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Revealing the Surge Phenomena Contribution of the Heavy Metals Inflow to the River Don Delta

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Purpose. The aim of the study is to evaluate the surge phenomena effect on the heavy metals inflow to the Don Delta based on the archival and expedition data analysis, as well as using mathematical modeling.
Methods and Results. To achieve the purpose, the *Hydrologic Engineering Center River Analysis System* (*HEC-RAS*) mathematical hydrodynamic model and the original model of the heavy metal compounds' transfer and transformation in the Don Delta, developed by S. V. Berdnikov were applied. The models included the irregular grid for the Don Delta region with the average resolution 100 × 100 m. The grid cells were grouped into the compartments according to the hydrological principle. Twelve scenarios of dynamics of the suspended solids, and the dissolved and suspended forms of Ni, Cu, Pb and Cd were calculated for the surges of various intensity under the conditions of variable water content and seasonal dynamics of near-water vegetation. In accordance with the scenarios, the graphs showing the changes in the suspended matter content and accumulation, and the maps of the deposited substance distribution resulted from the surges in the delta were constructed. During two days the calculations for which include the surges of varying repeatability and the variable water content, about 0.3–3 t of nickel compounds, 0.1–1.8 t of copper compounds, 0.2–1.8 t of lead compounds and 0.01–0.04 t of cadmium ones deposit in Don. The obtained results made it possible to reveal two regions where the increased accumulation of the precipitated suspended matter and the heightened concentrations of the heavy metal dissolved forms were observed: the interfluve of the Don shipping channel, and the systems of the Kalancha and Kuterma river branches.
Conclusions. As for their influence upon formation of the flow of the heavy metal suspended forms, the surge phenomena surpass the river flow. The suspended matter concentration in the Taganrog Bay waters during the surges is the governing factor for the heavy metals inflow to the Don Delta. At the same time, the regions characterized by the highest suspended solids sedimentation and the increased concentrations of the heavy metal dissolved forms are the closest to the Taganrog Bay areas covered by reed vegetation.

Keywords: heavy metals, Don Delta, mouth area, surge, hydrodynamic modeling.

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Introduction

River mouths, as contact zones of sea and river waters, are vulnerable to natural and anthropogenic fluctuations of river flow regime, sea level and water quality. The Don Delta is one of the most economically and socio-economically important estuarine regions of Russia. The interaction of sea and river waters here occurs under the enhanced anthropogenic impact of the Rostov-on-Don agglomeration. Significant changes in the Don mouth system in the last decade are described below.

Currently (2007–2020), the Don's water runoff has been reduced (to 13–16 km^3/year [1] at a rate of 22 km^3/year [2]), which is due to climatic reasons of its formation. In the current low-water period in the intensive economic activity areas in the Don basin, there is a shortage of water resources, which creates serious problems for water supply to the population, agricultural production, fisheries and the unique Don ecosystem preservation. In addition, in the modern period there is a significant decrease in the solid runoff of the Don River

The surface waters of the Lower Don are characterized by a high degree of pollution, being one of the sources of heavy metals for the its delta [1]. Another pollution source is the Taganrog Bay seawaters [3], supplied by the surge phenomena typical of the region. Under the observed conditions of low Don runoff, the effect of these sources on the content of heavy metals in water and soil may change.

Natural fluctuations in the characteristics of the hydrological regime of the Don and the Azov Sea lead to risks of negative impact of water on the population and economic facilities. As noted in the Water Strategy of the Russian Federation (URL: http://www.mnr.gov.ru/docs/strategii_i_doktriny/128717/), the risk of floods and other negative impacts of water will persist and increase in the future due to the increase in hazardous hydrological phenomena in new climatic conditions. For the Don mouth region, especially its delta, these are the risks of flooding as a result of water surges from the Taganrog Bay, an increase in the incidence of water penetration with relatively higher salinity (against the background of a low water runoff of the Don), deterioration of the drinking water quality and economic household water supply of the city of Azov and other settlements. Since 2007, the Southern Scientific Center of RAS (Rostov-on-Don) (the SSC RAS) has been monitoring the level in Donskoy khutor (the Don delta), at the Vzmorye post (the Taganrog Bay) and in Kagalnik village (the Don delta). Since 2013, water level observations at gauging stations was carried out using automatic level gauges with a time step of 10 minutes. In addition, regular complex expeditions to the Azov Sea and the Don River are annually carried out. As a result, the SSC RAS has accumulated an archive of hydrological and hydrochemical observations in the Don River, its delta (along the branches, yeriks and on the islands) and in the delta part of the Taganrog Bay of the Azov Sea. Based on the accumulated materials in 2018, surges for 2007–2018 were analyzed [4], the two-dimensional hydrological model HEC-RAS was adapted [5], the distribution of the Don delta roughness season was estimated and the Don delta zoning according to the degree of surge impact was carried out [6].

This present paper gives the results of modeling the inflow of heavy metals into the Don delta with surges of different recurrence in conditions of medium and high water content of this river.

Materials and Methods

To solve the problem of studying the role of surge phenomena in the inflow of heavy metals into the Don delta under modern hydrological and geochemical conditions, the results of measurements of the concentrations of heavy metals (Cu, Pb, Cd, Ni) in water and suspended matter in the Taganrog Bay and large and small branches the Don delta and the Don riverbed from Starocherkasskaya village to Rostov-on-Don within 2006–2019 were collected and analyzed. The database includes the results of both our own special geochemical studies of the SSC RAS and joint work with Moscow State University on the study of the geochemistry of aquatic landscapes of the Don delta [7], as well as fund data. A summary of the concentrations of heavy metals in water and suspended matter in the Don mouth area is given in Table 1. It should be noted that the concentrations of heavy metals in water and suspended matter are subject to seasonal changes. It can be seen when comparing the data for the summer-autumn low-water period in 2013–2014. [8, 9] and long-term average values. In addition, according to estimates [8], the flow of suspended forms of Ni, Cu, Cd and Pb with river waters decreases when moving from the delta top to the downstream sections, i.e., sedimentation of suspended forms of heavy metals occurs.

Table 1

Average values of the heavy metal contents in water (mkg/l) and in the suspended solids (mkg/g) in the Don Delta and the Taganrog Bay in 2006–2019

Objects	Cu	Cd	Pb	Ni
	Metal dissolved forms			
Don (*n* = 80)	3.1	0.63	1.60	8.2
Don (*n* = 25) (by [8])	1.4	0.05	0.10	2.3
Taganrog Bay (*n* = 93)	5.4	0.33	3.22	11.4
	Metal suspended forms			
Don (*n* = 80)	48.7	0.96	29.5	42.7
Don (*n* = 11) (by [9])	22.9	0.40	23.4	38.3
Taganrog Bay (*n* = 93)	35.9	0.73	38.6	30.9

According to the estimates [10], in Russia about 2,450 tons of lead enter water bodies annually, of which 1,000 tons – into soil and water from the destruction of batteries, 1,400 tons – as a result of hunting and only 50 tons – from stationary sources. Comparison of these estimates with the inflow of forms of heavy metals with surges into the Don delta is of interest for understanding the role of anthropogenic impact on the environment.

The data used for the surge simulation scenarios are presented in Table 2 and 3. For further work, the concentrations of heavy metals related to periods with an average water content of the Don (500 m^3/s) and averaged over a long-term period were selected from the database. To simulate the migration of heavy metals with an increased water content of the Don, characterized by water flow rates of the order of 2000 m^3/s, which was observed only twice in the 21st century – in 2003 and in 2018, the data of the own field observations and stock data of the *Azovvodokanal* (Azov Water Service Company) were used in the present study.

Analysis of Table 2 and 3 show that a suspended form is of the highest significance for the mass transfer of heavy metals between the Taganrog Bay and the Don delta, since the amount of suspended matter in the Taganrog Bay due to wind turbidity and inflow with river runoff is higher than in the river.

T a b l e 2

Concentrations of suspended matter and metal compounds in the water inflowing to the Don Delta at the 500 m³/s discharge

Component		Don (delta mouth)	Mouth of the Taganrog Bay (during a surge)
Suspended matter, mg/dm^3		17.00	60.00
Ni	dissolved form, mkg/dm^3	2.80	3.10
	suspended form, mkg/g	38.00	40.00
Cu	dissolved form, mkg/dm^3	9.40	2.10
	suspended form, mkg/g	29.00	25.00
Pb	dissolved form, mkg/dm^3	0.10	0.08
	suspended form, mkg/g	31.00	25.00
Cd	dissolved form, mkg/dm^3	0.14	0.16
	suspended form, mkg/g	0.30	0.50

T a b l e 3

Concentrations of suspended matter and metal compounds in the water inflowing to the Don Delta at the 2000 m³/s discharge

Component		Don (delta mouth)	Mouth of the Taganrog Bay (during a surge)
Suspended matter, mg/dm^3		19.00	71.00
Ni	dissolved form, mkg/dm^3	2.80	5.60
	suspended form, mkg/g	11.60	14.30
Cu	dissolved form, mkg/dm^3	1.80	1.70
	suspended form, mkg/g	5.20	4.80
Pb	dissolved form, mkg/dm^3	0.10	1.20
	suspended form, mkg/g	14.60	11.40
Cd	dissolved form, mkg/dm^3	0.11	0.14
	suspended form, mkg/g	0.26	0.40

To estimate the inflow of heavy metals and suspended matter sedimentation within the Don delta, a complex of hydrological models was used. It consisted of the HEC-RAS hydrodynamic model and the original model of transport and transformation of heavy metal compounds in the Don delta by S. V. Berdnikov [11]. The models were used sequentially – the results of hydrological calculations of the dynamics of water entering the Don delta with a surge and river runoff obtained using HEC-RAS model were the input data for calculating the inflow of heavy metals and suspended matter sedimentation according to the model of S.V. Berdnikov. Two-dimensional calculations in the HEC-RAS model are based on the solution of the Navier – Stokes equations in shallow water conditions; S.V. Berdnikov's model is based on the balance equations for the inflow and deposition of substances in selected areas (compartments). For the complex of models used, a general computational grid (with selected compartments), initial data and boundary conditions was developed.

F i g. 1. Hydrological areas of the Don Delta

To parameterize the complex of hydrological models, a computational domain was built. Its regular grid of cells 100 × 100 m was complicated by the boundaries of compartments, taking into account strict hydrological criteria. The water area of the Taganrog Bay and the water area of the main river waterways in the Don delta were chosen; the water area of the main river waterways was divided into sections of separate rivers and branches, which were then parted into shorter sections (up to 10 km), covering a homogeneous waterway element (reach, turn, etc.); the land area was divided between the designated waterways into right and left catchments, and the Taganrog Bay catchments were also separated. It should be noted that some part of the designated catchments can exchange water with different designated waterways (for example, due to a dense network of canals or yeriks), such territories were evenly distributed between the corresponding waterways. A total of 95 compartments were identified (Fig. 1).

In the computational domain used, there are two boundaries provided: along the Taganrog Bay water area and at the delta top along the Don waterway. In the HEC-RAS model, the water level dynamics in Donskoy khutor are set through the selected boundaries during the surge and costs in the Don River, accordingly. In S.V. Berdnikov's model, the concentrations of substances are specified for the water entering through the boundaries. For the computational domain, the roughness distribution used in [6] was also specified. It plays a key role in HEC-RAS calculations. In the S.V. Berdnikov model, it is assumed that for areas that are under water, the sedimentation rate of suspended solids depends on the surface roughness, and for channel sections of open water it is reduced to zero. For flooded areas overgrown with vegetation, including branches and waterways with aquatic vegetation, the sedimentation rate increases to a maximum of 10 times compared to a free waterway.

Results and Discussion

Similar to the approaches in [6], to analyze the inflow of suspended forms of heavy metals into the Don delta, various combinations of the Don water content, surge levels and roughness coefficients of reed thickets occupying 46.4% of the Don delta were considered. Combinations of these parameters were grouped into 12 scenarios (Table 4).

Table 4

Hydrological parameters of the model scenarios

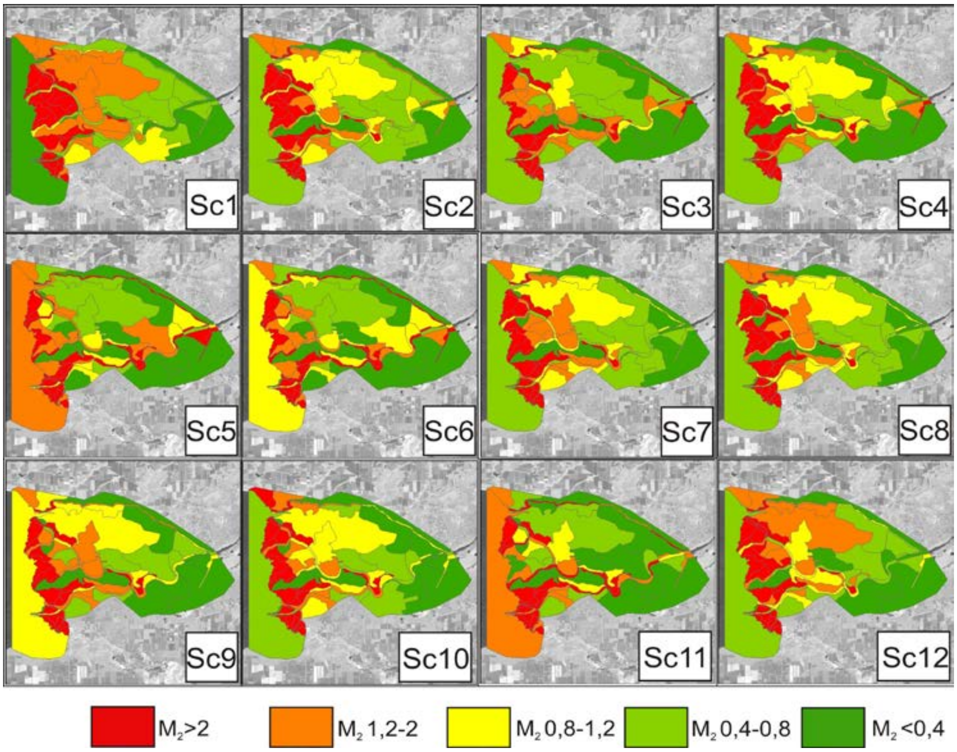
Scenario	Water discharge at the delta mouth, m^3/s	Water level rise during the maximum surge, m	Reed surface roughness
Sc1	2000	3.7	0.12
Sc2	2000	3.7	0.04
Sc3	2000	2.5	0.12
Sc4	2000	2.5	0.04
Sc5	2000	1.5	0.12
Sc6	2000	1.5	0.04
Sc7	500	3.7	0.12
Sc8	500	3.7	0.04
Sc9	500	2.5	0.12
Sc10	500	2.5	0.04
Sc11	500	1.5	0.12
Sc12	500	1.5	0.04

For each scenario, the distribution of the accumulated precipitated suspension over the compartments was estimated at the end of the second day of the calculation. Suspended sediment accumulated within each area. To estimate the role that each specific area plays in the suspended matter sedimentation during the mixing of seawater and river water that entered the delta during the surge, the share of accumulated sediment in the delta was compared with the area's share in the delta. For each area, the deposited matter accumulation index was calculated for two days of calculation (M_2):

$$M_2 = \frac{M_r / \sum M_r}{S_r / \sum S_r}, \quad (1)$$

where M_2 is the accumulation index of precipitated matter for two days of calculation; M_r is the mass of accumulated sediment in the area, kg; ΣM_r – mass of the accumulated sediment in the delta, kg S_r is the are square, km^2; ΣS_r is the delta square, km^2 (723.3 km^2).

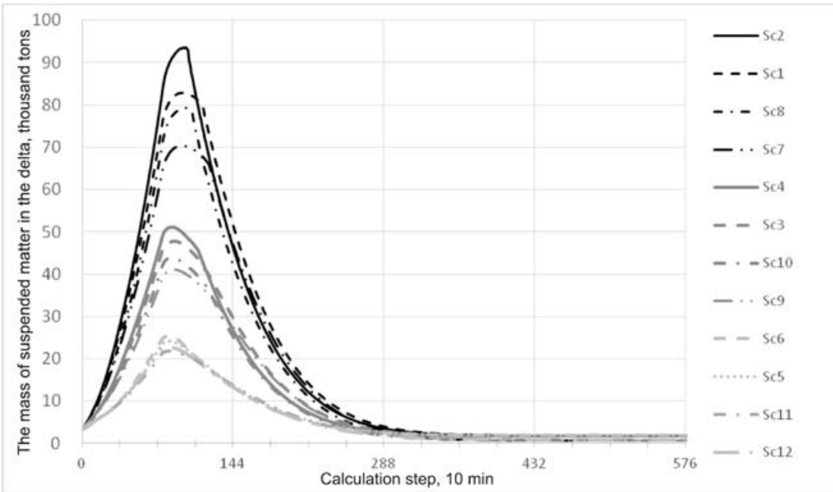
As a result, the spatial distribution of the M_2 index over the delta space was obtained (Fig. 2). For all the considered scenarios, the M_2 index varied in the range of 0–8.5. At the same time, as follows from formula (1), the index takes on high values with intensive sedimentation in the area under consideration.



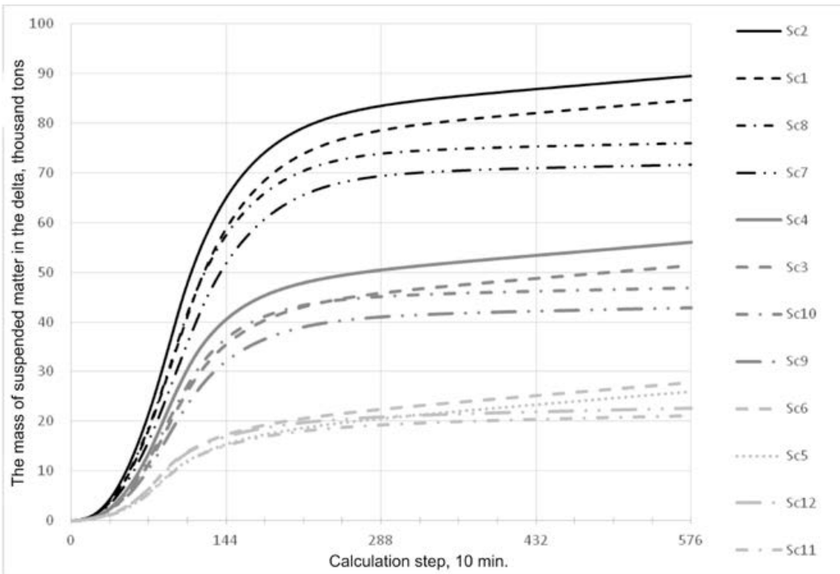
F i g. 2. Spatial distribution of the sediment accumulation index over 2 days of calculations (M_2) at various combinations of the Don water flow content, reed surface roughness and surge heights

As part of the scenario approach, using the compartment model, the volumes of suspended matter inflow into the delta (Fig. 3) and its deposition (Fig. 4) were calculated.

In the presented graph, the suspended matter inflow into the delta is grouped by the surge magnitude. It is shown that during a surge with a maximum of 1.5 m (according to the Baltic height system – BS), the mass of suspended matter in the delta at the peak increases by 4–5 times compared to the initial, with a surge of 2.5 m (BS) – by 8–10 times, with a surge of 3.7 m (BS) – 16–20 times. At the same time, at low roughness, the peaks are higher and begin to subside a little earlier. The increased water content also intensifies the peaks.



F i g. 3. Dynamics of the suspended matter inflow to the Don Delta according to the scenarios



F i g. 4. Dynamics of sediment accumulation in the Don Delta according to the scenarios

Fig. 4 shows that the mass of sediment in the delta as a result of the surge can reach 85,000 tons in two days of the surge with a high water content of the Don in conditions of low roughness (with a usual flood in early spring). In addition, the usual heavy surges, observed several times each year (the height of the level rise up to 1.5 m (BS)), lead to the deposition of about 20,000 tons of matter in two days, while extreme surges (2.5 m (BS)) – 40–50,000 tons (Fig. 4).

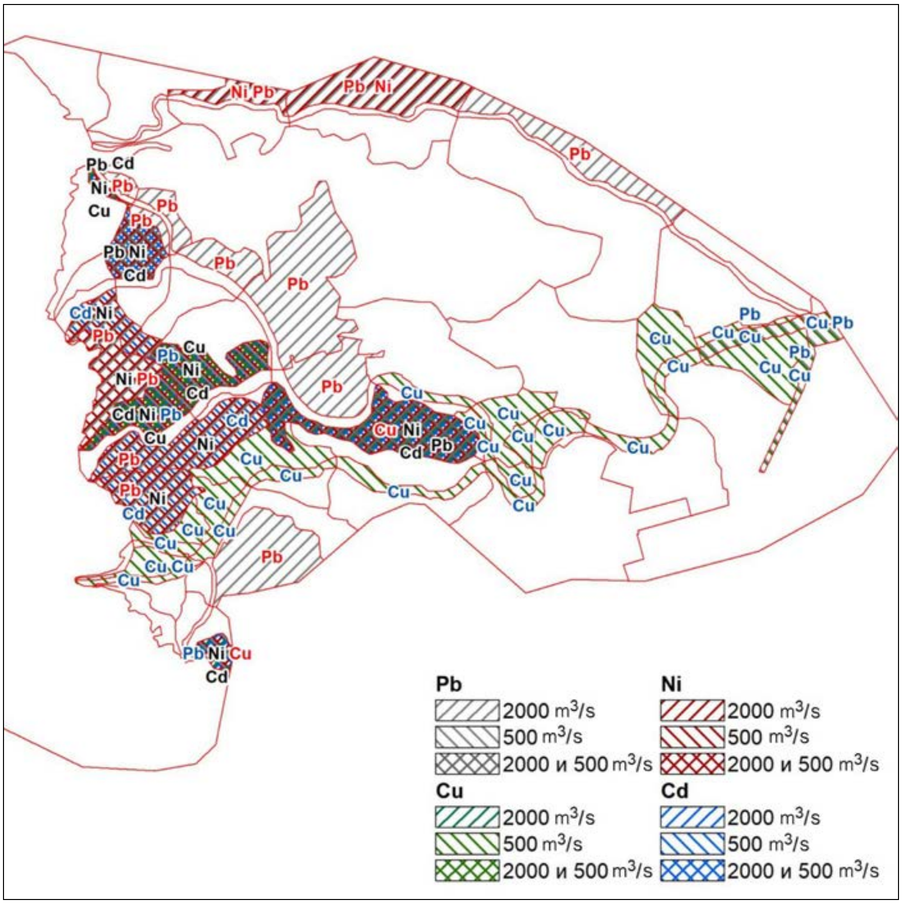
In terms of the average concentrations of the studied heavy metals in the suspension of the Taganrog Bay, estimates of the inflow, which are given in Table 5, are obtained.

Table 5

Surge-resulted accumulation of the heavy metal suspended forms (t) in the Don Delta by the end of the second day of calculation

Scenario	Ni	Cu	Pb	Cd
Sc1	1.1	0.4	0.9	0.03
Sc2	1.2	0.4	1.0	0.03
Sc3	0.7	0.2	0.5	0.02
Sc4	0.7	0.2	0.6	0.02
Sc5	0.3	0.1	0.2	0.01
Sc6	0.3	0.1	0.3	0.01
Sc7	2.8	1.7	1.7	0.03
Sc8	3.0	1.8	1.8	0.04
Sc9	1.6	1.0	1.0	0.02
Sc10	1.8	1.1	1.1	0.02
Sc11	0.8	0.5	0.5	0.01
Sc12	0.8	0.5	0.5	0.01

For each heavy metal in dissolved form, the calculations of the inflow into the Don delta were carried out according to the selected surge scenarios. As a result, areas with increased concentration values relative to the initial level were obtained. As shown in Fig. 5, they are mostly located in the central area of the delta, between the Stary Don and Kalancha rivers. The main areas of heavy metal concentration are the floodplain areas of the Kalancha and Mokraya Kalancha, the mouth of the Kagalnik and the branch of the Bolshaya Kuterma River. Attention is drawn to the increased concentrations of copper (along the main shipping route during surges in low water conditions of the Don, which is probably associated with the sea water inflow through the deepest navigable branch of the delta – the Stary Don), as well as lead (on the right banks of the Kalancha, Kuterma and Mertvy Donets) in the conditions of high water content of the Don.



F i g. 5. Areas with the heightened concentrations of the dissolved forms of heavy metals (Ni, Cu, Pb, Cd) after the 2-day surge for the scenarios of the increased and decreased water content in Don. Blue color indicates the elements with the increased concentration at the Don water content 500 m^3/s, red and black colors show the same – at the Don water content 2000 m^3/s and at both variants (500 and 2000 m^3/s), respectively

Conclusions

The hydrological regime variations in the Don delta, caused by surges and changes in its runoff, primarily determine the variability of the concentrations of heavy metal compounds observed here, both in dissolved and in suspended form.

Taking into account that the sedimentation rate of suspended matter when moving between the sections from the delta top to Uzyak khutor (the Stary Don branch) is 201, 64, 99 and 1.5 mg/s for Ni, Cu, Cd and Pb, respectively, for two days the external flow of suspended forms of heavy metals with river runoff will be from 0.13 kg for Cd to 17.4 kg for Ni for the considered section, and for the entire waterway network of the delta 47 kg Ni, 15 kg Cu, 23 kg Pb and 0.35 kg Cd. Comparing these indicators with the values given in Table 5, it is easy to see that even during a normal strong surge with a low water content in summer (scenario Sc11), 17–33 times more suspended forms of heavy metals enter the delta than with river runoff.

Taking into account the aforementioned data, it should be recognized that the effect of anthropogenic pollution with metal compounds seems to be less significant and of a purely local character. For two days of surge, about 0.2–1.8 tons of lead compounds, 0.3–3 tons of nickel compounds, 0.1–1.8 tons of copper compounds and 0.01–1.8 tons of lead compounds and 0.04 tons of cadmium compounds can be transferred to the Don delta from the Taganrog Bay. Moreover, the main areas of intensive sedimentation of suspended matter and increased concentrations of dissolved heavy metals after the surge are located in the interfluve of the Don navigable branch and the system of the Kalancha and Kuterma arms, which is characterized by widespread reed thickets along the banks and the effect of surges intensified in comparison with other delta areas.

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Aleksey V. Kleschenkov – review of studies of the hydrological regime of the Don delta, selection of hydrochemical parameters for model calculations and estimation of the calculation results

All the authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.