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## BOTTOM SEDIMENTS IN DELTAIC SHALLOW-WATER AREAS – ARE THEY SOILS?

**ABSTRACT.** This article is based on long-term research of aquatic landscapes in the Volga River delta which was held in 2010–2012 and included investigation and sampling of bottom sediments in deltaic lagoons, fresh-water bays, small channels, oxbow lakes, and part of the deltaic near-shore zone. Contrasting hydrological regime and suspended matter deposition together with huge amount of water plants in the river delta provide for the formation of different types of subaquatic soils. The purpose of this research is to reveal the properties of the subaquatic soils in the Volga River deltaic area and to propose pedogenetic approaches to the diagnostic of aquazems as soil types. It is suggested to name the horizons in aquazems in the same way as in terrestrial soils in the recent Russian soil classification system, and apply symbols starting with the combination of caps – AQ (for “aquatic”). The aquazems’ horizons are identified and their general properties are described. Most typical of aquazems is the aquagley (AQG) horizon; it is dove grey, homogeneous in color and permeated by clay. The upper part is usually enriched in organic matter and may be qualified for aquahumus (AQA) or aquapeat (AQT) horizons. In case of active hydrodynamic regime and/or strong mixing phenomena, the oxidized (AQOX or aqox) horizon, or property could be formed. It is yellowish-grey, thin, and depleted of organic matter. The main types of aquazems specified by forming agents and combinations of horizons are described.

**KEY WORDS:** subaquatic soils, soil classification, river deltas, aquatic landscapes, Volga River delta.

### INTRODUCTION

The upper layers of sediments in shallow lakes, ponds, coves, marine shelves and deltaic zones are referred to as soils by some scientists starting with the famous soil scientist and micromorphologist W. Kubiena, who separated the trunk of Subaqueous soils from the trunk of Semi-terrestrial and Terrestrial ones as early as in 1953 [Soils of Europe, 1953]. In the last decades, the traditional perception of soil as of a natural-historical

body on the earth surface with its genetic horizons and diverse ecological services (soil functions of [Dobrovolskiy and Nikitin, 1986]) has been expanded over technogenic and some other objects. The first “technozems” for rehabilitated coal mining wastes appeared in 1989 [Yeterevskaya, 1989], the next were the oil-modified soils [Solntseva, 1998, 2009] and sealed soils in towns [Prokofieva, 1998], then soils of other industrial and mining areas [Burghardt, 1996; Rossiter, 2007]; finally such soils found their place in the World References

Base for soil resources – WRB [2006, 2014] as Technosols. Among natural objects, the organomineral bloom on the walls of caves was argued to be soil as well [Semikolennykh, 2012]. Most striking was the inclusion of extremely thin algal films on the surfaces and in the fissures of hard rocks investigated in Antarctic [Goriachkin, et al., 2014]. In this array of objects pretending to be soils, those in shallow water with a differentiation into discernible strata with diffuse boundaries and affected by biota are not the last candidates.

This approach to some subaqueous bodies as to soils is proven by their inclusion into recent classification systems: the International system – WRB [2014], German system of 1975, and American Soil Taxonomy [1999]. They are absent in Chinese, Canadian, French, and Russian systems.

The history of subaqueous soil investigations is poor. Few publications are known in Russia [Batoyan 1983; Batoyan, Moiseenkov, 1988], simulation experiments with artificial gleying had some analogy with phenomena occurring in the underwater soils [Bloomfield, 1951; Zaidel'man, Narokova, 1978]. In landscape geochemistry, subaquatic landscapes are usually mentioned as final members of catenas [Perel'man, Kasimov, 1999], without specifying their soils. The tidal belts were studied not once by soil scientists, who identified special soils there, namely, acid sulfate soils [Krasil'nikov, Shoba, 1997] or Thionic Fluvisols of WRB, and there are no doubts on their pedogenic essence. At the same time, they seem to be intermediate members in the coastal soil-geochemical continuum: terrestrial alluvial soils – semiterrestrial acid sulphate soils – post-subaqueous soils [Kasatenkova, 2011].

A serious contribution to the subaqueous soils research was made by American scientists [Demas, Rabenhorst, 2001; Bradley, Stolt, 2003; Stolt, et al., 2011]. An important impetus for this research was an applied one: development of aquaculture of hard clams and oysters that require knowledge about the shallow-water environments [[http://nesoil](http://nesoil.com/sas/Ditzler_SubaqueousPaper_Draft.pdf)

[com/sas/Ditzler\\_SubaqueousPaper\\_Draft.pdf](http://nesoil.com/sas/Ditzler_SubaqueousPaper_Draft.pdf)].

Moreover, the subaqueous soils can be considered as a depot for pollutants. According to the isotope data analysis and, for example, heavy metals content, it is possible to follow the story of river landscapes pollution, and to assess the dynamics of pollution by comparing several water bodies in different places [Winkels et al., 1998; Chalov et al., 2016].

The thickness of subaqueous (or underwater) soil-like formations ranges from the first centimeters to a meter or even more. The reason to consider them soils is their vertical pattern resembling terrestrial (“normal”) soils with strata created by sedimentation of solids. In such underwater soils, the types of stratification patterns are repeated in similar environments, like types of soil profiles on the land; the transitions between strata are mostly gradual as between horizons in the majority of soils, and even some processes are common in terrestrial and underwater soils. In the latter, processes may operate in rather stable sites, where the currents are weak, and accumulation of bottom solid-phase substrates by sedimentation proceeds parallel to their pedogenic-like modification. Another important prerequisite is the growth of plants giving organic residues for humus-like layers to be formed in the upper parts of the underwater soils; fishes, mollusks and other animals surely contribute to accumulative and mixing phenomena.

Thus, among the numerous underwater objects only those may be identified as soils that meet the following requirements: (i) have a vertical differentiation; (ii) occur in shallow water bodies (< 2 m); (iii) are related to plants, either rooted, or floating. This means that they are in acceptable agreement with the classic Dokuchaev's formula  $s = f(c, o, r, p, t)$ ; the 'weaker links' of this chain are climate and relief ( $c$  and  $r$ , respectively): their effects are mitigated by the water layer and partly replaced by currents and casual sedimentation controlled by the underwater topography.

The purpose of this research is to reveal the properties of solid-phase bodies in the Volga River deltaic areas that allow qualifying these bodies as soils, and to propose pedogenetic approaches to them. Tackling them as soils, allows applying the appropriate methods for their investigation, namely, pedogenetic and landscape geochemical, enabling more adequate sampling, in particularly for isotope identification. Moreover, for their sustainable management, their functioning as soils should be taken into account.

**OBJECTS AND METHODS OF STUDY**

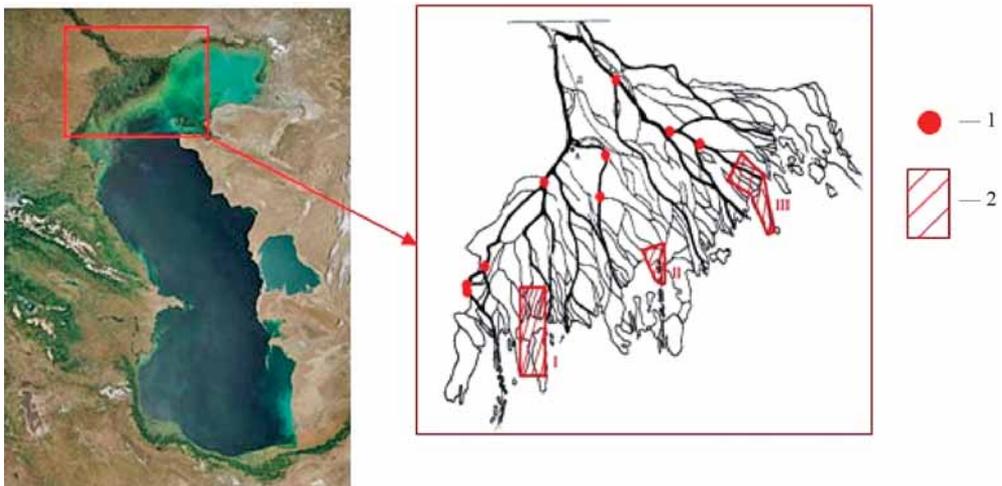
The advantage of deltaic areas for identification of subaqueous soils is the contrasting regime (hydrological and geochemical) of the ‘river – sea’ system [Kasimov et al., 1999]. The present research is based on the data obtained from the field studies of the Volga River estuarine zones in 2005–2012 [Lychagin et al., 2011]. The objects of the investigation were deltaic lagoons, fresh-water small bays, big and small channels, and also the part of deltaic near-shore zone (Fig. 1).

The methods to study the underwater soils are specific for morphological research,

and sampling, though they do not practically differ from the traditional methods used for analytical studies. Augering is the only means to obtain the profile and to identify horizons in it, which is rather a limitation versus the usual ‘field’ morphology: such common morphological properties as structure and consistence cannot be recorded; another limitation is the small horizontal size of the object determined by the diameter of the auger: 5–7 cm. However, there is also an advantage: all underwater soils are observed in similar conditions, and the inaccuracy caused by the differences in moisture content in terrestrial soils is avoided.

The following procedures were applied in the subaqueous soils investigation:

- morphological description of the whole thickness (profile) and of the individual layers (horizons), namely, thickness, color and its heterogeneity, texture, kind of transition, plant residues, and shell debris;
- pH, redox potential, and TDS express-test by HANNA-Instruments portable devices;



**Fig. 1. The study area:**

1 – The stations for studying water chemistry, suspended matter, and subaqueous soils in the Volga Delta;  
 2 – The key areas of the Astrakhan Biosphere Reserve, with a detailed study of subaqueous soils:  
 I – Damchiksky, II – Trehizbinsky, III – Obzhorovsky.

- granulometric analysis by Laser Particle Sizer “Analisetete 22” (Fritsch GmbH, Germany);
- organic carbon content (by the method of Tiurin).

Unlike the methodology for terrestrial soils developed by several research groups and individuals [Soil Survey Manuals in the USA and USSR; FAO Guidelines for Soil Description. 4th edition. Rome; Rozanov, 1983], only first steps are made in respect of underwater soils, and the morphological methods of their studies should be improved and developed.

Nevertheless, investigations in the Volga delta key sites were performed during several years, in different seasons, and the variants of subaquatic soils were the same irrespective of the season, as well as the trends of processes recorded.

## RESULTS AND DISCUSSION

The studies performed and analysis of rather scarce publications enable us to propose some operational terms for subaquatic soils and their horizons following the terminology and conceptual background of the ‘Classification and Diagnostic of Soils of Russia’ [2004]. The first and the main one is *aquazem* as a general term for solid-phase formations in shallow-water bodies. Although the name itself is linguistically an oxymoron as it combines two mutually excluding elements (water and earth), it was used for paddy soils in the early version of the Russian soil classification system [1997], but it was excluded from the later versions. Well-known Japanese pedologists – “fathers of paddy soils” Kawaguchi and Kiuma named them “aquorizems” in 1974. Hence, the term *aquazem* is “free” to be used for subaqueous soils.

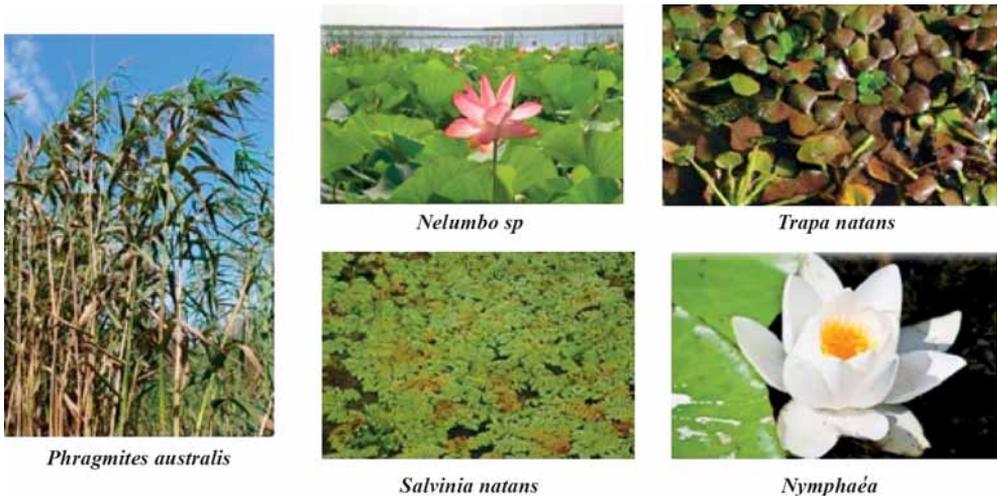
Assuming the study objects – aquazems – to be soils, they are discussed in terms and aspects applied to soils: profile and horizons, properties, environments or soil-forming agents, geography, ecological services.

### *Horizons and profiles of aquazems, and processes responsible for their formation.*

The profile of aquazems is weakly differentiated compared to terrestrial soils, and is dominated by ‘cold’ grey or dusky color. Its thickness ranges from 5 cm to 50-60 cm and even more, and two or three distinctly discernible horizons are common. It is suggested to name the horizons in aquazems in the same way as it is done for terrestrial soils in the recent Russian soil classification system, and apply symbols to them starting with the combination of caps – AQ (*aqua*).

The upper layer is usually represented by organic (humus?) horizons. Their thickness and organic carbon content vary from 3 to 10 cm and 1.5 to 6 % of humus; these parameters depend on soil formation conditions, the most significant among them being the kinds of water plants and current speed. The significant thickness of the horizon was recorded only in case of rooted plants providing the stability of substrate on one hand and regular input of organic residues on the other hand. Additional sources of organic material are not excluded; these may be fish and animal excrements, terrestrial sediments removed by erosion into shallow-water areas. According to our data, the rate of sedimentation in the lower part of the Volga delta is about 2–5 cm per year [Winkels et al., 1999]. The uppermost horizon is about 10 cm (up to 30 cm) thick, dove-grey, and humus content reaches 6 %. More favorable for humus formation is the lotus (*Nelumbo spp.*) community, less favorable – the reed (*Phragmites australis*) one (Fig. 2); reed is hard to decompose and its residues preserve recognizable plant tissues. (Future research is needed to reveal the dependence of the topsoils on plant communities). Hence, two variants of upper horizons may be identified: aquahumus horizon – AQA and aquapeat horizon – AQT.

Floating plants: chilim (*Trapanatans spp.*), water lily (*Nymphaea spp.*), floating moss (*Salvinia spp.*) etc. (Fig. 2) do not create any



**Fig. 2. Water plants**

stable horizon if the hydrodynamic processes are active, whereas if they are weak, the suspended material enriched in organic matter (erosion loss from terrestrial soils) is accumulated contributing to formation of a discontinuous greyish-bluish horizon. Its thickness does not exceed 2–3 cm, and humus content is not more than 1–2 %.

In active channels, mixing of the upper part of aquazem profiles by currents results in the formation of a thin yellowish-grey oxidized layer tentatively named (AQOX) with a very low content of humus: less than 1 %. (Fig. 3).

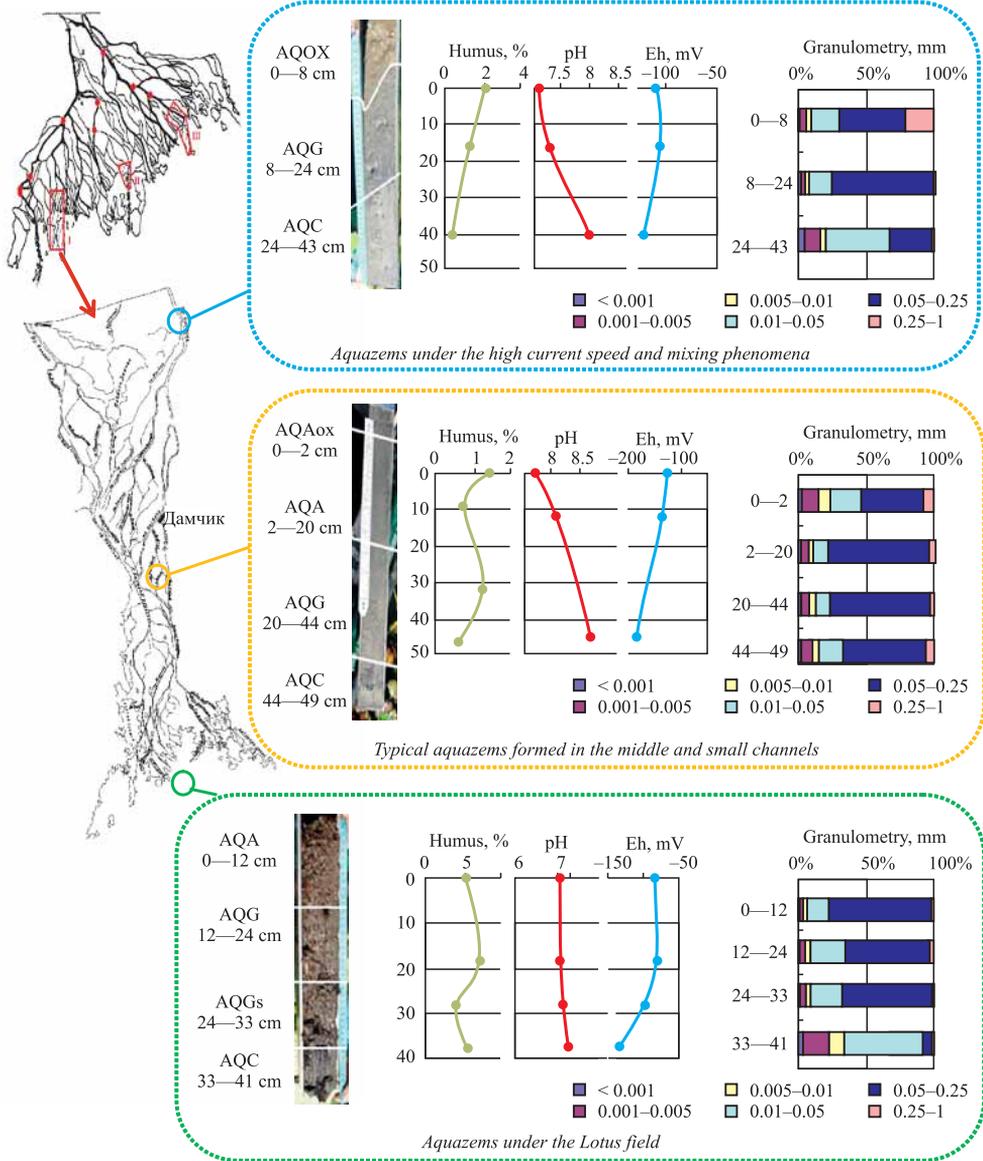
**Soil-forming agents**

Most typical of aquazems is their aquagley AQG horizon – homogeneous in color and consistence, clay-permeated, completely dominated by dove-grey color; these features are the same as in terrestrial gleys. The AQG horizon gradually merges into the parent material – stratified bottom sediments. They are frequently enriched in shell fragments.

The physicochemical properties are rather homogeneous both throughout the profiles and among the soils. The pH values are close to neutral (see Fig. 3) in the upper horizons, and become weakly alkaline downward, which may be attributed to the stronger

influence of marine water. Presumably, this trend may be also explained by the acidifying effect of decaying organic residues in the upper part of the profile. The humus profile pattern is similar to that in terrestrial soils, although sometimes it is irregular due to buried humus-enriched layers. Unlike terrestrial soils, this pattern is typical and is in no way related to translocation events. Redox potential values are always low, and vary in accordance with the hydrological regime and plant communities. The average value is about –80 to –100 mV, in all soils they decrease downwards to –120 to –150 mV; in oxidized horizons they may reach +80 mV.

The main prerequisite for aquazem formation is the shallow depth of the water body and weak currents. Depth limitation – less than 2 m of water above the soil, was introduced in WRB [2006], and it agrees well with the data obtained. In our case, it may be explained by the requirements of rooted plants to their environment, namely, illumination, alteration of seasons, and access of oxygen. Moreover, at shallow depth, the oxidation phenomena occur owing to wind paddling, as well as accumulation of fine particles from the suspended loads of river and/or sheet erosion on the shore. Seasons of the year are pronounced, although mitigated by the water layer. The latter is also responsible for



**Fig. 3. Properties of subaqueous soil in the different parts of the Volga delta**

the permanently reductive environment. The location of aquazems in the deltaic area and the history of the latter also affect the aquazem properties. Thus, aquazems in the marine edge of the deltas (Fig. 4) exist in an alternating subaqueous deep- and shallow-water regimes; they have stratified profiles: clay strata alternate with the sandy ones containing shell frag-

ments. Buried horizons may occur; they are dark, greyish and enriched in organic carbon.

In aquazems, like in terrestrial soils, the effect of parent material is distinct. Most soils of the Volga delta are formed on homogeneous silty loams, whereas specific soils are confined to the outcrops of contrasting rocks. For

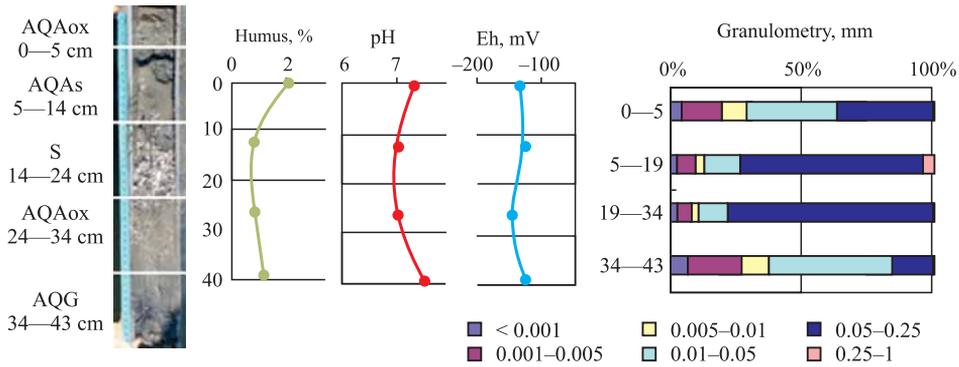


Fig. 4. Properties of subaqueous soil of the Volga marine delta edge

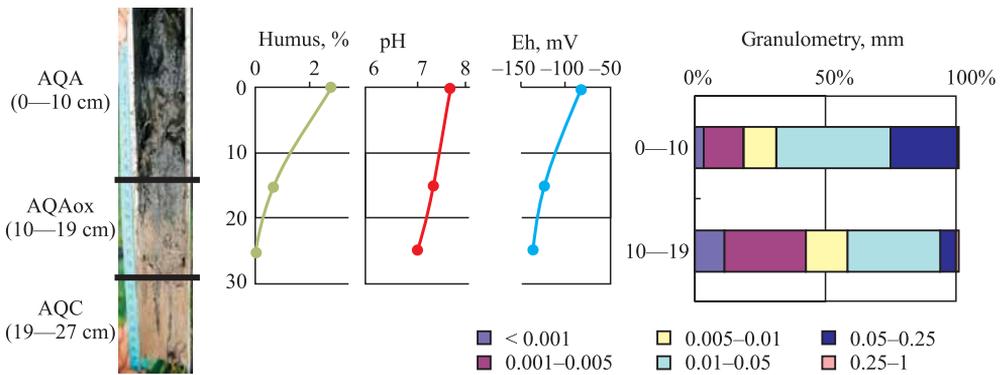


Fig. 5. Properties of subaqueous soils on "chocolate" clays

example, aquazems on the outcrops of Khvalyn "chocolate" clays [Svitoch, Makshaev, 2015] have a shallow profile and a specific color of the lower horizon (Fig. 5).

The particle-size composition primarily depends on the flowage degree and current rate (Fig. 6). In large channels with high current rate, the coarsest fractions are

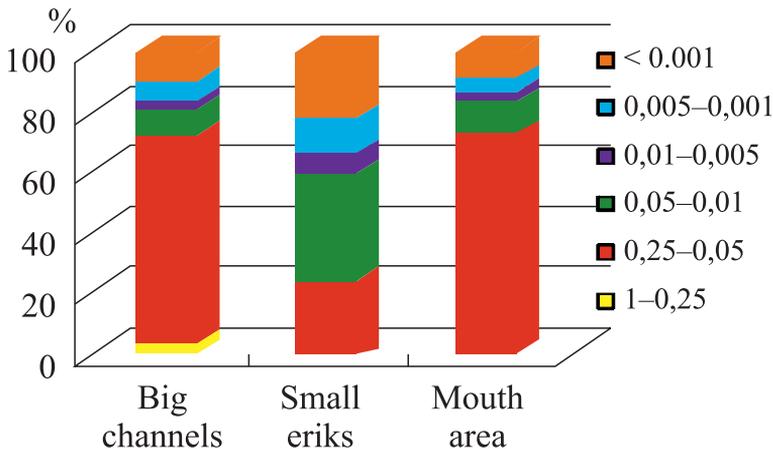


Fig. 6. Particle-size distribution in aquazems in different parts of the Volga delta.

deposited; fine fractions are predominant in weakly flowing watercourses. On the marine edge with its contrasting hydrodynamic conditions, effects of wind and waves, and intense water mixing characterized by texture heterogeneity, which rather depends on vegetation contributing to sediment stability, fine-textured substrates are formed.

### *Approaches to classification*

If accepting aquazems as soils, it seems reasonable to classify them within the framework of the new system of soil classification of Russia [2004], where the priority of soil properties is a basic principle. The data accumulated permit referring the aquazems to the *trunk of synlithogenic soils*, and provide a *special aquazems order* for them [Lychagin, Tkachenko, 2012]. For terrestrial soils, orders are specified by common trends of pedogenesis or by a common horizon; in our case both requirements are met. There is no need to argue the specific character of aquapedogenesis; as for a common horizon, the aquagley (AQG) horizon occurs in all aquazems. Following the rules of the classification system, types of aquazems may be specified by the combinations of horizons, hence, the following *types* may be recognized: typical (AQA-AQG-AQC-C), organogenic (AQT-AQG-AQC-C), oxidized (AQA-AQOX-AQG-AQC-C). The extension of studies is sure to find new types.

In American Soil Taxonomy [1999] the subaqueous soils refer to two suborders in two Orders: Wassents – subaqueous Entisols and Wassists – subaqueous Histosols. For the name of such soils the formative element *Wass* is used, which is derived from the German word “Wasser” for water. [[http://nesoil.com/sas/Freshwater\\_Subaqueous\\_Soils\\_RIWPC.pdf](http://nesoil.com/sas/Freshwater_Subaqueous_Soils_RIWPC.pdf)]

There is also a special place for subaqueous soils in WRB [2014]. The Subaquatic is a Principal qualifier in the Reference Soil Groups of Histosols, Fluvisols, and Gleysols. In Chinese,

Canadian, and French classification systems, subaqueous soils are absent.

### *Geography of aquazems*

It seems clear that if all necessary conditions are met, aquazems are formed in any water body, such as river, lake, pond, water storage reservoir, etc. Thus, the same aquazems types were found in the Don and Kuban Rivers deltas. The main differences between deltas are lower variability of aquazems types because of more homogeneous conditions in the Don deltaic landscapes, and higher pH and TDS values in the Don and Kuban aquazems because of the stronger sea influence there compared to the Volga delta aquazems.

Presumably, there is a zonal differentiation of the subaqueous soils like of the terrestrial soils. Aquazems may be subdivided in accordance with the organic/mineral material ratio. Aquazems dominated by organic material are mostly confined to the northern areas – tundra, northern and partially middle taiga, as well as to wetlands in other zones; aquazems on predominantly mineral parent material are more common in southern taiga, broadleaved forests, forest-steppe, and steppe. The first group may be correlated with Kubiena's organic subaqueous soils – Sapropel, Reed-Fen or Carex-Fen. The second group may resemble Gittja and Dy. It is not clear, whether the climatic (zonal) conditions affect the spatial differentiation of aquazems at a lower level.

Aquazems on the mineral substrates may be further differentiated in accordance with the chemical properties of the substrates. A special case is the artificial reservoirs since their bottom sediments are frequently composed of former terrestrial soils; moreover, some of these aquazems are enriched in organic material (remnants of former terrestrial plants) and artifacts. Aquazems compose their own ‘soil cover’ in a certain water body. It is regulated by ‘local’ topolithogenic factors that are more or less modified by the effects of currents.

The spatial diversity of aquazems seems to be lower than that of terrestrial soils, and there are at least three reasons for that.

1. More homogeneous and simple are the aquazems profiles, hence, lower is the 'aquapedodiversity'.
2. Whereas terrestrial soils have been studied during more than a century, the time dedicated to the aquatic soils reconnaissance hardly exceeds several years, and this relative homogeneity may decrease with the new knowledge acquired.
3. The aquatic environment is more homogeneous in comparison with the terrestrial soil cover owing to the mitigating effect of the water layer and particularities of the sedimentation process.

#### *Ecological services of the subaqueous soils*

Like the terrestrial soils, the aquazems perform several functions in the ecosystems. They serve as habitat for organisms and plants. Like the terrestrial soils, they could be changed and used for subaqueous agriculture, for example for algae cultivation, or shrimps and oysters production.

Furthermore, subaqueous soils, as the storage system, can accumulate pollutants, for example, heavy metals. Thus, in the Volga delta, the concentrations of the majority of heavy metals well correlate with the clay content in the subaqueous soils [Kasimov et al., 1999; Kasimov, Lychagin, 2002]. That is why, geochemical anomalies of heavy metals may be confined to the parts of watercourses with low current rates or with changes in redox conditions (mouths of channels on the marine edge, thickets of aquatic plants of the delta front); geochemical barriers are formed there, and fine particles are accumulated. The Volga delta is retaining a considerable portion of heavy metals [Kuryakova, 2011]. If the environment changes, for example, owing to the fluctuations of the sea level or river

discharge, heavy metals may be re-mobilized from bottom sediments (or subaqueous soils) in suspensions and contaminate the river water. Understanding their functioning as soils will help predicting the risks of environmental pollution.

#### CONCLUSIONS

The review of publications and the experimental data obtained in the deltaic areas of the Volga River delta permitted applying a 'pedological' approach to the unconsolidated sediments under shallow water. They have much in common with terrestrial soils, and may be named *aquazems*.

In aquazems, like in terrestrial soils, *diagnostic horizons* may be identified: subaqueous analogues of the humus-accumulative and peat horizons, gley and redoximorphic horizons, parent material that may be calcareous due to shells. The thickness of horizons is less compared to that in terrestrial soils. Combinations of these (and probably some other) horizons correspond to several *types of aquazems*.

*Methods* to study aquazems' properties are basically the same as for terrestrial soils, although the number of morphological characteristics is less; among the analytical procedures, measurement of redox potential is expedient.

The *subaqueous soil-forming agents* perform their functions less obviously compared to terrestrial soils; most important is vegetation, primarily, the rooted plants, the effect of climate is mitigated by the water layer, as well as that of relief owing to currents, which partially perform the function of matter redistribution; parent material is mostly homogenous, since its particle-size composition is determined by the sedimentation regime within the narrow range of depths: 0.5 to 2 m. Time is rather short for aquazem profiles to be formed, as the deltaic areas have a pronounced seasonal and annual dynamics.

The *ecological services* of aquazems comprise: substrate for aquatic plants, habitat for bottom living organisms, accumulation and immobilization of pollutants. In the same time, "secondary" release of some

pollutants caused by changes in the aquatic environment is not improbable, and once the changing currents may enhance the aggravation of pollution. ■

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