

ORIGINAL RESEARCH ARTICLE

Hazards of riverbed processes in Russian rivers: Evaluation criteria, mapping and regional analysis

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ABSTRACT

The danger of riverbed processes is considered. Their speed varies from the first few months of the flood to the most dynamic process in nature. It happened in front of people. This may make life on the river bank and the utilization of river resources more difficult. This paper introduces the causes and consequences of the danger performance of riverbed processes, and focuses on the mapping methods of the danger assessment of riverbed processes: determining the danger degree of riverbed processes and different methods of displaying it on the map. An example of displaying danger on the previously drawn map is given, and the distribution of different types and expression degrees of dangerous riverbed processes under various natural conditions in Russia is briefly analyzed.

Keywords: Riverbed; Floodplain; Riverbed Process; Danger; Mapping; Distribution

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1. Introduction

Due to coastal erosion, sediment deposition, river “leaving” residential areas, lower or higher bottom signs (scouring/flooding), river processes are characterized by the continuous reconstruction of riverbeds, which is always a great or small threat to human life and activities. It is caused by the deformation of the natural riverbed, and its strength and manifestation depend on the stability of the riverbed and its morphological and dynamic types, the composition of runoff and sediment forming the riverbed, the flow conditions forming the riverbed, the erosivity of rock and sediment in contact with river flows, and other factors determining the riverbed regime of rivers—a set of characteristic changes in riverbeds under the action of water (river) flows in time^[1]. At the same time, carrying out economic activities in rivers, natural areas and river basins related to the construction of water conservancy facilities, the development of mineral resources on riverbed, agricultural and entertainment development, water intake, communication construction, coastal protection and flood control measures, change factors and riverbed regime, can eliminate dangerous manifestations in some cases. In other cases, it produces new forms or enlivens them.

Small-scale mapping, widely used in practice in recent decades, forms the basis for assessing the danger to human life and activity of riverbed processes within river basins, administrative-territorial formations, large regions or the country as a whole^[2,3] and allows expertly evaluation of possible investments in the development of any type of river resources at the pre project level.

The manifestations of dangerous riverbed processes include: a) horizontal riverbed deformations, including the displacement of riverbed on the plane, coastal scouring/flooding, the development of some riverbed and the death of other, the bending and straightening of radiation—their periodicity and directionality; b) vertical riverbed deformations—cutting (deep erosion) or accumulation of sediment, accompanied by changes in riverbed markers; c) dynamics (alluvium, scour, displacement) of riverbed topography in accumulation form (transitional, side effects, settlement). When the coast is scoured, coastal buildings, roads and other communication facilities are damaged, including bridges built far away from the river, bank columns of bridges, sagging pipelines (pipelines, communication cables) across the river, and loss of fertile land and forest land. Coastal reinforcement is often the primary problem of many coastal settlements, but especially the problem of urbanized river reaches. **Figure 1** shows the washout of the concave right bank of the Ob riverbed near the town of Kolpashevo, where part of the urban territory was destroyed: due to the curvature and displacement of a steep curve, the bank receded for 1.5 km in 100 years^[4].

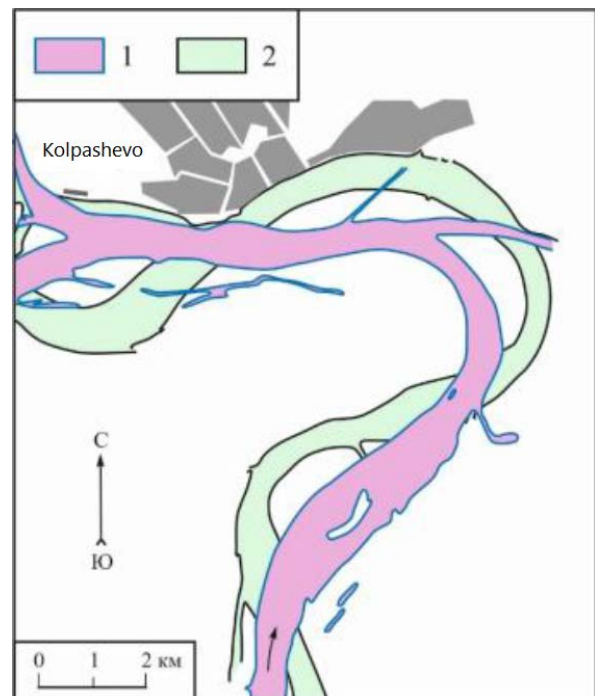
The undetected periodicity of riverbed deformations often leads to unreasonable adjustment of riverbed for the benefit of shipping and other users (water users, builders) and coastal reinforcement methods, so as to separate the permanently reinforced reach from the influence of water flow, while the adjacent parts of the river are eroded.

The change of riverbed topography (inclination, sub inclination and subsidence) causes serious difficulties to navigation, which often leads to ship grounding and transportation interruption. Sediment (shoal) accumulates on water intake and sewage discharge, hindering industrial and public water supply and reducing the dispersion effect of harmful impurities^[6]. The coast opposite the shoals of natural conditions is usually scoured, creating an emergency for engineering and other facilities on it. **Figure 2** shows a section of the Ob River above Barnaul, on the left bank of which the main municipal water intake of the city turned out to be fenced

off from the main riverbed by shoals. Therefore, in order to ensure the supply of water, dredging works are carried out regularly and trenches for water supply are developed. On the other side on the right, there is a power pole on the horizontal line of the water intake. In order to protect the power pole and other power poles, a revetment structure must be built with a stone nearly 1.5 km long to prevent the whole concave bank from being washed out. Ports and docks are filled with moving sediment, causing an emergency and hindering river transport^[7].



(a)



(b)

Figure 1. Reshaping of the Ob riverbed creates danger to Kolpashevo. (a): eroded bank; (b): changes in the channel as the concave bank erodes and the bend shifts. The riverbed position: 1—in 1910; 2—in 2010^[5].

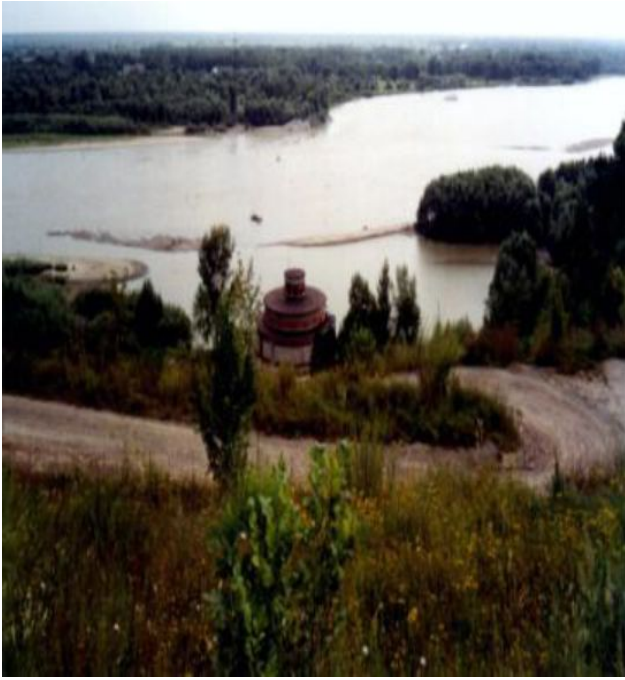


Figure 2. The water intake on the Ob River near Barnaul, blocked by shifting shallows, and a power line support (to protect it from erosion, the right bank was strengthened with dumped riprap).

The development of dangerous riverbed processes on the river is even more impressive. In the Lena River near Yakutsk^[8], the riverbed reshaping in the 20th and early 21st centuries led to the directional “withdrawal” of the river from the city. At present, only its lower part (industrial area) leads to the left arm, where there is a city’s water intake, ferry wharf and industrial enterprises, and a channel to the port. But they are constantly documented. In 50 years, their sleeve water has been reduced from 70% to 30%–40%, and dredging is carried out regularly to ensure all water users. However, in the long run, it is possible to turn the arm into a low-water channel, similar to the above-mentioned Gorodskaya, on the bank of which the city of Yakutsk was founded and which was the main arm of the Lena in the first half of the 20th century (today, its water content is 5%–7% of the river flow).

Human activities on the riverbeds and floodplains have long become a real factor in their transformation, causing no less danger than natural riverbed processes. In medium and large rivers, they are related to the function of reservoirs, mass extraction of construction materials (sand and gravel mix ASB) from the beds. In the downstream reservoirs and during mass development of ASB, the

main dangerous process is channel incision (in the case of quarries, it is superimposed on artificial deepening of the channel), which causes “landing” of levels, drying of water intakes, pipeline breaks, accompanied by settling of floodplain landscapes, in some cases worsening of navigation conditions due to exposure of rocky soils on the bottom. Above the reservoirs, the accumulation of sediment leads to shallowing of the channel, waterlogging, and in the levee part, sanding of the floodplain, and deterioration of floodplain meadows.

The dangerous phenomenon caused by human interference with the life of small rivers is related to the deposition of small rivers, which is usually caused by scouring the soil from the catchment area. In this case, the source of groundwater will freeze, thus reducing the water flow of the river, filling the intake and inundating the floodplain land. When mining mineral resources from and on the riverbed, the destruction of the whole riverbed complex will also be dangerous: the transition of runoff from above-ground to underground disrupts the hydrogeological conditions of riverside areas, leading to waterlogging, problem subsidence under buildings and structures^[9].

Makaviev^[10] stressed that “riverbed processes cannot be regarded as a series of phenomena, and the development of these phenomena is isolated from the geographical environment without considering the specific characteristics of the watershed landscape.” Extensive domestic literature^[11] and foreign literature^[12–15] are devoted to the geography of riverbed processes, the characteristics of riverbed development and the dissemination of morphological and dynamic types. However, only the first step has been taken at the regional level of the Russian Federation with regard to the dangers of riverbed processes and the revelation of their geographical patterns under conditions of natural and man-made changes^[5,16]. The purpose of this article is to describe the dangerous performance of riverbed processes in large areas of Russia based on the small-scale map drawn for the whole country and its regions and the synthesis of the risk estimates of small and medium-sized rivers and large rivers in various regions.

2. Criteria for assessing the risk of river erosion and accumulation in riverbed and floodplains

As a natural phenomenon, the complexity of riverbed processes makes it difficult to select or calculate a single risk indicator applicable to all rivers in the territory, regardless of their size and aquifer. In addition, it is a systematic mistake to combine, firstly, differently directed manifestations of hazard, secondly, hazard natural and anthropogenic caused by possible negative impact of economic activities (the impact of water technology on rivers may lead to neutralization, reduction of level, and even elimination of the danger of riverbed process), thirdly, hazard of riverbed processes on small and medium-sized rivers. Therefore, all hazardous manifestations of riverbed processes are studied in four groups, and each group has its own hazard degree index^[3]. These components are divided into natural and anthropogenic hazards, which determine different prevention or protection methods, hazards on large (medium) and small rivers, which are related to the quantitative and qualitative differences of parameters for evaluating hazards, and hazards caused by different types of deformation.

The basis for evaluating hazards caused by the manifestations of riverbed processes is to rank each process according to its quantitative criteria and qualitative characteristics, and evaluate hazards of all possible forms. **Table 1** shows the type, quality and quantity of dangerous natural riverbed processes and their socio-economic impact. In **Table 2**, hazardous riverbed processes caused by the economic activities of the river and its banks are identified and evaluated separately.

The proposed scale is unified to assess the risks of all natural and anthropogenic hazards in the rivers of Russia and the former Soviet Republic. In particular, riverbed processes are usually not catastrophic in form and intensity of manifestation, but

it can be regarded as an individual case of destroying human settlements or causing emergencies, although the speed of bank scouring or other riverbed deformation does not exceed the maximum speed of the river. Therefore, the maximum degree of hazard corresponding to 5 points is excluded from the analysis, although it should be kept in mind that it may occur at the local level (for example, it is characteristic of the Amu Darya in Central Asia—“deigish”—extreme catastrophic bank erosion, for the great Chinese rivers, for which an extremely high intensity of sediment accumulation is typical).

The manifestation of riverbed processes is independent of each other. Therefore, the criteria for determining the hazards they pose vary. However, since a unified risk rating table is adopted for all groups, rivers of different sizes and characteristics can be compared. For example, riverbed processes of a large river assessed as medium risk (3 points) can be compared with the natural hazard of small rivers and the anthropogenic hazard of large rivers and small rivers, which is also rated as 3^[5].

For medium and large rivers, the riverbed stability index is a comprehensive index of the natural hazards of riverbed processes: Lochtin's number $L = d/H$ and N.I. Makkaveev's riverbed stability factor $Kc = (d/ibr) \times 1000$, where d is average diameter of bedload, mm; H is kilometric drop, m/km; I is slope, br is channel width during low-water periods^[5]. Their analysis for more than 500 rivers of Russia and the CIS countries showed a good correlation between them, on the one hand, and the rate of bank erosion, the length of the erosion front, the periodicity and the rate of reformation of the channel. The left part of **Table 1** shows the correspondence of the characteristics and scores of the hazard of riverbed processes in medium and large rivers, caused by different processes, and indicators of channel stability at different hazard degrees.

Table 1. Danger of riverbed processes on rivers (numerator—medium/large rivers, denominator—small rivers)

Process types by hazard degree	Hazard index		Hazard quantification				Expected development
	Score	Medium rivers	Coastal erosion		Deformation period of horizontal riverbed	Change speed of riverbed topography, m/year (medium and large rivers)	
			Average speed, m/year	Length of scour zones, % of the river section length			
Hazardous	4	<2	10	>60	Fast (year)	>300	Destruction of piers, embankments, port walls; undermining of bridge crossing piers, sediment loading of water intakes, fracture and breakage of underwater pipelines and other communications. Continuous roll-over areas with complex seasonal and multi-year reformation regimes. Widespread reduction of coastal farmland. Frequent changes in the locations of hazardous manifestations
Moderately hazardous	3	2-5	$\frac{2-10}{1-5}$	$\frac{20-60}{10-30}$	Gradual (previous decades)	50-300	Destruction of individual buildings on the coast, intermittent inlets and pier tributaries, complex reconstruction and shallow water nature of individual trails, local reduction of coastal farmland, time arrangement of dangerous performance sites and specific forms of riverbed
Low hazard	2	5-10	$\frac{2}{0-1}$	$\frac{<20}{5-25}$	Slow (hundreds of years)	<50	Individual inclinations that complicate shipping; it may include access to docks and ports, water intakes, destruction of buildings on river banks, and reduction of farmland. The location of dangerous manifestation and its rare incidence
Minor hazard	1	>10	Within defined accuracy				Occasionally, there are some slopes and wharf passages. Sparse scouring and landslide sections on the river bank

Table 2. Anthropogenically hazard of riverbed processes

Process types by hazard degree	Large rivers		Small rivers		
	Score	Quantification of vertical deformation (accumulation, incision), cm/year	Expected development	Quantitative estimation of the degree of anthropogenic change (siltation), % of the river length	Expected development
Hazardous	4	>5	a) desiccation of water intakes, erosion and destruction of the bases of bridge crossing supports, sagging and rupture of underwater communications; exposure of rock ridges on the bottom, interrupting navigation in the low-water; desiccation and destruction of quay walls, bank protection, embankments; sedimentation and loss of fertility of floodplain lands; b) intensification of bank erosion, water intakes, shallowing of rivers; swamping and waterlogging of nameplate lands	Complete (80%–100%)	Complete blockage and death of Russell or its mechanical damage; waterlogging, in the South —salinized riverbed and coastal areas, input water, rivers are no longer a source of water supply
Moderately hazardous	3	3–5	a) partial drying up of water intakes; sagging of sections of underwater pipelines; exposure of hard to erode rocks on the bottom, limiting navigable depths; separate destruction of bank protection and embankments, steeping and loss of fertility of meadows on high floodplain; b) water intakes, deterioration of navigable conditions in the zone of variable backwater, waterlogging of floodplains	Part (20%–80%)	River painting, death of upstream part, waterlogging of riverbed, serious blockage of domestic and construction waste and wood
Low hazard	2	<3	a) possible complication of navigational conditions at approaches to berths; reduction of floodplain productivity; b) partial flooding of water intakes, deterioration of navigable conditions on some rifts in the zone of seepage of variable backwater, waterlogging of low and middle floodplain	Local (<20%)	Partial silting of the upper reaches of rivers, canalization of riverbeds with their subsequent filling in, partial littering of riverbeds with trash and timber
Minor hazard	1	0	Possible local complications on underwater communications	No available	Possible local channel changes

The rivers with the least stable riverbed ($L < 2$) are characterized by the highest rates of bank erosion (on average more than 10 m/year), maximum length of erosion fronts, rapid periodicity of deformations and very high rates of displacement of channel relief forms. All these values correspond to a hazard type of 4. On the contrary, in rivers with high stability scores ($L = 5–10$), deformation rates are low, the location of bank sites is fragmentary, their location is easy to predict, periodicity is long-lasting and has little effect on current use of river resources and conditions of life in river valleys. Such processes are rated as low hazard—2 points.

In rivers with stable riverbed, especially those

with absolutely stable riverbed, the deformation speed of riverbed is very slow and there is almost no danger (cut riverbed composed of gravel and boulder sediment). Although they also produce other adverse hydro genetic phenomena: at low water levels, gravel and boulder intersections and rock protrusions on the riverbed will produce overflow effects, resulting in the reduction of additional “falling” level and depth and serious difficulties for the waterway.

In small rivers, the manifestation of danger is the same as that in large rivers: bank scouring and displacement of riverbed landform, but the intensity of these processes (especially the latter) is much

lower (**Table 1**). (1) The degree of danger is reduced accordingly. Therefore, with the same qualitative and score, the quantitative standard of process risk of small rivers is lower than that of large rivers. Due to the attachment to the fixed position in the riverbed, the displacement of riverbed landform in the form of accumulation on small rivers—the bending between riverbed or the particularity of bank configuration—is not considered at all. On smaller rivers, riverbed processes whose intensity is determined as dangerous (4 points) by a unified scale do not exist—they only show moderately dangerous and weak processes. Due to the scale distortion of Lokhtin's number, it is also not suitable for small rivers. Therefore, the comparison of the risk degree of processes and phenomena can only be carried out according to the physical (actual) indicators of danger—coastal erosion rate, periodicity of riverbed shape change, etc. This method of dealing with small rivers is determined to some extent by the fact that they are often quite neglected in the design of structures and activities: modern techniques and technologies make riverbed processes negligible. In reality, this leads to emergencies—coastal erosion, pipeline sagging, bridge crossing accidents, etc.

The main comprehensive index to determine the hazard degree of anthropogenic-driving processes of large rivers is the vertical riverbed deformation—incision or sediment accumulation. In the rivers of Russia and CIS countries, this deformation can be ignored under natural conditions. They usually only appear outside the normal operation time of engineering facilities. The right side of **Table 2** shows the values of the speeds of these processes, which determine the hazard degree. The hazard of siltation of small rivers is evaluated according to the proportion of silted rivers in the area (basin, area). If almost all rivers are silted up (completely silted up), the above situation is considered dangerous, which is estimated to be 4 points; in some cases, this means siltation of some small rivers in the area (such as those in reclaimed areas), or siltation in the upstream (streams and rivers of 1–2 orders), while maintaining runoff on the upstream river, or in the coastal area of riverbeds when the flow and sedi-

ment are maintained in the active part. According to the number of silted rivers and the nature of siltation, this siltation is considered to be medium or low hazardous. This situation is considered to be slightly hazardous when most of the rivers in an area are unlicensed. Only anthropogenic siltation related to plowing of watersheds and accelerated soil erosion is considered hazardous; natural siltation of rivers, accompanied by the formation of barrel channels, is not dangerous, although it is more vulnerable to anthropogenic influence.

Zavadskiy^[17] suggested that the specific current power (w/m^2) be used as the hazard standard together with the dynamic type of riverbed morphology, average velocity and the length of coastal erosion front, and included in the total hazard score. The unit power of water flow is related to the average scouring velocity of the easily scoured coast, so it can be regarded as a potentially dangerous feature of riverbed processes. This indicator allows the assessment of hazards in the absence or impossibility of coastal erosion rate data; but when applying this indicator, it is necessary to understand the geological and geomorphic conditions of the development of riverbed deformations: it is only applicable for channel formation in erodible soils and does not work in hard-to-erodible or non-erodible, especially rocky ones.

3. Hazard maps of riverbed processes

Drawing hazard maps of riverbed processes needs to develop various methods to show hazards, so as to analyze their content and obtain the necessary distribution data. A necessary requirement of hazard maps is a clear assessment of the hazards caused by different forms of riverbed processes. Therefore, such a map must be based on a single hazard index and integrate all hazard manifestations of riverbed processes. This indicator is to evaluate hazards in the form of integral to reflect the quantitative and qualitative characteristics of the main hazard types.

The difference in the size and particularity of riverbed processes between large (medium) rivers and small rivers determines the different methods of

drawing hazard maps of riverbed processes of large (medium) rivers and small rivers^[12]. For medium and large rivers, the hazard degree can be directly reflected, which is provided by the non-scale strip map of the streamline along the river displayed on a geographical basis. The width of the belt reflects the width of the channel (under discrete gradient): under the same other conditions, it is obvious that the wider the riverbed is, the more forms and hazard types may appear in riverbed processes (in this case, the width of the river is the same as the water property and flow of the river). The color of the tape corresponds to the hazard degree of riverbed processes: red indicates a predominance of hazardous (4 points), orange—moderately hazardous (3 points), yellow—low hazard (2 points) and green—negligibly hazardous (1 point). The thickening of the right edge or left edge (or both) of the zone indicates only erosion on the left bank, right bank or both banks. If scour alternations on the left and right banks are observed on the riverbed, for example, for freely tuned rivers, the thickening of the belt boundary also alternates on the map in staggered order. The thin edge of the ribbon indicates that there is no coastal erosion. Within the channel ribbon, vertical channel deformations are also shown: channel incision by hatching the ribbon, sediment accumulation by mottling, and the denseness of the hatching or mottling can reflect the intensity of the process. Figures corresponding to the directly measured (recorded) bank erosion rates in these locations are placed in circles next to the tape-diagram.

The hazard of riverbed processes on small rivers is evaluated by means of zoning of the territory. Color qualitative background gives districts according to the character of erosion of small rivers' banks, by mottling—according to the degree of siltation of their channels. In this case, the color, presence or absence of crabs only reflects the information of small rivers flowing within a specific contour. The risk of riverbed processes on small rivers is significantly lower than that on large rivers: the maximum scouring speed of the coast rarely exceeds 5 m/year (in a large amount, this is already extreme scouring), and the length of the scouring

area does not exceed the first tens of meters. Therefore, the coastal erosion risk of small rivers is divided into three categories: medium (3 points), low (2 points) and slight (1 point). According to silting of small river channels, there are two types of areas: with silting of predominant part of small river channels in the contour (hazard degree of 2–4 points) or with its episodic nature (hazard degree of 1 point).

Areas where there is no hazard of riverbed processes on small rivers are mainly related to mountainous areas. Horizontal riverbed deformation is slow or non-existent when there is almost no riverbed or its low width and lithology. The deformation of vertical riverbed can also be said as follows—the incision of riverbeds into rocky bedrock; the longitudinal bend of the river is an exception. Sediment accumulation may increase due to the decrease of slope, but these areas are locally distributed and are usually related to intermountain basins or foothills. Large slope and high velocity are the main reasons for no sedimentation in small alpine rivers. However, in mountainous areas, the slope process of transporting large clastic materials to rivers (landslides, rockslides, mounds) is very dangerous and sometimes blocks these materials. In some cases, these materials are caused by river flows scouring steep slopes, especially mudflows, being even in rivers receiving mudflows from tributaries, an important and quite common factor of sharp intensification of riverbed deformation, their extremity and catastrophic manifestations^[18]. A notable example of this effect is the Baksan river near Tyrnyauz^[19].

The boundary between small river and large river (medium/large river) divides the dangerous information transmission mode of riverbed processes on different maps, which is not clearly expressed on the river scale; in general, this depends on the scale of the mapping. Experience has shown that the length of the river directly displayed on the map must be a multiple of the zoom of the map. Therefore, on a scale of 1:15,000,000, the hazard map shows rivers with a length of more than 1,000–1,500 km, and its width cannot be displayed. The color of the tape reflects the hazard degrees, while

the strokes or edges reflect the directionality of the vertical deformation. The map with scale of 1:4,000,000 shows the river with length of 400–500 km, and there is no restriction when using the riverbed width map.

The legend of a riverbed process hazard map is basically the natural and anthropogenic hazards on large and small rivers shown in the above table (**Tables 1 and 2**) add color and barcode fields to indicate a hazard.

In 2006–2010, hazard maps of riverbed processes in some federal regions of the Russian Federation is drawn according to the above method^[20]. By summarizing the information of these maps into the whole territory of Russia, we can obtain a comprehensive riverbed process hazard map, some of which are used as examples (**Figure 3**), and conduct geographical analysis on the riverbed conditions and distribution of different degrees of riverbed process hazards, frequency of occurrence of this or that hazard degree in rivers and/or in their basins^[16].

4. Hazard assessment of riverbed processes in Russia rivers

Through the analysis of the raw materials used in drawing the maps and the maps themselves, we can evaluate the rivers throughout Russia, evaluate the existence and intensity of the negative risk performance in the riverbed process, determine and evaluate the most unfavorable areas of small rivers in this regard.

Among the large (medium, large and largest) rivers, the most dangerous to engineering facilities and structures is the river flowing under the condition of free development of riverbed deformations, where riverbeds are formed in loose sandy, sandy loam, light loam and loess-like sediments. The natural accumulation pattern of sediment in the rivers, which reduces riverbed stability, also increases the possibility of danger caused by coastal erosion and reduces the stability of the riverbed. Dangerous with respect to riverbed processes (4 points) are the lower Terek, the upper and middle Ob, the lower Amur, the Lena in part in the middle (especially from the area of Yakutsk to the mouth of Aldan) and

lower reaches, Northern Dvina between the mouths of Vychegda and Vaga, Kolyma in the lower reaches, the lower Volga, whose channels are unstable or weakly stable, the average rate of channel bank scour exceeds 10 m/year, while the maximum reaches 60 m/year.

North Dvina below the mouth of Vaga, Vychegda, Sysola, Vashka, Mezen, Desna, Seim, lower Oka, rivers of the east and southeast of the Russian plain (Volga and Zavolzhye), most of the river channels of Western Siberia, Central-Yakutian, Lower Amur, Yano-Indigir, Kolyma and other coastal lowlands of the Arctic zone are characterized by moderate natural danger of riverbed processes (3 points)—while somewhat greater (in terms of indicators) stability of riverbeds, especially branched into arms, they are characterized by intensive reformation—straightening of bends, development and dying off of arms, a complex mode of deformation of rifts. In the upper reaches of large rivers, flowing on plains, composed of easily erodible soils, riverbed processes are characterized by less danger, manifested primarily in bank erosion, since the size and erosion capacity of rivers are small and correspond to the characteristics of small riverbeds.

The rivers with the least hazards are those that flow through the plain under limited bed deformation conditions, where incised riverbeds, formed in hard to erode soils—rocky crystalline or sedimentary (sandstones, limestones, etc.), boulder loam, clays are spread. This applies to the west, northwest, north and northeast of Russia, the central highlands of Russia, the east of the Donetsk mountains, the western edge of the West Siberian lowlands (Ural) and the whole Central Siberian Plateau. Here, the rivers are almost endless riverbeds, composed of pebbles with sediment at the bottom. At the same time, the danger caused by water flow to the banks of these rivers is also increasing, and the slope process of these rivers—collapse, gravel, and landslide—that may be caused by the subsidence of the basement.

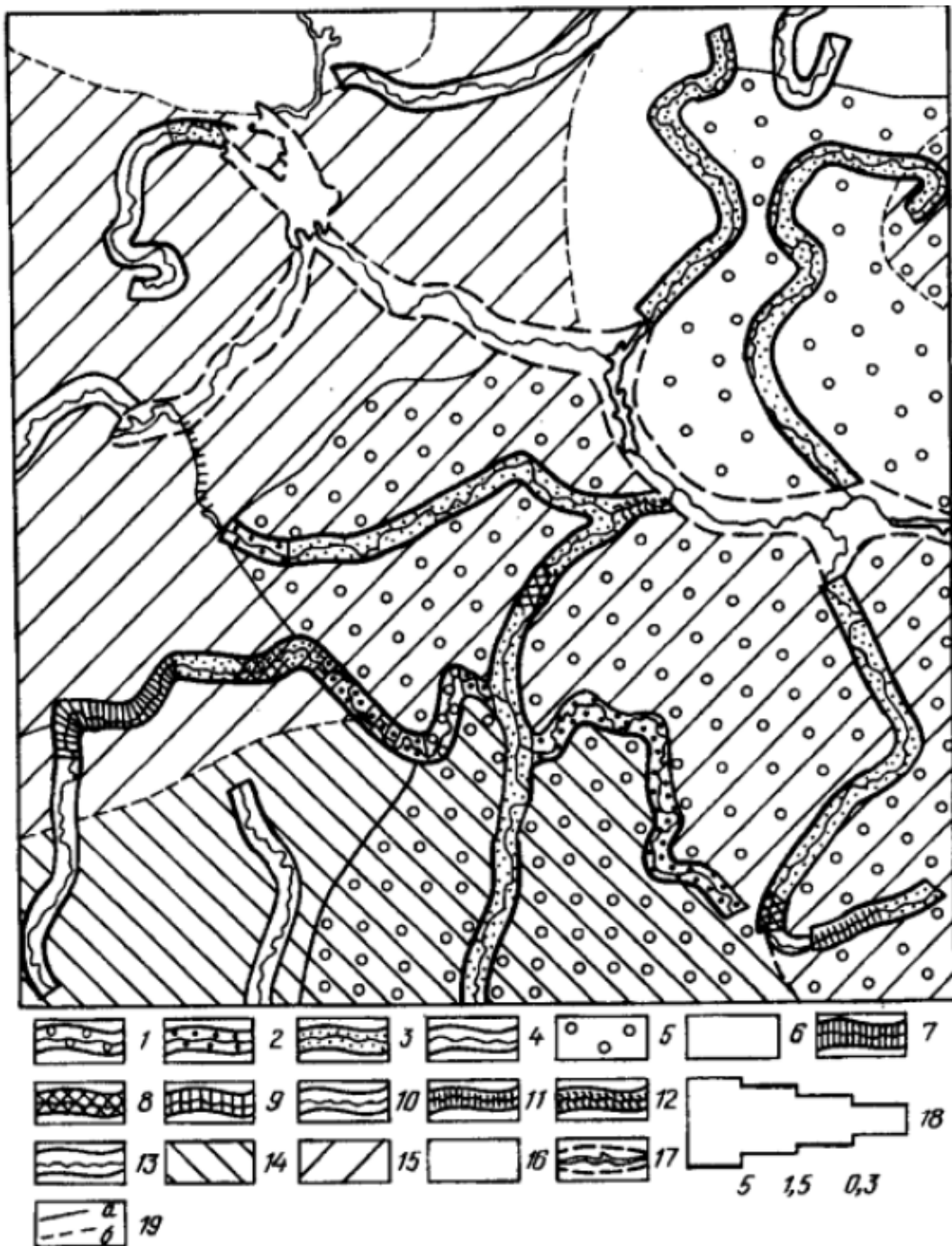


Figure 3. Fragment of the map "The hazard of riverbed processes on rivers of Russia".

Legend: Riverbed processes on large and medium-sized rivers: 1—hazardous (4 points), 2—moderately hazardous (3 points), 3—low hazard (2 points), 4—slightly hazardous (1 point). Riverbed processes on small rivers: 5—moderately hazardous (3 points), 6—low hazard (2 points). Anthropogenically altered riverbed processes on large and medium-sized rivers—cutting in the lower reaches of waterworks and during the development of riverbed quarries: 7—hazardous (4 points), 8—moderately hazardous (3 points), 9—low hazard (2 points), 10—slightly hazardous (1 point); accumulation in the upper reaches of waterworks: 11—moderately hazardous (3 points), 12—low hazard (2 points), 13—slightly hazardous (1 point). Anthropogenically altered riverbed processes on small rivers: 14—environmentally hazardous (full siltation—4 points), 15—moderately hazardous (partial siltation—3 points), 16—slightly hazardous (local siltation—1 point). Others: 17—territories adjacent to reservoirs; 18—scale of riverbed widths in kilometers (5, 1.5, 0.3 km); thickened scale lines show the presence of bank washouts (right or left, respectively); 19—borders of areas with different natural (a) and anthropogenic (b) hazards of riverbed processes on small rivers.

Anthropogenic hazards on large rivers are closely related to the industrial centers of large ur-

ban agglomerations. Outside these centers, it is the lowest (1 point) on most of these rivers, as well as

in the northern and eastern rivers of forest areas and mountains, as well as the rivers of grassland and forest grassland (middle Don, Khoper, middle Ural, lower Ishim, etc.), but in the vicinity of big cities, industrial centers and agglomeration areas, and in mining areas, it has been growing. It is characterized by almost all the rivers above the downstream hydropower stations and reservoirs, which are subject to the return accumulation of sediment, as well as the rivers that mine a large amount of gravel mixture in riverbed quarries such as the middle Oka, Kama, Sura, Tom, Vyatka, Irtysh, Ob, Volga (near Nizhny Novgorod, where the reservoir cascade breaks up, and downstream).

On the rivers in northern European part of Russia, anthropogenic hazards are mainly weak—2 points. Here, it is related to timber floating (until recently, with mole floating). It is also weak on the rivers of central and southern European Russia, but due to the development of riverbed quarries of building materials, although on the Oak, it is moderate due to the quality of its location (3 points). There is little hazard in the main and largest rivers near the city—on Northern Dvina near Kotlas, on Ob near Surgut, on Lena and its tributaries near Olekminsk, Vilyuisk, Tommot, on Amur near Komsomolsk-on-Amur and others, which themselves have little impact on the state of rivers.

Moderate and severe hazards of riverbed processes (3 and 4 points) are formed on regulated rivers below and above reservoirs, as well as on those areas of large and medium rivers where large-scale gravel mining from riverbed quarries is or is being carried out. Here, it is related to the rapid incision of rivers and dredging of riverbeds, excessive accumulation and flooding of land above reservoirs, and rivers flowing through industrial centers and densely populated areas: Yenisei between Sayano-Shushensk and Krasnoyarsk reservoirs and near the Angara mouth, Lena below Osetrovo port and in the area of the city of Yakutsk and the Amur River. Yakutsk, Amur near Khabarovsk, Tom near Tomsk and in Kuzbass, Irtysh near Omsk, Kama between reservoirs, upper reaches of Ural and Moscow, Oka, Volga between Nizhny Novgorod hydrounit and Cheboksary reservoir, lower Volga,

Belaya, Ufa, Sura, lower Don, plain rivers of Stavropol – Kuma and Kuban. Strong danger (4 points) is peculiar to rivers of oil-producing areas of Western Siberia and Pechora lowland and areas of placer deposits extraction (upper Aldan basin, lower Amguema, middle and lower Kolyma, lower reaches of Yana and Omoloy), and also rivers below large cities, in particular Moscow river below the city.

In urban areas, hazards of riverbed processes are usually evaluated with the highest score. In the case of zoning, urbanized areas are divided into special areas, including large and small parts of rivers and streams. For the latter, the hazard is more ecological, as rivers become sewers and are filled with utility and construction waste. The actual hazard as a phenomenon causing damage in small rivers in cities, especially large ones, is small in terms of speed, length and occurrence of areas of bank erosion, as well as due to implementation of bank-protecting measures in cities.

Ecological hazards determined by the deposition and degradation of small rivers or the mechanical changes in their riverbeds and floodplains are more important. Therefore, the zoning of the territory of Russia according to the hazard of riverbed processes on small rivers is essentially ecological and carried out under the condition of free development of riverbed deformations. In plain areas, there are five types of areas, which are characterized by different degrees of ecological tension caused by siltation of small rivers and riverbed changes^[21]. On small rivers in mountainous areas, the hazard of riverbed processes is special, which mainly depends on the passage of villages or outflow from village tributaries, as well as slope collapse and accumulation. The largest area with the minimum hazard on small rivers (1 point) almost coincides with the tundra and taiga areas on the plain and the mountainous areas of the North Caucasus, the North Urals, Siberia and the Far East, i.e. with the belt of underdeveloped agriculture. Here, there is no main reason for siltation of small rivers, mechanical changes in riverbeds and floodplains, etc. At the same time, in areas with relatively concentrated industrial or agricultural production, there are low and medium hazards (2–3 points). These are

the areas of Chukotka, Kolar, Kolima, the mining area of Kamchatka Peninsula, the agricultural area in central Yakutia, and the areas adjacent to the Vilyuyskaya and Zeya hydropower plants.

The areas with low hazard of riverbed processes (2 points) are located in the forest grassland and southern forest zone in European Russia and western Siberia. In eastern Siberia, Transbaikalia and the Far East, it is the characteristic of mountainous areas and agricultural grasslands along the banks of Dauria, Priamurye and south of Primorye. Of particular note is the urban industrial cluster of Moscow, where moderate or even severe hazards of riverbed processes are formed on small rivers^[22].

The grassland areas in European Russia and western Siberia have the characteristics of moderate hazard of riverbed processes (3 points). Among them, the negative phenomena such as riverbed siltation and riverbed fertility decline in Russia are the most serious, which is due to the reduction of flood duration and frequency, or the stop due to the regulation of rivers by ponds; rivers dried up in different periods, and pollution and mechanical transformation increased. The northern boundary of the region is uneven, and the area with intensive industrial development deflects northward, resulting in ecological tension. Here, due to slight siltation, the mechanical changes of riverbed and floodplains on small rivers increase sharply. These are St. Petersburg, Moscow, Orel and Bryansk regions, the eastern slopes of the central and southern Urals, and Kuzbass.

The zone of dry steppes of the Volga Region, Volga and North Caucasus, as well as the southern Trans-Ural are areas of high ecological hazard of riverbed processes (4 points), in which the siltation and death of small and medium-sized rivers and the change of riverbeds increase their long-term drying up, typical for lower basin of many ponds in small rivers and stream valleys, reducing the water content of rivers related to the mass withdrawal of water for irrigation.

In the Russian part of Donbass, the development of industry, including mining, has had an impact on intensive agriculture in arid areas. There are

similar areas in the east of Chelyabinsk and the west of Kurgan region.

Due to the different hazard degrees in the formation of riverbeds, the geographical distribution of these areas shows that the main anthropogenic impact is regional and related to the agricultural development of the region. They are influenced by industrial decisions; they have caused the interruption of the regional distribution with different hazard degrees of riverbed processes, confined to the industrially developed areas.

5. Conclusion

The scientific and reference maps of riverbed process hazards and the regional analysis of its distribution on Russian rivers enable people to fully understand the possible hazards caused by the dangerous manifestations of riverbed deformations when developing water resources and other river resources in the vast and naturally diverse territory of the country. Their purpose is to obtain information when assessing coastal erosion and other dangerous riverbed manifestations before the project, which should be taken into account when using the river's water, minerals, recreational resources, developing coastal areas, laying communications, etc. However, the methods developed to identify, rank and disseminate dangerous riverbed manifestations can also be used for the mapping of large-scale river basins, federal bodies and other natural administrative complexes. In this case, the level of detail reflects hazards of riverbed processes, and the level of detail will be greatly improved with the increase of the scale of mapping. In some areas, when connecting the elements of industrial and social infrastructure, hazard maps of riverbed processes can determine the risk level of riverbed processes of existing settlements and enterprises, and evaluate the possibility of preventing the risk from reducing to disappearing from an economic point of view. On smaller rivers, due to the less chance and intensity of the process, the hazard of riverbed processes caused by destruction or abandonment of facilities is relatively small, but due to the deposition and degradation of these rivers, the hazard is mainly ecological.

In order to detail regional assessments of riverbed process hazards in the past 10 years, regional maps of riverbed processes hazards for the Ural River and its basin rivers^[23], the Amur River bordering with China, and its left tributaries, and separately the Ussuri River and its right tributaries, the Ussuri River and its right tributaries and the Sungachu River^[24], the Selenga River (within Russia and Mongolia)^[25], and the Moscow Region^[14] were prepared. A summary of the regions for which riverbed process hazard studies have been conducted is presented in the literature^[26].

Obviously, the larger the scale of drawing the hazard map of riverbed processes, the more specific will be the places of its manifestations, forms and intensity. This will help to identify risks in the development of river resources and formulate measures to prevent or reduce risks.

Conflict of interest

The authors declared no conflict of interest.

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