Bottom ice in historical perspective

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Abstract. The article describes the history of the study of anchor ice attached to bottoms of the rivers of the European part of Russia and Siberia. Having analysed a large number of publications, the author of the current research attempts to collect, summarize and analyse the results of observations of anchor ice from the first mentions to the beginning of its study in natural and laboratory conditions. For the first time, this phenomenon was found on the bottoms of Siberian rivers at the end of the XVIII century; most of the observations relate to the Angara River. On the rivers of the European part of Russia, the beginning of the study of bottom ice dates back to the end of the XIX century and is associated with the needs of navigation and water supply. The article considers the contribution of the shipping inspector L.L. Vladimirov to the study of this phenomenon. He was the first to establish the dependence of ice jams in winter and flooding resulted from bottom ice melting. The article also estimates the role of the commission for the study of bottom ice, which revealed its widespread distribution almost throughout the country, as well as the role of scientists such as M.F. Tsyonglinskiy, L.A. Yachevsky and V.Ya. Altberg. The latter is the author of a theory of bottom ice formation.

1. Introduction
The study of ice phenomena on rivers is of great importance. This is especially related to the rivers of our country covered with ice for many months. Knowledge of the ice regime of rivers is necessary for the needs of navigation and water supply, for the design and operation of hydraulic facilities, as well as for the study of channel deformations caused by ice phenomena. It is natural that the ice regime of the rivers has long since been paid attention to by meteorologists and hydrologists. First, in the interests of navigation, it was necessary to know the timing of the opening and freezing of rivers. In 1845 K.S. Veselovsky for the first time collected and processed data concerning this issue and in 1886 M.A. Rykachev published his great work "Opening and freezing of waters in the Russian Empire". But in addition to studying the ice phenomena by statistical methods, the researchers also sought to understand the very essence of the process of ice formation. In this regard, there was an interest in such a complex phenomenon as the formation at the stage of freezing-up of the so-called bottom (intra-water) ice to be dealt with for ensuring the normal functioning of hydraulic facilities. For successful results, it is necessary to know the conditions and features of the process of its formation.

2. Sources and methods
The study was carried out based on a huge number of identified, systematized and analysed sources describing observations of the formation of bottom ice. These are, first, the notes of scientists who travelled to Siberia in the XVIII–XIX centuries, the report of the shipping inspector L.L. Vladimirov on the formation of ice on the bottom of rivers, the report, the explanatory note and the questionnaires of
the commission for the study of anchor ice, the results of observations and experiments, as well as other works on this issue, published in the XIX-early XX centuries.

3. Observations of the bottom ice formation on the rivers of Siberia

The first observers of the formation of ice on the river bottoms, anchors, and fishing gear were boatmen and fishermen. Most scientists in the 18th century rejected the very possibility of the formation of bottom ice because it contradicted their usual ideas.

In 1790-1794 I. Sievers, travelling in Siberia, caught sight of the fact that the ice in the Angara and on Lake Baikal has a "special property": it is formed first on the bottom, and then floats up and is carried away by the stream.

In 1817 N.V. Semivsky in his work "The Latest Narratives About Eastern Siberia" described the freezing of the Angara: "Sometimes it is not seen any single ice floe on the surface of it, when suddenly a lot of them appear from under the water, which, sticking to other ice floes, connect and freeze one to another, from which they are made in different places like dams, flooding all along the banks of its lying meadows and valleys, also low, embankment villages and part of Irkutsk; through which the very bottom of the Angara annually noticeably deepens" [1].

Captain of the Royal Navy, J. Kohren, travelling in Siberia in 1820-1822, also observed the formation of ice on the bottom of the Angara. Because of its lightness, this ice floated and floated on the surface of the river. M.M. Hedenstrom in his work "Excerpts From Siberia" confirmed the process of ice formation on the bottom of the Angara and proposed that this process leads to excessive cooling of the banks and the bottom of the river. The researcher A. Weitz confirmed the same fact in the article "On the origin of ice along the bottom of some rivers". In November, he observed the formation of ice on the Kan River: "ice is formed there in the form of long prismatic and pyramidal crystals, accumulating among themselves in various, sometimes huge masses, located on the bottom of the river, and attached to it in some way... Not often, such ice floes brought to the surface sand and pebbles of various sizes, which were carried away by the stream" [2]. According to A. Weitz, this phenomenon is specific to the Volga and other fast-flowing rivers and requires a detailed study. At the end of the article, the author wrote about the channel-forming value of bottom ice. The same opinion was shared by N.S. Shchukin, who in 1820-1844 observed the opening and freezing of the Angara and some other rivers in Eastern Siberia. He noted that the cold penetrated to the river bottom through the stones "connecting the bottom with the outside air", which led to excessive cooling of the bottom layers of water.

In 1847-1850, E.K. Hoffman, who led the RGO expedition that explored the northern regions of the Urals, wrote that the anchor ice is a "foam-cellular" mass consisting of thin plates arranged out of order.

Academician A.F. Middendorf believed that anchor or bottom ice is a constant phenomenon for the whole of Siberia, playing a major role in the freezing of rivers in which it rises from the bottom in the form of a solid mass [3]. He also reports that the locals call the ice that has risen from the bottom by "shuga" and the ice plates formed on the surface of the water by "salo" [4].

In the second part of the XIX century, the hypothesis of the formation of bottom ice due to excessive cooling of the banks and bottom of the river was shared by many researchers: T.N. Schwartz, who conducted observations on the Olekme River in 1850 and the Angara River in 1855-1856; V.A. Obruchev, who, however, considered it impossible to transfer the cold over the boulders to the bottom of the Angara; Ya.V. Stefanovich, who in 1896-1897 studied ice phenomena on the Lena, Bodaibo rivers and mountain tributaries of the Chae, Cheu and Chechue, etc. On the latter, growing in large masses, the bottom ice very much hindered the fishermen, as it trapped the meshes (nets). And the jam caused by bottom ice and flooding on the Bodaibo River harmed gold production at the Zakharyevsky mine. The gold production decreased by 50%.

Ya.V. Stefanovich wrote that bottom ice is very common on the rivers of Yakutia, but almost no observations of this phenomenon were made. Meanwhile, bottom ice often causes great harm, leading to spills, stopping water supply, etc. Therefore, its study is of great practical importance because only by studying the formation of bottom ice in all details, it will be possible to develop rational measures to combat this phenomenon.
4. Study of bottom ice on the rivers of the European part of Russia

On the rivers of the European part of Russia, observations of bottom ice began to be carried out only at the end of the XIX century, much later than on the Siberian rivers. These observations were made by the needs of shipping and water supply.

On February 13, 1904, at a meeting of the Imperial Russian Geographical Society, the inspector of navigation on the Sviri River, L.L. Vladimirov made a report "The formation of ice at the bottom of rivers", in which he presented the results of his research in 1889-1903. He was the first to establish that the floating bottom ice can form a jam on the river and cause flooding in winter.

In May 1904, the commission for the study of bottom ice was established, which began its work with the identification of its area. Specifically for this purpose, a short instruction and a questionnaire were developed and sent out in the amount of 6400 pieces. The Commission found that bottom ice is widespread, and when water bodies freeze, its formation is observed both in the European part and in the Asian part, not excluding such southern regions as Transcaucasia and Turkestan. Bottom ice plays a predominant role in the phenomena of river ice drift, ice formation and jamming. The formation of bottom ice occurs not only on rivers but also on some lakes, for example, on Lake Baikal and Lake Ladoga. Of these phenomena, the most practical interest is caused by ice jams, which have serious consequences (spills and floods). Figure 1 shows a map of the European part of Russia with an indication of the distribution of bottom ice. These data are based on the report of the commission for the study of bottom ice for 1905.

Figure 1. Map of the European part of Russia with an indication of the distribution of bottom ice. The observations were made at 411 locations. Red circles indicate places where bottom ice was observed, green circles indicate places where no bottom ice was found, and red – green circles indicate points where there is conflicting information.
In 1903-1904 M.F. Tsyonglinsky in his work "On observations on the freezing of the Neva River and studies of jams on it" confirmed the conclusion of L.L. Vladimirov that the jams and the flood coming after them are the results of a mass accumulation of bottom ice in the riverbed. As a result of the research, he obtained a detailed technical material consisting of the measurements of the channel and ice thickness, profiles, levelling, observations at water measuring posts, etc., as well as the observations on the formation of bottom ice. However, the question of the formation of bottom ice remained open.

In addition to the work, carried out by M.F. Tsyonglinsky, the Department of Inland Waterways in 1904 commissioned V.M. Lokhtin to study the same issue and make the necessary observations. After conducting a series of experiments in standing, semi-standing, chute-flowing water, and other observations, he proved that ice is not formed at the bottom. In conclusion, he wrote: "It should be better not to pay attention to the Neva jams and its flooded places, and for those who suffer damage from them, it should be better to take possible and easily feasible measures themselves" [5].

The beginning of the laboratory study of bottom ice dates back to 1915, when, after the fifth failure of the Petrograd water pipeline in 1914, the Main Physical Observatory took up this problem. L.A. Yachevsky led the work for some time. Using data from the Main Physical Observatory for 1908-1914 he found out what meteorological factors affect the freezing of the Neva, namely the temperature of the air, water and cloud cover: "The first thing that is of interest in this seven-year cycle of observations is that during the seven years of observations, there are 12 periods during which the river is frozen. This means that only in some years the Neva freezes immediately, but usually, the first freezing is not strong, and such an unstable state sometimes lasts for more than a month, as, for example, took place in 1914" [6]. It is very rare to set the time of transition from ice drift to ice formation. What role the bottom ice plays in the formation of the ice cover in the part of the Neva near the Observatory is unknown, since no observations are available in this regard. "In all the above, I refrained from any generalizations and hypotheses and only allowed myself to point out the obvious connection of the mass formation of bottom ice with an obvious or poorly covered sky" [6].

In 1915 V.Ya. Altberg supervised the special studies of ice formation processes in natural and laboratory conditions to solve some scientific and practical problems. It was necessary to find out the significance and role of each factor involved in the process of cooling water and the formation of bottom ice. A closed water flow method was used, in which the same mass of water circulating through a closed channel was subjected to cooling. This method made it possible for the first time to approach the process of bottom ice formation from the quantitative side and connect it with the thermal return of water to air [7]. As a result, during the winter of 1915-1916, more than 50 experiments were performed, from which it follows that when slightly supercooled water moves "in the presence of seed", plate bottom ice is always formed on underwater objects, without exception, regardless of the external conditions under which the water reached the above-mentioned state. All experiments were carried out in small tanks and were regarded as preliminary. For further actions, a special tank was built, surpassing the previous one many times. It was found out experimentally that the flowing water carries away the heat that develops during crystallization, which explains the increased formation of bottom ice in rivers, despite the slight supercooling of the water at this time. "The protrusions of the bottom, as places continuously washed by supercooled water, are the most favourable points for the release of crystals, which is due to the formation of ice on the bottom of rivers" [7]. Laboratory experiments have also shown that more vigorous release of loose ice occurs in places with a fast stream.

5. Conclusions
V.Ya. Altberg is the author of the most advanced theory of bottom ice formation. According to this theory, bottom ice origin occurs not on the surface, but in the thickness of the stream and on the river bottom, as a result of turbulent mixing and heat transfer, leading to supercooling of the mass of water throughout the entire thickness of the stream. Finally formulated in the 1930s, this theory became a
significant contribution to solving the complex problem of the formation of bottom ice and was worthily appreciated by scientists around the world.

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