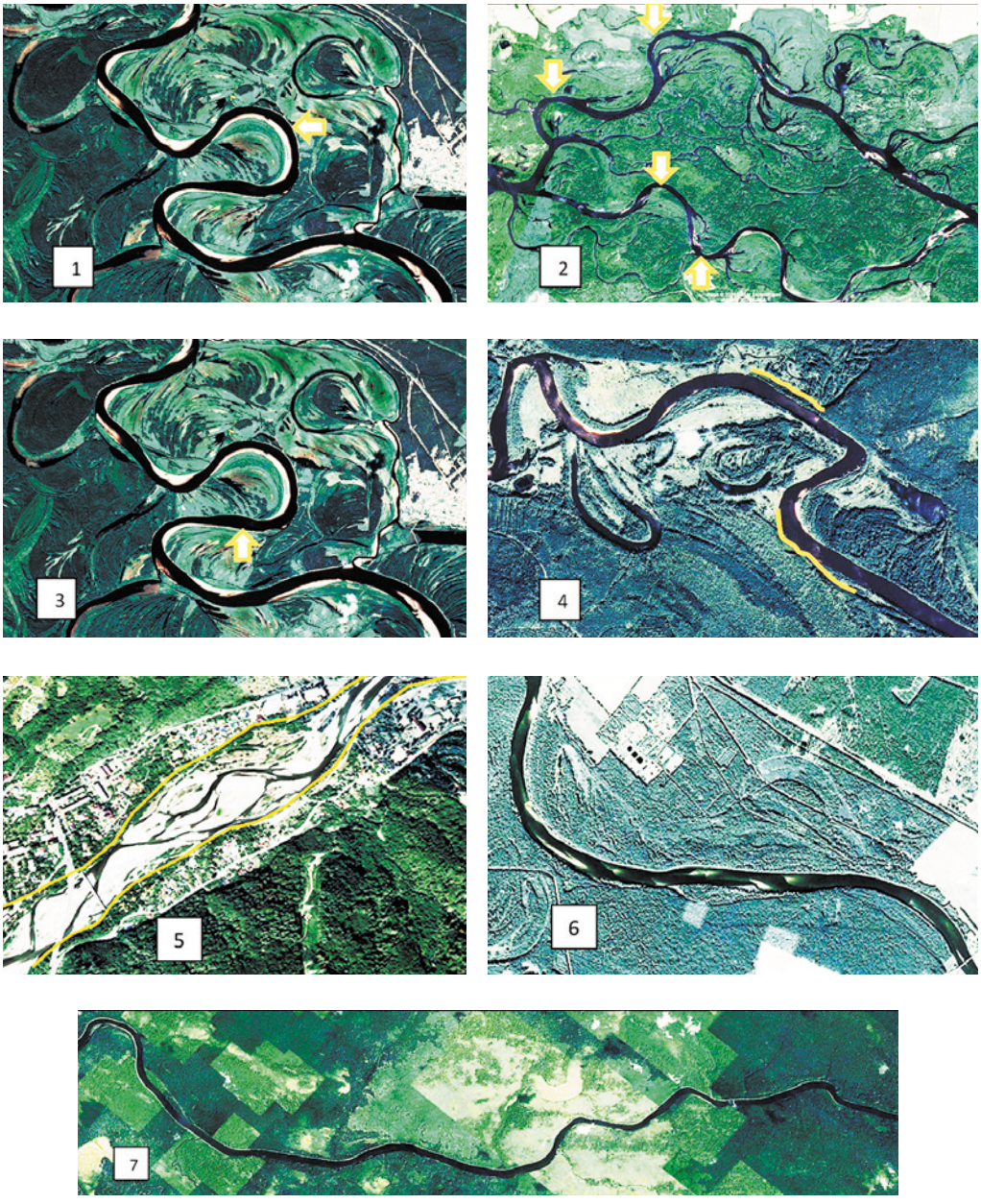


Fig. 2. The sequence of relative stability increasing of eroded riverbed banks:
1 – concave banks at the tops of bends of free and limited meandering; 2 – concave banks at the tops of bends of incomplete meandering and multihorn floodplain; 3 – inflection points of bends of any type of meandering; 4 – outcrops of erosion-resistant rocks at the tops of bends; 5 – banks of flood riverbeds; 6 – banks of flood-free riverbeds; 7 – bedrock (non erodible) banks of orographic embedded riverbeds

Table 4. Hydromorphological classification of the hazard of potential horizontal deformations

Deformation intensity index	Deformation sites	Channel process type	Deformation hazard degree
1	2	3	4
III_1	Floodplain concave banks at the top of bends	Free and restricted meandering	Extremely dangerous
III_2		Incomplete meandering and floodplain incomplete meandering and floodplain multi-armed channel	
III_3	Floodplain banks at bend points of bends	Restricted, free and incomplete meandering, free and incomplete meandering	Dangerous
III_4	Outcrops of difficult to erode rocks on concave banks at the top of bends	Restricted, free* and incomplete* meandering, multi-armed channel and mountain floodplain multi-armed channel	Moderately dangerous
II_5	Bedrock or inherited flood channel banks	Valley wandering on the mountain river, middle-bar type type	
II_6		Side-bar type, band-dune type	Low-dangerous
I_7	Inherited and bedrock banks of orographic channels	Absence of river channel type, structureless and structural sediment transporting	Not dangerous

Note: * types of channel processes with disturbed deformation pattern.

Thus, the whole range of potential deformations intensity, the most potentially stable Type I channels included, is divided into 7 levels and ranked by increasing natural bank stability with indices from 1 to 7, and the degree of danger of potential deformations is divided into 6 levels, as shown in Table 4. We assume that the sequence presented in the table reflects the dependence of deformations hazard on morphological elements of the river channel, type of channel process and hydromorphological type of the river channel most adequately at the qualitative level.

RESULTS AND DISCUSSION

During the development of methodology for determining the hazard of horizontal deformations of river channels, residential river channel sections of different regions of Russia with different physiographic characteristics of basins and types of water regime (basins of the Severnaya Dvina, Mezen, Pechora, Amur, Kuban rivers and those of the Black Sea coast of the Caucasus) were investigated within the framework of the budget studies for 2020-2023.

In total, about 250 sections of 30 Russian rivers (from small to very large rivers) were assessed in this work with respect to the degree of hazard of potential bank deformations.

The analysis of the obtained results for all surveyed areas within the settlements revealed the predominance of sites with active manifestation of the limiting factor with the corresponding degree of hazard of horizontal deformations (from moderately hazardous to non-hazardous). The reason for such statistics is as follows: although the genesis of the eroded banks of the surveyed rivers differs in different basins, the morphological and geological structure of the sample rivers (at sites near settlements) is characterized mainly by potentially stable banks, since the safest river sections are always selected for settlements.

For example, river sections of mountain and submountain regions with active manifestation of the limiting factor account for 95 per cent in the Kuban basin and 80 per cent in the Amur basin. Rivers of the northern territories flowing along ancient erosion troughs in valleys have banks formed during glaciation periods which have a layered structure. Under modern conditions, layers of inherited sediments difficult to erode act as a limiting factor and restrain potential deformations of these rivers. Therefore, for the Severnaya Dvina, the Mezen, the Pechora and their tributaries, residential areas with active manifestation of the limiting factor are also widespread and account for 50 per cent, 71 per cent and 62 per cent, respectively.

CONCLUSION

The present paper presents a methodology for rapid assessing the potential danger of horizontal deformations of river channels in residential areas developed on the basis of hydromorphological typification of river channels, supplemented and improved typification of the channel process within the framework of the hydromorphological theory of the SHI.

The proposed methodology is based on one of the most important postulates of the hydromorphological theory of the channel process stating that all natural deformations of river channels and floodplains are an external form of manifestation of development and movement of discrete morphological riverbed elements in the river channel (forms of movement of channel-forming bed load).

The proposed methodology is based on the distribution of bank deformation intensity by morphological elements of the river channel taking into account the structure of eroded banks, the type of channel process and hydromorphological type of the channel, types of river channels and types of channel process determined with the help of topographic maps and publicly available space images using classification descriptions set out in the current SP 493.1325800.2020.

The proposed methodology comprehensively considers general regularities of channel formation processes, the genesis and development of discrete mor-

phological elements of river channels and forms of transporting channel-forming sediments determining the degree of potential hazard of deformations of river channels associated with channel processes. It makes it possible to assess the direction and relative intensity of possible river bank deformations promptly and without significant costs and, consequently, make estimated forecasts of their development at a qualitative level. Such qualitative assessments of the potential danger of bank deformations provide for more reasonable development of regional programs for federal monitoring of the state of the bottom and banks of water bodies and development plans for residential areas, including procedures for allocation of land for construction in riverside areas. In addition, one can promptly take into account peculiarities of the morphological structure of the river channel within residential areas when determining the potential position of the bank line and periodicity of its specification in accordance with Resolution of the Government of the Russian Federation No. 377 of April 29, 2016 "On Approval of the Rules for Determining the Location of Waterline (Boundary of a Water Body), cases and periodicity of its determination and on making changes". This circumstance gives an advantage to the proposed methodology in comparison with the approaches outlined in the introduction.

The disadvantages of the methodology include its qualitative nature. Therefore, in each specific case, in the presence of actual rates of horizontal bank deformation determined in the course of monitoring of the state of the bottom and banks of water bodies, the assessment of the degree of deformation hazard should be carried out on the basis of SP 115.13330.2016.

CONFLICT OF INTERESTS

The authors declares no relevant conflict of interests.

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About the authors:

Victor M. Katolikov, Candidate of Technical Sciences, Leading Researcher, Head of the Channel Processes Department, State Hydrological Institute, V.O. Second Line, 23, St.-Petersburg, 199053, Russia; ORCID: 0000-0003-3538-9450; e-mail: v.katolikov@mail.ru

Nataliya I. Katolikova, Senior Researcher, Channel Processes Department, State Hydrological Institute, V.O. Second Line, 23, St.-Petersburg, 199053, Russia; ORCID: 0009-0007-3852-0684; e-mail: iamnik2@yandex.ru

Olga A. Petrovskaya, Candidate of Technical Sciences, Senior Researcher, Channel Processes Department, State Hydrological Institute, V.O. Second Line, 23, St.-Petersburg, 199053, Russia; ORCID: 0000-0002-3330-2430; e-mail: river-channel@yandex.ru

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