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Determination of the ecologically effective channel depth for the purpose of extraction of non-metallic building materials in lowland rivers

Abstract: Extraction of non-metallic building materials from channels of lowland rivers is an important factor of technogenic impact on river channel processes, which has already led to significant changes in riverbeds of several rivers in Russia, flowing close to large cities. In order to minimise the negative impact of riverbed quarries (also referred to as river sediment extraction sites) on the environment, it is necessary to determine the ecologically effective parameters of deposit exploitation from river channels. This paper proposes criteria for the permissible (effective) depth of riverbed quarries. The objective of the permissible depth is to ensure the minimum water surface slope in the longitudinal profile and the flow velocity not lower than the velocity limit for deep erosion to occur. The calculation methods for permissible depth has been tested for the Oka River.

Keywords: riverbed quarries, sediment run-off, water surface slope, non-metallic building materials (NBMs), Oka River

1. Extraction of NBMs from riverbeds as an important factor of technogenic impact

At present, one of the main methods of economic use of rivers in Russia is the acquisition of alluvial deposits (sand, gravel, pebble and their mix) for construction purposes. The main advantages of extracting the material from river channels is its good quality compared to land-based quarries, as well as the low cost of extraction and transport to consumers. This method of river sediment extraction for construction purposes developed rapidly in the period from the 1960s to the 1980s. The demand resulted from the intensively developing industry and the rapid growth of low-budget housing. By the end of the 1980s, due to the lack of restrictions on the extraction of non-metallic building materials (NBMs) from river channels, navigable rivers close to large cities were basically transformed into permanently inundated open-pit mines, in some cases stretching for tens of kilometres. This was the case with several rivers, including the Tom river near Novokuznetsk and Tomsk, the Irtysh river near Omsk, the Ob river near Barnaul and Novosibirsk, the Belaya river near Ufa, Sterlitamak, Ishimbay, the Oka river near Aleksin, Serpuhov, Kashira, Kolomna and many other rivers.

Of all the local technogenic effects on riverbeds (bridge construction, water abstraction, pipelines buried under riverbeds, dredging and other engineering works), the creation of riverbed quarries for NBMs extraction has the largest impact on a river channel and a river as an ecological unit. This is due to technological aspects of NBMs extraction from river channels: 1 – a high rate of streambed transformation, much higher than the natural erosion rate; 2 – a significant volume of the material extracted, which may exceed the sediment runoff dozens of times; 3 – the irreversible nature of the introduced changes.

The main objective of this work is to introduce a new criterion for the ecologically effective depth for NBMs extraction from river channels and to propose one of the available methods of its calculation.

2. The mechanism of the impact exerted by a quarry on the river channel

The impact of a quarry on the river channel results from two main factors – changes in morphometric parameters of the channel and interception of part of the sediment runoff in a river (Berkovich, 2005). Extraction of the material from a river increases the cross-sectional width of a river channel within the quarry section. This in turn contributes to a sudden water surface decline in this river section and the associated sudden reduction in the values of longitudinal water surface slope and, consequently, a decrease in the water flow velocity. At the same time, the reduction in the water level and the flow velocity upstream from the quarry section rapidly increases (a recession curve is formed), which leads to a water level decline also in this section. The water level decline upstream from the quarry section is also facilitated by the increased rate of deep erosion caused by the increased flow velocity.

Partial or complete sedimentation of suspended particles within the quarry section leads to a deficit of sediments in the downstream river section. This deficit is restored to the value corresponding to the river's sediment transport capacity through increased erosion of the river channel, mainly deep erosion. As a result, the water level drops also downstream from the riverbed quarry. Therefore, the main effect of the sediment extraction from stream beds is the change in the water level within specific sections of the river channel. As a result, the previously regular longitudinal slope of the water surface is transformed into a step-like profile, both within the riverbed quarry site and the adjacent river sections. The range of the section characterized by the changed longitudinal profile of the water surface depends on the natural conditions (the longitudinal water surface profile before anthropogenic transformation) and the size of a sediment extraction site (quarry). As a rule, the impact of a quarry is observed within 10-20 km sections downstream and upstream from exploitation sites.

3. Ecologically effective parameters of NBMs extraction from river channels

The unlimited extraction of NBMs from the riverbed significantly damages the whole river system. At the same time, rivers in densely populated areas are often the only local source of materials for industrial, municipal and residential developments. Moreover, river ports which mainly extract the riverbed NBMs are an important element of local infrastructure, providing employment for a significant part of the local population. Therefore, it is extremely important to find a compromise between the economic interests of sediment mining companies and environmental protection when planning such industrial developments.

This objective is implemented by identifying the ecologically effective (permissible) parameters for riverbed NBMs extraction. They include: the permissible annual amount of extraction within the whole extraction zone as well as within its individual parts, the size of a quarry, its location in the channel, including the minimum distance from the river bank and other extraction areas, and the sequence of exploitation.

The State Hydrological Institute's recommendations are currently used in Russia as instructions for river channel processes and the exploitation of riverbed quarries (STO FGBU «GGI», 2012). The document proposes criteria for the acceptable impact of NBMs extraction on aquatic systems. It contains a detailed (although not indisputable) methodology for assessing the impact, which is based on "the river channel concept" presented by the State Hydrological Institute. Furthermore, a methodology was developed at the N. Makkaveev Laboratory of Soil Erosion and Fluvial Processes to assess the permissible operation parameters of riverbed quarries. The methodology has been improved based on long-term research of riverbed quarries in major rivers of Russia.

At present, the main standards of permissible impact of NBMs extraction on the river channel have been established. It is generally accepted that the total annual volume of extracted NBMs at one location should not exceed the average volume of the sediment runoff at the upper cross section of this river stretch, and the extraction volume should not exceed the volume of naturally accumulated sediments (Berkovich et al., 2013).

It has been established that small river quarries have the least negative impact on the river system. The length of a small quarry does not exceed the average width of the channel under flood conditions; the width is 25-30% of the channel's width (STO FGBU «GGI» , 2012). It is typical of small quarries that the eddy zone occupies a large part of a quarry. The occurrence of turbulences reduces the transit transport of sediment runoff and favours its accumulation within a quarry (Snishchenko et al., 1990). Apart from the bedload restoration process described above, the small length of the sediment exploitation zone is also conducive to a smaller reduction of the water level above a quarry compared to larger objects. In the case of a large quarry, the development should be carried out through several small quarries, separated by untransformed sections of a similar length as those transformed ones.

4. Criterion for ecologically (effective) permissible depth of river sediment extraction

The depth of a quarry is an important parameter (the height of the extraction margin). The depth of a quarry determines the water surface level, its longitudinal slope within the mining area and hence the water level decline downstream and upstream from a quarry. Excessive dredging in the extraction zone adversely affects the river bank stability, contributes to the deterioration of water quality and siltation of the river channel. In addition, excessively deep quarrying does not bring any economic benefits when all ecological standards are implemented, due to the fact that the depth of quarrying changes the width of an unusable river bank, which is maintained in order to protect the bank. In general, the smaller the natural slope of the waterlogged ground and the greater the depth of exploitation within a quarry, the wider the river bank protection zone should be. Therefore, the increased benefits resulting from increased exploitation make it necessary to incur higher expenditures on river bank protection.

Even though the depth of a quarry has a significant impact on the ecological condition of the river channel system, academic sources and normative documents do not provide any noteworthy guidelines how to measure it. As recommended by the State Hydrological Institute (STO FGBU «GGI», 2012), the depth of sediment extraction within a quarry is defined as a value depending on its volume, width and length. In the field work carried out by the Laboratory of Soil Erosion and Fluvial Processes, based on the principles of preserving the basic, natural characteristics of the channel morphology, the ecologically permissible depth of a quarry is set at the largest depth of the natural stream pool in the channel section used for extraction purposes. Such defined rules may apply to large river sections with well-developed meanders, e.g. the Kama river downstream from the Votkinsk Hydroelectric Station, where the depths at meanders' upper parts reach 6-12 m. At the same time, the depth of the river channel does not exceed 3-4 m in the upper reaches of the Oka river, downstream from the city of Kaluga, within the section of poorly developed bends and meanders. In this case, the exploitation depth resulting from these parameters would not be satisfactory for mining companies.

The maximum depth of extraction is usually limited either by the volume of the usable river alluvium, or by technical capabilities of dredgers used. Due to that, dredgers with a maximum depth of 18 m are used on the Oka river.

In order to determine the ecologically permissible depth of a riverbed quarry, the principle should be observed that the technogenic impact must not affect the ability of the river channel to recover, otherwise the river will gradually degrade. It is known that the recovery of the channel occurs due to sediment runoff, and the process is most effective when the water discharge does not exceed the riverbed-forming discharges, whose range corresponds to the normal filling of the channel within the floodplain. To ensure the sediment runoff, the flow velocity should not be lower than the erosional velocity limit. It can therefore be concluded that the permissible depth of exploitation under conditions of bankfull discharges should provide for at least a minimum water surface slope in the longitudinal profile within the quarry section and the water flow velocity not lower than the erosional velocity limit.

Considering the above findings, the calculations may be limited to determining the average depth of the channel under conditions of bankfull discharge, with a specific slope of the water surface (1 cm/km as a minimum value) and the average water velocity equal to the erosional velocity limit for sand sediments with a defined average particle diameter.

5. Hydrological and morphological description of the Oka river in the section between the Dugna village and the Beloomut village

The ecologically permissible depth was calculated for a riverbed quarry in the section of the Oka between Dugna and Beloomut (250 km long). The upper part (200 km) of the analysed section (until the Moskva river mouth) belongs to the upper reaches of the Oka river, the next 50 km belong to its middle reaches. The total length of the Oka river is about 1,500 km, the total watershed area – 2,425,000 km^2, the average longitudinal slope of the water surface in the river along the researched section is 0.06‰. The Oka river runoff is mostly affected by snowmelt (60%), followed by rainfall (20%) and groundwater (less than 20%). The Oka river represents the eastern-European hydrological regime, characterized by significant flooding in spring, very dry summer, increasing runoff in autumn and low water levels in winter. Typical discharges at three hydrological stations located at the Oka river are presented in Tab. 1.

Between the Dugna stream mouth and the Moskva river mouth, the Oka river has a slightly meandering course, and consists of winding sections and mostly straight channel sections. Only a small number of meanders are present in this stretch. The average width of the channel increases in the downstream direction, from 160 m to 270 m. Below the Moskva river mouth, the Oka freely mean-

Table 1. Typical water discharges during selected observation periods (Osnovnye gidrologicheskie harakteristiki rek bassejna Verhnej Volgi, 2015)

Hydrological station	Distance of the station from the river mouth [km]	discharge, $m^3 \cdot s^{-1}$				
		average	max	annual	min.	annual
Kaluga	1100.9	294	541	1908	138	1921
Kashira	920.8	364	612	1933	210	1975
Polovskoye	644.9	551	862	1994	324	1943

ders and forms large meanders, alternating with poorly developed bends. The average width of the channel in this area varies from 300 to 350 meters, with the widest part reaching 450-550 m.

The Oka riverbed is transformed over the entire analysed section as a result of long-term NBMs extraction as well as dredging and other engineering works within riffle sections. Therefore, the present channel of the Oka river is characterized by alternating artificial (technogenic) sections with artificially increased width and depth and sections of partially preserved natural channel relief. The average depth of technogenic sections ranges from 5 to 8 m. The depth of modern quarries on the Oka river between Dugna and Kolomna villages are 8–11 m (maximum – 15 m), in the area between the city of Kolona and the village of Beloomut – 12 –15 m (maximum – 18 m).

6. Calculations of the ecologically permissible (effective) depth of sediment extraction; the case study of the Oka river

The average permissible depth of the stream (h_q) in the sediment extraction section was determined based on the Chézy formula:

$$h_q = \frac{v_n^2}{c^2 l_q} \quad (1),$$

where:

v_n^2 – non-erosive velocity according to G. Shamov (1954)

$$v_n = 4{,}6 d^{\frac{1}{3}} h^{\frac{1}{6}} \quad (2),$$

I_q = 0.00001 – minimum value of the longitudinal water surface slope in a riverbed quarry under conditions of bankfull discharge.

C – Chézy coefficient determined according to R. Shestakova's formula (Shestakova,1963):

$$C = 18{,}5 l^{-0.1} \quad (3),$$

I – slope under conditions of bankfull discharge prior to sediment extraction.

d – average diameter of sand sediments. In the described situation, it is 0.61 mm in the researched river section.

h – average depth under conditions of bankfull discharge prior to sediment extraction.

The conducted calculations provided the average permissible depth of sediment extraction within the quarry section under bankfull discharge. The calculated value is reduced to the water level planned during exploitation. Then, the maximum permissible depth of sediment extraction from the river channel is calculated for such conditions based on the ratio of normal to maximum river channel depth along the exploited river section, equal to 1.43. This ratio is determined for existing quarries based on bathymetric plans of a channel.

The results of the calculations, using the morphologically homogenous sections in 2013 are presented in Tab. 2. Morphologically homogenous sections are distinguished based on the longitudinal slope of the water surface. The calculations show that the ecologically permissible depth of the extraction depends on local conditions and amounts to 8-13 m for the planned water level. The given data are approximate and must be specified considering the field measurements of channel morphometry, the longitudinal slope of the water surface and lithology of bottom sediments, which are obtained before river sediment extraction.

Table 2. Calculations of the permissible extraction depth for the Oka river for morphologically homogenous channel sections

Sections' limits by km of waterway DDS[1] mark, m BS		values for bankfull discharge								values for the expected water level			
		Q, $m^3 \cdot s^{-1}$	h, m	B, m	d, mm	I, $^0/_{00}$	C	$v_н$ m/s	h_q, m	PL[2] mark, m BS	Average permissible depth, m	Maximum permissible depth, m	
800	820	103.5	3631	6.8	393	0.61	0.023	54	0.54	10.0	100	6.5	9.3
820	830	104.3	3605	6.8	438	0.61	0.098	47	0.54	13.2	100	8.9	12.7
830	852	105	3503	8.6	520	0.61	0.022	54	0.56	10.8	100	5.8	8.3
852	876	105.8	2678	10.1	403	0.61	0.044	50	0.57	13.0	100.1	7.3	10.4
876	894	106.9	2602	8.5	346	0.61	0.071	48	0.56	13.6	100.6	7.3	10.4
894	928	108.4	2509	10.8	380	0.61	0.046	50	0.58	13.5	101.5	6.6	9.4
928	940	109.9	2455	8.5	448	0.61	0.11	46	0.56	14.8	102.7	7.6	10.9
940	970	111.8	2426	8.7	386	0.61	0.074	48	0.56	13.6	104.9	6.7	9.6
970	992	113.7	2373	9.2	382	0.61	0.087	47	0.56	14.2	106.5	7.0	10.0
992	1008	115.2	2305	8.9	309	0.61	0.072	48	0.56	13.6	108.3	6.7	9.6
1008	1046	116.9	2209	10.0	332	0.61	0.055	49	0.57	13.5	109.9	6.5	9.3
1046	1052	118.3	2152	8.5	243	0.61	0.11	46	0.56	14.8	111.3	7.8	11.2

[1] DDC – drawdown curve

[2] PL – expected water surface level

7. Conclusions

The following conclusions can be drawn on the basis of the analysis:

1. The depth of a quarry is an ecologically important parameter of sediment extraction, which determines the water surface elevation within the exploited river section, as well as the new anthropogenic step-like longitudinal profile of water surface resulting in the water level decline within the adjacent sections of a river. The issue of determining changes in the longitudinal profile is poorly addressed.
2. In order to determine the ecologically permissible (effective) depth of a riverbed quarry, the assumption should be made that the technogenic impact cannot interfere with the river's ability to regenerate, otherwise the river may be doomed to gradual degradation.
3. The paper proposes a criterion for permissible depth of river sediment extraction. It provides for at least the minimum values of the longitudinal water surface profile and the flow velocity not lower than the erosional velocity limit under conditions of bankfull discharge along the exploited section.
4. The ecologically permissible depth of river sediment exploitation can be calculated based on the data related to the channel morphology before extraction of sediments, the longitudinal profile of water surface and lithology of bottom sediments using the Chézy formula.

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