Scientific substantiation of dredging volumes on the Ob river -
the most important source of water resources in Western
Siberia

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Abstract. The purpose of the work is to substantiate the volume of dredging operations intended to ensure navigation on the Ob River. It is particularly important to find an option to reduce the impact of dredging on the river as a source of water resources. The method for determining the optimal dredging is based on theoretical research in the field of channel formation. A retrospective analysis showed the presence of different intensity dredging stages: superintensive dredging in the 80s, extremely low stage in the 90s, and the optimal one, which began in the 21st century. Limiting riffles were determined on the basis of the channel stability criteria. Dredge tracks were outlined and the volumes of dredging operations were calculated to create and maintain guaranteed track dimensions on all transit river fairways. For each of the riffles, options for the location of capital and operational dredge tracks are proposed. In total, it is necessary to develop 79 capital tracks, 86 obligatory annual and operational tracks, to erect 21 longitudinal dams and 31 series of spur dikes. The volume of capital dredge tracks in their various versions should be about 8 million m³, and the minimum required volume of operational tracks in various versions is about 7.6 million m³. The main dredging operations fall on the sections of the Upper and Middle Ob. The volumes are assessed as very significant, but absolutely necessary to stabilize the route of the fairway.

1. Introduction
At present, inland waterways on the Ob, Irtysh, Yenisei, Lena and Amur rivers are the most important components of the transport complex of Russia, connecting railways and economically developed regions of the south with the central and northern regions of Siberia and the Far East. Water transport acts here as one of the significant water users. At the same time, the largest Siberian rivers are a source of water resources for several million people, including those living in such large cities as Novosibirsk, Omsk, Krasnoyarsk, Barnaul. The Ob River is the largest waterway connecting the agricultural regions of Altai, the industrial Novosibirsk region with the raw material regions of the North. By the end of the 1980s of the twentieth century, thanks to large investments and the implementation of capital straightening and dredging operations, the radical reconstruction of the river channel on the Ob, a modern water transport highway was created, providing the delivery of economic goods to remote areas of Yugra and Yamal.
However, in the subsequent period, a sharp reduction in the volume of operations led to a partial restoration of the natural state of the river, a decrease in the guaranteed dimensions of waterways, primarily their depths, and the impossibility of maintaining them during the limiting period, especially in low-water years. Natural channel deformations combined with a shortage of financial and technical means and a decrease in the volume of dredging operations on the fairway have led to negative changes in areas with an unstable and weakly stable channel, which do not permit to fully solve the problems of maintaining inland waterways with guaranteed dimensions of fairways. For many years, dredging volumes have been determined not on the basis of scientific evidence, but on the basis of available, often completely insufficient, economic opportunities.

In this regard, it has become especially relevant to determine and comprehensively substantiate the volumes of dredging required to return the Ob waterway to the previous state of an economically efficient transport highway.

The purpose of this work was to determine and substantiate the necessary volumes of dredging on the Ob River to ensure the guaranteed dimensions of fairways and, accordingly, to meet the needs for the transportation of goods and passengers, and to create safe navigation conditions.

2. Materials and methods

The research methodology consisted in analyzing all source materials collected over the past 10-20 years concerning the morphodynamics of the channel, types of channel processes, characteristics of shallows, volumes of dredging operations on transit sections of waterways, designing new dredge tracks and calculating the volumes of excavated soil taking into account hydrological conditions.

The most difficult areas were identified based on the frequency of dredging operations over many years.

Considerable attention was paid to the morphodynamics of the channel. To do this, we used the approaches of N.I. Makkaveev Laboratory of Soil Erosion and Channel Processes at M.V. Lomonosov Moscow State University, in which the arrangement of riffle areas is associated with the morphodynamic type of the channel [24]. Morphodynamic types are taken into account at each of the Ob sections from the confluence to the mouth, and also the characteristics of branched channels are given. In addition, river sections that are difficult for navigation are classified according to the complexity and need for dredging using the channel stability indicators and the channel stability coefficient (see tables 1 and 2).

For each riffle area, several options for capital and operational tracks were proposed, and, if necessary, for channeling and bank protection structures; for all options, the volumes of excavated alluvium were calculated. To automate the calculations of volumes, the Trimble Geomatics Office program was used, which allows taking into account the coordinates of the tracks and the depths of the characteristic points.

Table 1. Channel stability indicators - number Jl, N. I. Makkaveev stability coefficient Ks, and the morphometric index of Makkaveev – Shataeva A and their relationship with drift rates of shallows, shoals, shallow spits $D_s$ (m / year) and the frequency of changes in the water content of the branches T (years) of the Ob River [by 24]

| Section                                      | $Q_{avg}$, $m^3$/sec | Stability indicators | Deformation rate |
|----------------------------------------------|----------------------|----------------------|------------------|
| confluence of Biya and Katun - mouth of Charysh River | 1150                 | 1,6-1,7, 1,6-5,9     | 300-350, 3-10    |
| mouth of Charysh River - Barnaul             | 1470                 | 1,9-5,5, 1,3-6,6     | 200-250, 10-20   |
| Novosibirsk - mouth of Tom River            | 1730                 | 6,3                  | 9,0, 1,06, 50-200|
| mouth of Tom River - the village of Sosnino  | 2810 - 3620          | 6,7                  | 8,5, 20-50      |
| the village of Sosnino – mouth of Irtysh River | 4520             | 15-17                | -                |
| mouth of Irtysh River - Salekhard            | 8230 – 10300         | 21                   | -                |
Table 2. The coefficients of stability of the channel $K_s$ and of frequency of dredging operations production per 1 km of the waterway $n_{dred}$ [by 24].

| Ripple area                           | $K_s$ | $n_{dred}$ |
|---------------------------------------|-------|-----------|
| Bazikovskii – Dregunovskii            | 2.6   | 1.9       |
| Krivoshchekovskii – Mochishchenskii   | 3.6   | 1.6       |
| Mochishchenskii – Bazikovskii         | 5.2   | 1.2       |
| Kozhevnikovskii – Taganski            | 5.4   | 1.0       |
| Verkh. Kameshkovskii – Nizh. Kameshkovskii | 6.1 | 0.9       |
| Nizh. Elganski – Kozhevnikovskii      | 7.0   | 0.8       |
| Bogorodskii – Bazanakovskii           | 10.0  | 0.7       |

On the most complex, multi-branched sections of the river, containing whole groups of limiting riffles, methods of mathematical modeling were applied. In particular, an analysis of the system of equations for solving the problem of calculating water discharge was carried out. For this, an algorithm was used to solve the problem of calculating water discharge in river systems, which is implemented in a software module that makes it possible to perform the necessary calculations of river channel sections based on channel survey data [14, 15].

3. Survey of literature

For many years, a team of employees of the Siberian State University of Water Transport has been dealing with the problem of scientific substantiation of the volume of dredging operations. Numerous scientific reports, monographs, textbooks, articles constitute a valuable information fund, and the developed methods, recommendations, regulatory documents have made a practical contribution to the effective transport use of the river.

In particular, in recent years, a method has been developed that makes it possible to assess the ongoing dredging operations both in the transport and the hydroecological aspects [15]. An overall assessment was given to transit dredging operations and the hydrological factor [12]. Approaches to substantiating dredging volumes and increasing the safety of the navigable route were reflected in the works of Professor V. A. Sedykh [19, 20].

The success of the applied work of Novosibirsk specialists was largely determined by the fruitful cooperation with the N. I. Makkaveev Research Laboratory of Soil Erosion and Channel Processes, Faculty of Geography, M. V. Lomonosov Moscow State University, under the guidance of Doctor of Geography, Professor R. S. Chalov. The works of this research team have laid a solid scientific basis for the design of sustainable shipping routes, taking into account all the features of channel morphology [11, 16, 22–26].

Also, among the studies by Russian authors, it is necessary to mention the works of the staff of the Institute of Water and Environmental Problems of the SB RAS, which consider the water resources of the Ob River as a whole [17, 18, 21]. These works can serve as a basis for forecasts of the water content of the river, and therefore for plans for the arrangement of the fairway in the long term.

Over the past few years, foreign authors have published a number of articles aimed directly at the problem of the impact of operations in river channels on the hydrology and hydroecology of water systems.

D. Barbe, K. Fagot and J. McCorquodale [1] published a paper entitled "Effects on dredging due to diversions from the lower Mississippi River." The article analyzes the long-term impact of dredging on fitting levels on the Mississippi River (downstream of the river up to the Gulf of Mexico) A numerical model called HEC-6 was proposed to calculate sediment accumulation forecasts, which, according to the authors, realistically reflects the processes in the channel of Mississippi River. Backfilling of soil modeling option has been added to the enhanced model.

H. Cai, H. Savenije and others [2] model the influence of river discharge and dredging operations on the spread of tidal waves in the Modomen Estuary (China). Dredging in the estuary has had a tangible impact on the spread of tides. The paper includes an assessment of the impact of these human
interventions through the use of a new analytical (hydraulic) model that calculates tide spread and damping as a function of depth and river discharge.

The works of G. Cook and A. Int [3] are devoted to the description of a pilot dredging project on the small river Wekiva in Florida.

The topic of the influence of nonmetallic building materials quarries on the ecology of water bodies is relevant for such countries as USA, Great Britain, Australia, and Japan. It is reflected in the studies by J. Freedman and J. Stauffer [4].

R. Frings, B. Berbee, G. Erkens established that large-scale operations on the Waal River (Netherlands) led to a change in the morphology of the channel [5].

F. Gob, G. Houbrechts, J. Hiver and F. Petit [6] studied the consequences of dredging in the Ardennes rivers (in particular, the Semois, the channel of which is characterized by large meanders, narrow floodplain and pebble bars), which is usually carried out in small volumes. The extraction of soil here is intended to prevent flooding, the amount of gravel removed from the channel is small. The dredging resulted in a stable track several kilometers long and about 2 m deep, which functioned as a sediment settler (which in turn should discourage flooding). In order to investigate the efficiency of this settler, mathematical modeling methods based on the transport equations of Meyer-Peter and Müller were applied, and then the simulation results were compared with empirical data; the total values diverged, i.e. the proposed model could not adequately describe the situation.

An article by S. Hossain, B. Eyre, L. J. McKee [7] discusses the extensive dredging operations in the Brisbane River estuary.

The intensification of the use of water resources is also taking place on the Korean Peninsula. J Lee, S. Lee, S. Bai (S. Wu) and D. Shin [8] proposed a hydrological “framework model” for the calculation and maintenance of river dams, the general development of river areas, and the calculation of the consequences of dredging on rivers. The model is interesting in that it takes into account both hydrological parameters and economic costs.

J. Morin, P. Boudreau, Y. Secretan, M. Leclerc [9] modeled the consequences of dredging on the St. Lawrence River. A two-dimensional hydrodynamic model was used to obtain a quantitative description of the processes; data collection was carried out at 300,000 points, the data were compared with indicators of the late 19th century. Hydrodynamic simulations show an increase in flow rates for shallows and a decrease in rates in deeper areas. Dredging and straightening of the channel around Cornwall have led to changes in the hydrological regime in almost 2/3 of the river sections, and changes are also noted in the sediment accumulation in the channel.

In general, based on the analysis of literary sources, it can be argued that the correct determination of dredging volumes and an increase in the efficiency of dredging operations must take into account the following:

- Changes in water levels: dredging may reduce water levels, but the degree of change will depend on local hydrological conditions; reduction does not occur automatically in all cases.
- Increased risks of flooding downstream areas.
- A decrease in the amount of drift, especially in the downstream of dams, leads to the washout of alluvium.
- “Forced” dredging of the waterway (without taking into account the hydraulic capabilities of the river) leads to the return of the original situation, i.e. to decrease of the level of depths.
- It is important to study drift sources and their distribution in the channel: zones with negative and positive drift balance should be taken into account both before and after dredging. It is also worth considering the balance of drifts and reducing their input from off-channel sources (for example, by regulating the washout of solids from agricultural land); ideally, the impact on this process can be a major factor in the trackworks.
- It is important to apply “supportive” dredging methods: to conduct it along already laid waterways in order to reduce the impact on geomorphology and ecology.
- The shipping lane must be stable, the interaction of the bed-stream system should be built in such a way that the repetition of work is minimal.
4. Results and discussion

The analysis of the temporal dynamics of dredging volumes is presented in Figures 1 and 2. It can be seen from them that the bulk of the work falls on the areas under the jurisdiction of the FBI "Administration of the Ob BVP", the FBI "Administration" Ob-Irtyshvodput accounts for only a small part of the Ob River dredging, which is associated with a small number of limiting riffles and significant depths on the lower Ob River.

**Figure 1.** Dynamics of dredging volumes in the sections of the inland waterways belonging to the jurisdiction of the FBI "Administration" Ob-Irtyshvodput" (1980-2013)

**Figure 2.** Dynamics of dredging volumes in the sections of the GDP belonging to the jurisdiction of the FBI "Administration" of the Ob BVP" (1980-2013)
In the late 1980s, dredging volumes reached record levels (up to 43 million m³) and continued to be very significant until the first half of the 1990s. During this period, a radical change in the channel took place, a large-scale attempt was made to provide a single, stable route for the fairway with a simultaneous increase in the guaranteed depths.

However, by the end of the 1990s, the river began to return to its natural state. Thus, such methods of maintaining and improving the characteristics of inland waterways turned out to be practically unjustified, financially costly and, of course, unrealizable in modern conditions from an economic and technical points of view.

From the mid-1990s to the mid-2000s, the dredging volumes, on the contrary, turned out to be extremely low (from 0.1 to 3 million m³), which turned out to be completely insufficient to maintain guaranteed depths, led to their decrease, difficulties during the navigation period, ineffective the use of the fleet. Maintaining the volume of dredging at this level, it will become more and more difficult to maintain guaranteed depths every year.

Thus, there are two periods of dredging on the Ob River: the "super-intensive" one 1970s, 1980s, early 1990s) and "obviously insufficient" one (second half of the 1990s, 2000s), and neither is the optimal. At present, a scientific substantiation has been given for the annual operational and capital dredging on the Ob up to 14 million m³ per year, followed by a decrease to 9-10 million m³ per year.

In total, since 1990, in the section Slianie - Ust-Charyshskaya Pier about 66 riffles were worked out, from Ust-Charyshskaya Pier to Barnaul - 34 riffles, from Barnaul to Kamen-na-Obi – 39 riffles, from Novosibirsk hydroelectric power station to the mouth of the Tom River - 98 riffles, from the mouth of the river Tom to the mouth of the Nerga river – 27 riffles, from the mouth of the Nerga to the village Sosnino - more than 20 riffles. Since 1980, 87 riffles were worked out on the Lower Ob River, but the volumes were rarely significant.

Based on the analysis, options for the location of capital and operational dredging tracks for each of the riffles are proposed. In total, it is required to develop 79 capital, 86 obligatory annual and operational tracks, 58 tracks operating depending on hydrological conditions and seasonal regime (i.e. the number of operating tracks to be developed annually ranges from 86 to 144), to erect 21 longitudinal dams and 31 series of spur dikes (i.e. 52 straightening structures).

The results of mathematical modeling of the tracks made it possible to draw the following conclusion: small operating tracks, previously made in these areas, are unstable; to stabilize the route of the fairway, capital tracks, channeling structures, and a whole range of straightening works are required. For such tracks, the rates of initial deformations were calculated and the timing of sediment accumulation was determined in the Nizhni Kudriashovskii - Medvezhi, Orsko-Borskii, Ust-Animskii - Rovnyi, Talitskii, Nizhni Saltanakovskii sections. It is shown that, in general, the proposed tracks are stable, and their deformations are minimal.

### Table 3. Required volumes of operational dredging

| Waterway area | Annual operational dredging mln.m³ |
|---------------|-----------------------------------|
|               | Initial                          |
|               | Taking into account recurrence    |
| Barnaul       | 1.2                              |
| Novosibirsk   | 2.0                              |
| Tomsk         | 1.5                              |
| Kolpashevo    | 1.2                              |
| Total         | 5.9                              |
|               | 1.56                             |
|               | 2.6                              |
|               | 1.95                             |
|               | 1.56                             |
|               | 7.67                             |

Studies have shown that the annual volume of dredging in the Ob River (the area of responsibility of the FBI "Administration of the Ob BVP") during the development of operational tracks will amount to 7.67 million m³. Depending on the hydrological characteristics of a particular year, perennial and seasonal deformation of the riffles, as well as the need for repeated dredging (repair and restoration) operations, arising for the same reasons, this value should be increased by 30%, i.e. the volume of annual operational dredging will amount to 9.97 million m³. Of these, the Ob River sections in the area
of responsibility of the Administration of the Ob Basin of Inland Waterways account for 5.9 million m$^3$ per year along the primary tracks and 7.67 million m$^3$ - taking into account the repetition of work, including in the areas of waterways.

The volumes depend on the slot routing options. It should be noted that these dredging volumes are generally consistent with the estimates of the chief engineers of the waterway and shipping area of the FBI "Administration of the Ob BVP".

The minimum volumes of operational dredging on the Ob River required to maintain transit fairways in working order must be at least 300 thousand m$^3$ per year for the FBI "Administration" Ob-Irtyshvodput "

The final volumes for capital dredging are presented in tables 4 and 5.

**Table 4. Volumes of dredging on inland waterways under the jurisdiction of the FBI "Administration of the Ob BVP"

| Name of section (river reach) | Calculated dredging volumes, thousand m$^3$ | Volumes of proposed tracks | Volumes analyzed in retrospect | Total |
|-------------------------------|---------------------------------------------|----------------------------|-------------------------------|-------|
| Slianie - Ust Charyshskaia Pier | 991                                         | 226                        | 1217                          |
| Ust Charyshskaia Pier - Barnaul | 333                                         | 42                         | 375                           |
| Barnaul – Kamen-na-Obi         | 361                                         | 255                        | 616                           |
| Kamen-na-Obi – sluice of Novosibirsk HEP | 317 | 0 | 317 |
| Mouth of the Novosibirsk access channel - mouth of the Tom River | 1016 | 2005 | 3021 |
| Mouth of the Tom River - mouth of tributary Nerga | 142 | 1024 | 1166 |
| mouth of tributary Nerga - Sosnino | 806 | 561 | 1367 |
| TOTAL                         | 3966                                        | 4113                       | 8079                          |

**Table 5. Volumes of dredging on inland waterways under the jurisdiction of the FBI "Administration Ob-Irtyshvodput "

| Name of section (river reach) | Calculated dredging volumes, thousand m$^3$ | Volumes of proposed tracks | Volumes analyzed in retrospect | Total |
|-------------------------------|---------------------------------------------|----------------------------|-------------------------------|-------|
| For all river reaches         | 260                                         | 50                         | 310                           |
| TOTAL                         | 260                                         | 50                         | 310                           |

* - approximate data (due to low volume of dredging operations)

It should be noted that tracks location options and, consequently, the determination of the total volume of soil was carried out in two ways: taking into account the previously performed dredging operations and not taking them into account, based on the analysis of channel processes.

Obviously, after completing the planned work, it is necessary to compare the results obtained in practice with the calculated data. To do this, the following monitoring system can be proposed.

I. Annual complete survey and measurements with drawing up plans;

1) along the entire length of sections 1. Confluence of Biia and Katun - mouth of the river Alei (I category of complexity) and 4. Novosibirsk hydroelectric complex - the mouth of the Tom river (II category of complexity);

2) on ripples and riffle areas of the 1st high and 2nd average difficulty rank in all other sections - 2. Mouth of the river Alei - the city of Barnaul; 3. The city of Barnaul - the city of Kamen-na Obi; 5. Mouth of the Tom River – village Sosnino; 6. Village Sosnino - mouth of the Irtysh River; 7. Mouth of the Irtysh River - mouth of the Ob River (Salekhard).

II. Mandatory repeated surveys of:

1) ripples and riffle areas of the 1st high difficulty rank during flood recession and in low water at levels close to the design level (at least 2 per navigation);

2) ripples and riffle areas of the 2nd rank of difficulty in all sections, regardless of their complexity;
3) riffles of the 3rd difficulty rank (depending on the situation).

III. Preliminary and control surveys of all riffles on which dredging operations are carried out.

Based on the results of monitoring, recommendations can be given for further dredging, taking into account the ongoing reformation of the channel, possible changes in the water regime and sediment runoff of the river, affecting the state of the channel of the capital dredging operations performed, as well as possible other types of technogenic impact on the channel (sand-gravel quarries, onshore construction, pipeline laying, etc.).

It is also required to develop a general scheme for stabilizing the fairway by carrying out a set of straightening works (erection of spur dikes and longitudinal structures), which should ensure the inadmissibility of lowering the design water level of the section Lower access channel - the mouth of the river Tom.

5. Conclusion

Based on the results presented in Figures 1-2 and Tables 3-5, the following can be stated.

On the transit sections of inland waterways, which are under the jurisdiction of the FBI “Administration of the Ob BVP”, the volume of dredging is insufficient to ensure the guaranteed dimensions of the fairway during the navigation period.

To maintain the transit passageways in working order, operational dredging of at least another 7.6 million m³ is required (taking into account the repeatability of the work). Taking into account the options for routing the slots and the variability of hydrological conditions, this indicator can vary from 5 to 9 million m³.

The volume of capital dredging tracks in their various versions should be about 8 million m³. At first glance, the result seems quite large (taking into account the need to perform operational dredging), however, one should take into account the variability and sequence of work: the volume according to the main option can be 4.6 million m³, and the volume of the first stage is about 1.8 million m³. Summing up this figure with the minimum required volume of operating tracks, we get a value of 9.0 - 9.4 million m³. The volume can be assessed as a very substantial (it is close to the potential capabilities of the dredging fleet of the “Administration of the Ob BVP”, which amount to about 9.7 million m³ per navigation). It is quite natural that it is necessary to start large-scale work from the areas with the most intensive shipping (Novosibirsk - the mouth of the Tom river), moving to those with less heavy traffic. At the same time, capital dredging and channeling are absolutely necessary to stabilize the fairway route.

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