HYDROPHYSICAL PROCESSES

The Density of Bottom Sediment Particles in Water Bodies

Sh. R. Pozdnyakov[a] and A. V. Revunova[a], *

[a]Institute of Limnology, Russian Academy of Sciences, St. Petersburg, 196105 Russia

**e-mail: reina_abc@mail.ru*

Abstract—The density of particles in the bottom deposits of water bodies is an important characteristic, which determines the rate of interaction between bottom water layers with the surface layer of bottom sediments and which in the modern studies cannot be assumed constant. In the presented article, the variability of this characteristic is evaluated for Lake Ladoga. This variability requires correction of the existing procedures for particle-size analysis of bottom sediments in natural water bodies.

INTRODUCTION

Many hydrophysical and hydrochemical processes in water bodies are largely governed by the interaction between the water mass and the solid particles suspended in it and deposited on the bed. The rates of the processes of such interaction are determined by several characteristics of solid particles. One of the most important characteristic is their density and parameters associated with it, in particular, the hydraulic size. Indeed, the hydrodynamic and physicochemical interaction between solid particles and the ambient water in water bodies, as well as the processes of sediment roiling and settling are mostly determined by their hydraulic size. This is true for both particles suspended in water mass and solid deposits on the bed. The generally accepted term *hydraulic size u* (m/s) denotes the velocity of uniform dropping of a particle in water at rest (unperturbed). Many classical theoretical and experimental studies of the hydraulic size of particles, pioneered in the works of J.G. Stokes in the mid-XIX century, were intensely developed in the late XX century. Here we can mention the basic studies of M.A. Velikanov, V.N. Goncharov, A.V. Karaushev, etc. [1, 2, 5–7]. These studies yielded formulas and tables characterizing the dependence of the hydraulic size on particle diameters, water temperature, and the shape of particles (for coarse sediments at turbulent and transitional settling regime [6]). The results of these studies were used to prepare methodological recommendations on the practical grain-size analysis of particles, which were included in appropriate Regulations and applied on Roshydromet network [8]. In the case of fine particles with laminar settling regime, Stokes theoretical relationship [5]

$$U = k_l g d^2 (\rho_s - \rho) / 4 k_v \rho,$$

was commonly used, where ρ is water density, kg/m^3; ρ_s is the density of sediment particles, kg/m^3; k_v is the kinematic viscosity coefficient, m^2/s; g is free fall acceleration; d is the diameter of a ball with a volume equal to that of the particle; k_l is a constant factor which Stokes took equal to 0.22 for spherical particles. This relationship was confirmed by experiments in numerous studies throughout the XX century, e.g., in [5].

An important feature is to be mentioned. In practically all studies, the density of solid particles was commonly assumed constant and equal to 2.65 g/cm^3. This is typical of all classical works [1, 2, 6]. The studies of variations of the density of solid particles in natural water bodies are not enough even in special cases [10]. At the same time, if we consider, e.g., bottom sediments, their formation is governed by a number of various mechanisms, i.e., the input of river and eolian sediments, as well as the products of bank abrasion into the water bodies, the accumulation of products of chemical reactions, sedimentation of the remains of dead organisms (either allochthonous, i.e., entering the water body from outside or autochthonous, i.e., forming in the water body itself). In addition, the specific features of the modern anthropogenic impact cause the formation of new types of solid particles in water bodies, e.g., microplastic particles. The densities of all these components vary within a very wide range. The density of sediment particles can reach very large values when running water erodes ore veins, containing, for example, silver, gold, or other metals. On the other hand, solid organic particles commonly have

Table 1. The substances forming bottom deposits and their density

Substance	Density, g/cm³
Foam plastic	0.2—0.4
Polypropylene	0.9
Polycarbonate	1.2
Polyvinylchloride	1.34—1.43
Quartz	2.2—2.65
Granite	2.5—3.05
Aluminum	2.68
Marble	2.6—2.84
Mica	2.6—3.2
Basalts	2.7—3.2
Apatite	3.1—3.2
Corund	3.9—4.5
Pyrite	5.0
Iron	7.87
Silver	10.5
Gold	19.32

Table 2. Density of bottom sediment particles at sampling stations in Lake Ladoga

Point no.	Station no.	Particle size distribution (visually)	The density of bottom sediment particles, g/cm³
1	R2	Silt	2.367
2	82	"	2.696
3	105	"	2.557
4	109	Clay	2.576
5	204	"	2.585
6	52	"	2.652
7	86	"	2.658
8	95	"	2.569
9	14	Sand clay	2.782
10	S	Fine sand	2.743
11	76	"	2.703
12	36	Sand	2.705
13	25	"	2.773
14	38	"	2,644
15	G	"	2.771
16	62	"	2.687
17	17	Coarse sand	2.821
18	49	"	2.753

lesser density. The particles of microplastic can have even lower density (Table 1).

Thus, we see that the hydraulic size by the Stokes relationship can vary widely even for particles with the same diameter. For example, the value of hydraulic size calculated for a particle with diameter 0.001 mm and density 2.65 g/cm³ will be 0.00000078 m/s. On the other hand, this value for a particle with the same diameter but with a density of 2.0 g/cm³ will be 0.00000047 m/s, and in the case of density of 3.5 g/cm³, it will be 0.00000118 m/s; i.e., strictly speaking, the current methods of grain-size analysis of suspended sediments and bottom deposits, based on the density value of 2.65 g/cm³ [5], are not quite correct (in particular, in what regards the times of particle sampling on pipette apparatus, recommended in the Regulations [8]). Particles with a diameter of 1 μm and a density of 2.65 g/cm³ at temperature 17.6—22.5°C will settle to the depth of 4.4 cm over the recommended time of sampling of 15 h 35 min, while those with a density of 1.2 g/cm³ (i.e., polycarbonate or kapron), to the depth of as little as 0.5 cm. Therefore, a water column 5 cm in height, as recommended for taking samples for determining the concentration of particles <1 μm [8], will contain many larger fragments, though with lesser density. This was recorded in check experiments in the Institute of Limnology, Russian Academy of Sciences, with the use of membrane filters with pore diameter 1 μm. This issue will likely require additional analysis and revision in the nearest future.

In addition, the process of roiling and transport of bottom sediment particles into the bottom zone of the water body also largely depends on their density. This parameter explicitly enters the developed formulas for the quantitative assessment of this phenomenon. An example is Goncharov equation for the so-called tearing velocity, i.e., the least velocity of flow which tears off grains from the bed and at which the mean level of pulsation lifting forces is nearly equal to the weight of the grain in water [2]:

$$V_c = \log(8.8h/d)[2g(\rho_s - \rho)d/1.75\rho]^{1/2},$$

where V_c is the tearing velocity, h is the depth.

Note that the characteristic $(\rho_s - \rho)/\rho$ enters the absolute majority of similar relationships [5, 7, 9]. We can state that the density of solid particles of the bed largely determines the rate of interaction between bottom water layer and the top layer of bottom deposits, which, eventually, can affect even the microforms on bed surface. It should be noted that the rate of interaction in this part of the water body can have a considerable effect on the processes of secondary pollution, which eventually determines its actual environmental state.

In this context, it is of interest to analyze the changes in the predominant density of sediment particles for an individual water body. Such studies, carried out in the Institute of Limnology, Russian Academy of
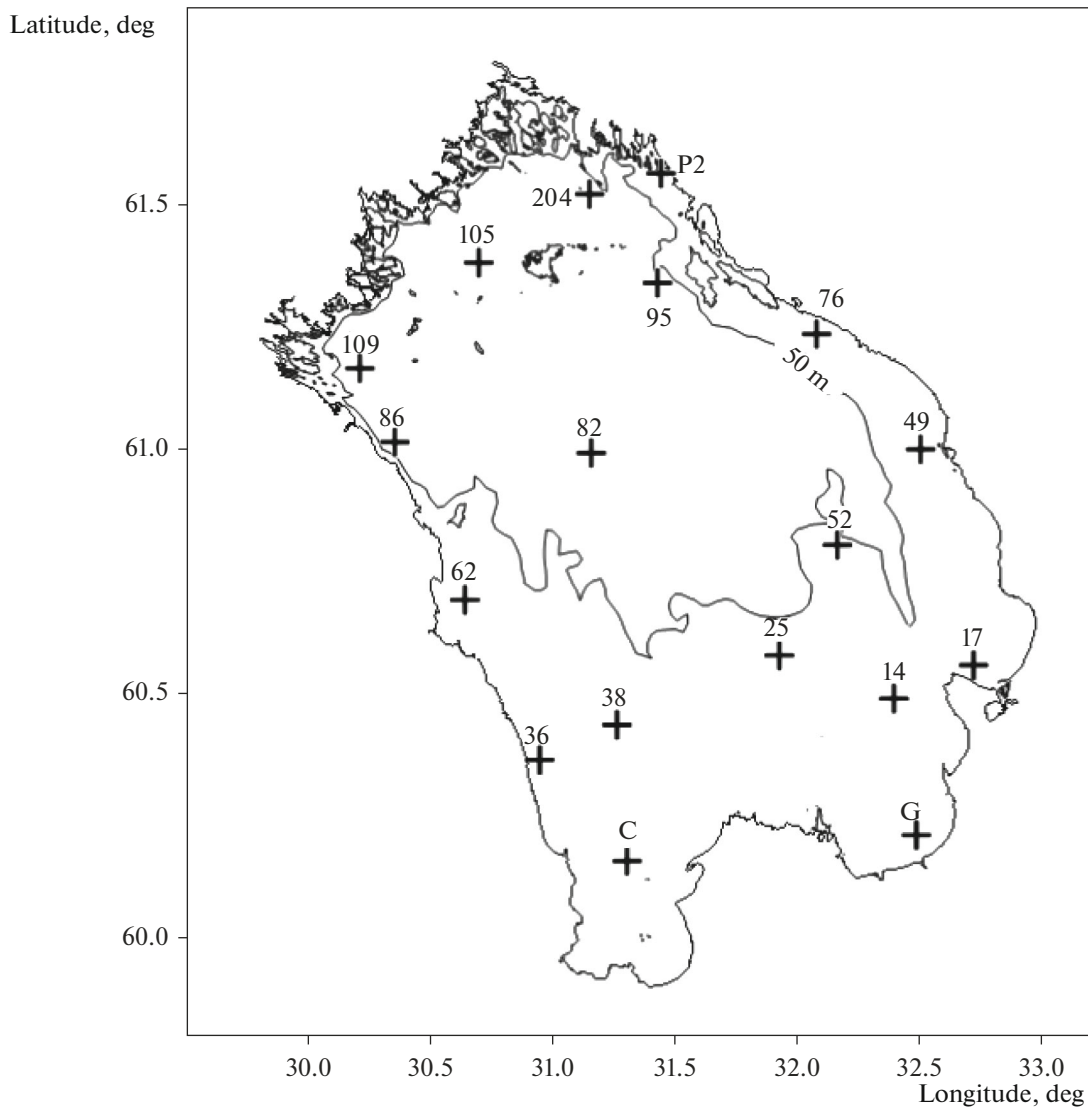
Fig. 1. Layout of the stations of bottom sediment sampling in Lake Ladoga. The crosses show the sampling points and the letters/digits at crosses are station numbers.

Sciences, were focused on the bottom deposits in Lake Ladoga. In the course of these studies, samples were taken from typical bed areas.

Figure 1 gives sampling stations used in the expedition studies.

The density of particles was determined in all taken samples. The analysis was made by bottle method in accordance with the State Standard [2]. Table 2 give the results of the analyses.

These results were used to construct, for the first time, a schematic map of the distribution of bottom sediment density in Lake Ladoga, given in Fig. 2. As can be seen from this scheme, the density of bottom deposits in this lake is largest in the zones where the mineral component dominates in the total composi-

tion of the deposits, i.e., in the areas of occurrence of sandy soils, mostly in the southern part. To evaluate the percentage of the organic component in bottom deposits, some samples were tested to determine the losses on ignition in a muffle furnace. The results of these analyses and the density of particles are given in Table 3.

In Table 3, the stations are arranged in the increasing order of the measured particle density. The table shows that the northern deep-water zone features lesser values of density and larger organic components in the samples, compared with southern regions. In this study, fragments of bed were compared visually in typical areas with different particle densities. This was made with the use of photographs of the appropriate bed areas, made with the use of Limnoskaut undersea
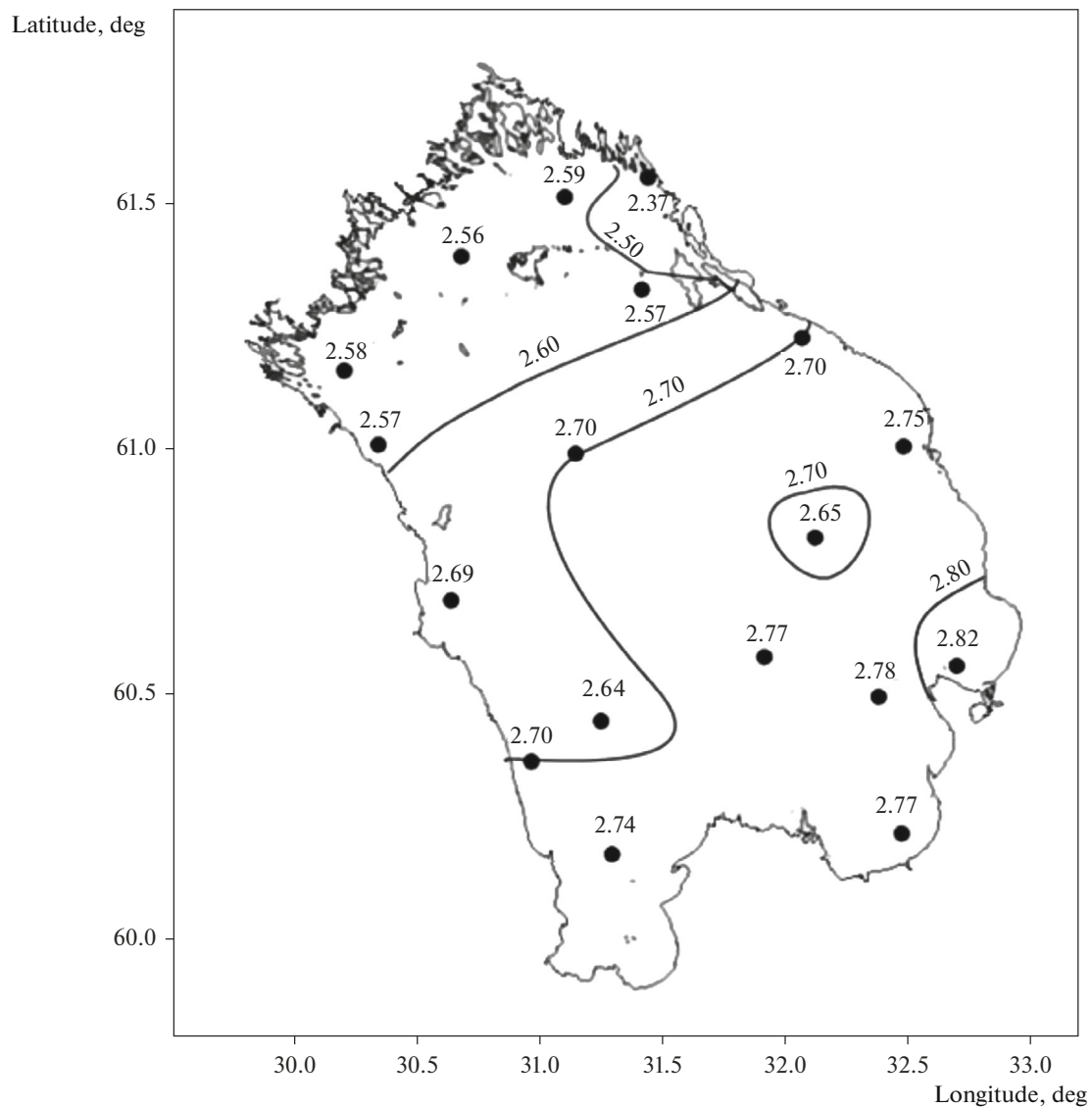
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Fig. 2. Schematic distribution of bottom sediment density (g/cm^3) in Lake Ladoga.

Table 3. The proportions of organic component and particle density in bottom deposits at sampling stations in Lake Ladoga

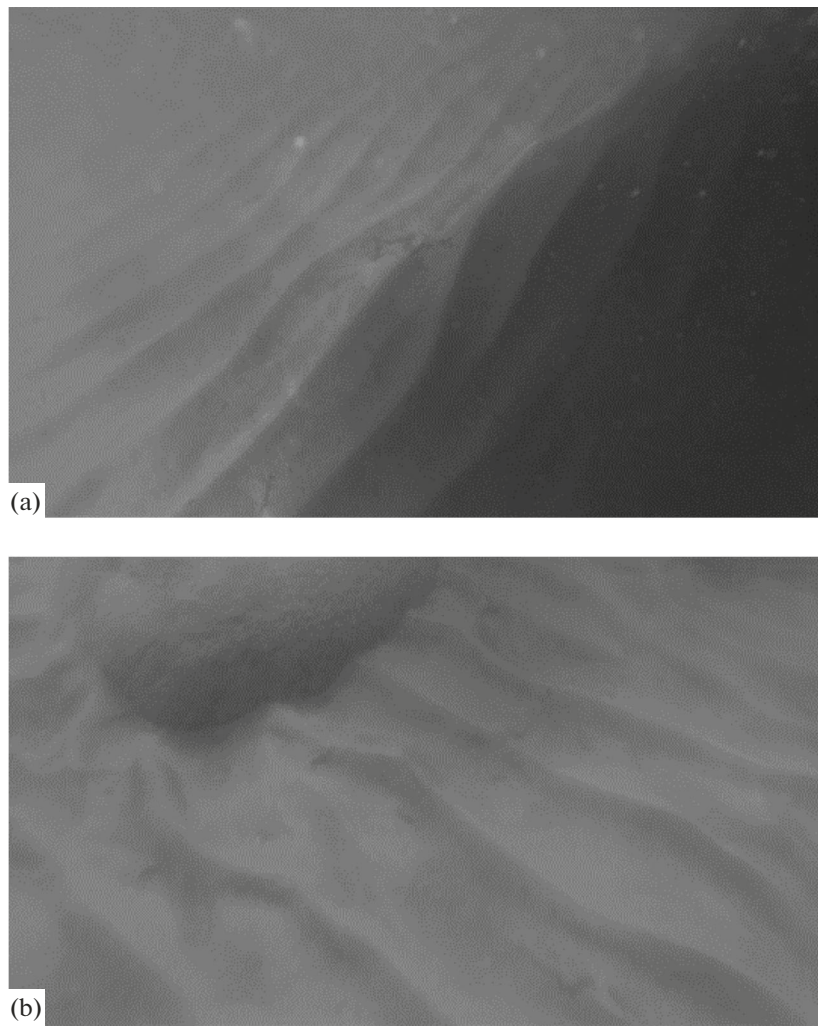| Station no.	Particle size distribution (visually)	The density of bottom sediment particles, g/cm^3	The proportion of organic component (LOI), %
R2	Silt	2.37	19.7
105	Clay	2.56	10.5
109	"	2.58	10.2
204	"	2.58	10.4
52	"	2.65	8.6
86	"	2.66	11.6
62	"	2.69	1.2
36	"	2.70	0.6
76	Fine sand	2.70	0.6
S	"	2.74	0.5
49	Coarse sand	2.75	0.9
25	Sand	2.77	1
14	Sand clay	2.78	3.7
17	Coarse sand	2.82	0.7

Fig. 3. The bed of Lake Ladoga near st. 17. The density of bottom sediment particles is 2.8 g/cm^3 (The photo was made by M.O. Dudakov with the use of Limnoscout underwater vehicle).

vehicle, designed and made in the Institute of Limnology, Russian Academy of Sciences. This apparatus can make photographs at maximal depths typical of Lake Ladoga [4]. The photographs made near station nos. 17 (2.8 g/cm^3) and 105 (2.56 g/cm^3) are given in Figs. 3a, 3b, and 4a, 4b, respectively. As can be seen from the photo, the microforms consisting of particles with different densities and sizes and in different parts of the bed differ considerably. Clearly, the bed relief in both cases is formed under the effect of a very large number of various factors. However, it can be clearly seen that the density of bottom sediment particles affects both the resulting forms and the conditions of interaction between solid particles and water mass in the bottom zone.

The obtained results demonstrate the dependence of the density of bottom sediment particles on the pro-portions of organic and mineral parts of the total volume. In this case, either organic or mineral parts themselves can vary within very wide limits under the effect of many factors. This creates a very diverse pattern of the density of bottom sediment particles, which should be taken into account in the current analysis of the cause-effect relations between the factors of an ecological conditions of a water body. A schematic map of the distribution of bottom sediment density given in Fig. 2 is unique either in Lake Ladoga or for large water bodies in general. This case demonstrates a decrease in the density of bottom sediments at the passage from southern to northern parts of the lake. Obviously, the scheme gives the most general notion of the distribution of this characteristic in Ladoga. We can expect that detailed measurements of the density will be required, depending on the specific problems and
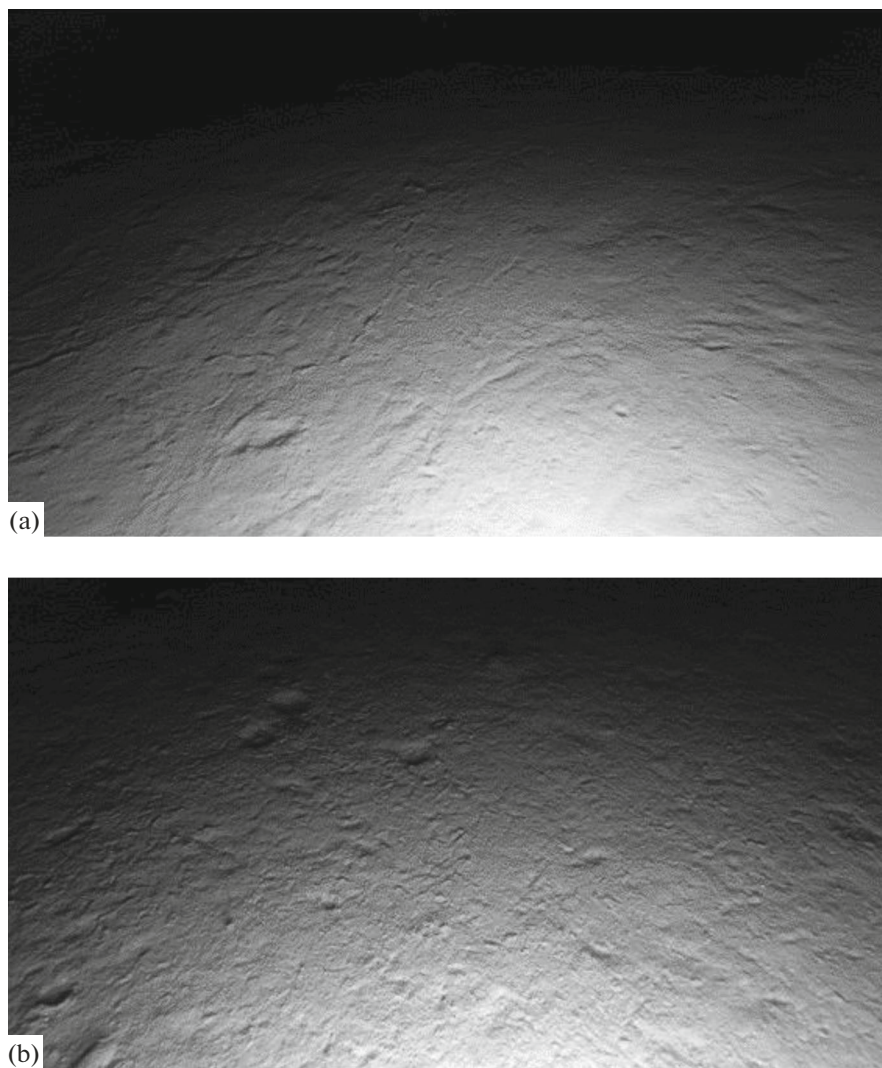
Fig. 4. The bed of Lake Ladoga near st. 105. The density of bottom sediment particles is 2.56 g/cm^3 (The photo was made by M.O. Dudakov with the use of Limnoscout underwater vehicle).

features of the study area in the lake. In fact, this is required for any large water body in the present-day studies of the interaction between bottom sediments and water masses in the evaluation of the internal load, the simulation of changes in the ecological conditions, and the solution of other problems.

CONCLUSIONS

The density of bottom sediment particles in water bodies, which depends on many external and internal factors, cannot be assumed constant for large lakes and reservoirs in the present-day studies. The correct identification of the causes of an ecological state of a water body requires taking into account the variability of this characteristic and its effect on the processes in the system.

The existing methods for the analysis of particle-size distribution in bottom sediments of the natural water bodies requires correction, taking into account the variability of particle densities.

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