

Modelling of Ice-Jam Floods in the Lower Part of the Danube Basin: Case Studies During the Winters of 2011/2012 and 2016/2017

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Abstract: The design flood (DF) for flood defence systems for large rivers is typically determined by taking into account the maximum water levels of the year, which typically occur in Central Europe between May and June (rivers like the Danube, Tisza, and Sava). The DF is typically calculated using a 1% probability of a flood peak and an additional 0,8-1,2 meters of freeboard height. Hydraulic models have been also employed to analyze scenarios of probable maximum floods (PMF). Nevertheless, despite their substantial influence on flood processes, ice-jam floods (IJFs) are rarely taken into account. Compared to open-channel flooding, the processes controlling the formation of peak flood waves under ice-jam conditions are very different. Consequently, these processes must be incorporated into calculations for probable maximum floods due to ice jamming (PMFice). Despite recent advancements in instrumentation, modelling techniques, and laboratory research, accurately defining hydraulic parameters under ice-covered conditions still requires direct field measurements. This study utilizes published hydrometric data from gauging stations along the Serbian part of the Danube River during ice-jam events in the winters of 2011/2012 and 2016/2017. Case studies were selected on a river section identified as critical during these periods. The analyses presented in this paper indicate that the Manning roughness coefficient for the entire river channel, including the ice cover, is approximately $n_c \approx 0.0186 \text{ ms}^{-1/3}$, while the coefficient for the ice sheet alone is estimated at $n_i \approx 0.0145 \text{ ms}^{-1/3}$. Hydraulic modelling of the studied river section yielded a Manning coefficient for the main channel of $n \approx 0.0225 \text{ ms}^{-1/3}$, which may pose a challenge for designers. Since air-water friction is negligible in open-channel flow conditions, the hydraulic gradient under ice-covered flow conditions can be explained by the fact that it is roughly half of that in open-channel flow ($R = H/2$).

Keywords: Danube river; hydraulic modelling; ice cover; ice-jam floods; Manning coefficient

1 INTRODUCTION

During winter, prolonged periods of subzero temperatures (observed on the Danube to last approximately 15 days, depending on the cumulative sum of average daily negative temperatures) can lead to ice retention in certain river sections and the formation of ice barriers. This phenomenon reduces water conveyance capacity and increases flow resistance, which may result in elevated water levels compared to those occurring in the absence of ice barriers. If this occurs during high water levels or flood waves, even if they are not extreme events, the risk of water overflowing protected areas increases. This can lead to the overtopping of embankments and flooding of developed land, including residential, industrial, and infrastructure areas, as well as agricultural land. Furthermore, structures located within the river channel, such as bridges, docks, and marinas, may suffer damage [1]. Beyond direct structural damages, economic losses may arise due to disruptions in navigation, reduced hydropower production, and environmental impacts, including water quality deterioration [2].

The literature presents several definitions of ice jams, including the one provided by the National Oceanic and Atmospheric Administration (NOAA) [3]:

"An ice jam, or ice dam, happens when chunks of ice clump together to block the flow of a river. Ice jams are caused by melting snow and ice in the springtime."

This definition applies to rivers where, due to low temperatures, a continuous ice cover forms over the entire water surface during an extended winter period. In the spring, as temperatures rise, the ice cover melts and moves downstream, where it may accumulate in certain river sections, forming an ice jam. For the rivers that, like the Danube in its middle course, are not in a zone of extreme negative temperatures, the following definition is more appropriate [4]:

"Pieces of floating ice carried with a stream's current can accumulate at any obstruction to the stream flow.

These ice jams can develop near river bends, mouths of tributaries, points where the river slope decreases, downstream of dams and upstream of bridges or obstructions. The water that is held back may cause flooding or flash flooding upstream. If the obstruction suddenly breaks then flash flooding may occur downstream".

Ice jam floods have also been studied by the World Meteorological Organization (WMO) [5], which states:

"An ice jam flood including debris is defined as an accumulation of shuga including ice cakes, below ice cover. It is broken ice in a river which causes a narrowing of the river channel, a rise in water level and local floods".



Figure 1 Satellite images of the Danube bend at Dalj, 1358-1348 km

Based on the definitions derived from the genesis of ice jam formation on numerous rivers, as well as experiences from the middle course of the Danube, from Budapest (Hungary) to the Iron Gate 1 Dam (km 943), it can be concluded that this phenomenon occurs in two cases. The first occurs when formed ice floes travel downstream and encounter a river bend (a developed

meander), where they gradually accumulate on top of one another along the concave side of the bend due to inertial forces, progressively obstructing the flow cross-section. A characteristic example of this case is the bend in the Danube near the town of Dalj (Dalj Bend) at km 1358-1348, as shown in Fig. 1.



Figure 2 The section of the Danube near Novi Sad (Serbia) experienced an ice jam on February 18, 2012. [6]

In the research by Chenetal. [1], experimental measurements were made to determine the flow capacity under ice using the Froude number. The research by Beltaos [12] forms the governing equation for modeling of water flow beneath ice cover. However, results from experimental flumes are not applicable to large rivers with a depth-to-width ratio (H/B) below 0.1.

Publications [19] and [20] state that despite advances in research in this field, and new modeling capabilities and available equipment, it is still necessary to use field measurements to define the parameters required for calculations. For this reason, researchers have turned to field observations collected directly from rivers at the moment when an ice jam forms, as shown in publications [15-17, 22]. The advantages of using a combined friction coefficient defined through the Belokon-Sabaneev formula are highlighted in the literature [21]. The issue of defining the Manning friction coefficient under complex flow conditions beneath ice has been analyzed by many researchers, as presented in the literature [24].

The primary objective of this study is to define a coupled hydrological-hydraulic modeling approach for flow in large river systems under the formation of ice barriers. This will enable the forecasting of potential impacts of ice-related flooding in the future, particularly under changing climate conditions. To achieve this, the first part of the study will focus on defining the performance of the hydrological-hydraulic model, incorporating all specific features of flow under ice barrier conditions. The second part will evaluate the model's functionality and performance using selected historical events, with the aim of forecasting flow beneath ice cover and linking it to water levels. The established model will serve as a tool for future early warning systems, enabling timely alerts for potential ice-induced floods along specific river sections, depending on river discharge conditions.

In the second case, the formation of an ice jam is characterized by the accumulation of ice floes that originate in the upstream section of the river and are carried along the water surface, accumulating in narrowed river profiles. A representative example of this occurs in the river section near Novi Sad (km 1255), as shown in Fig. 2.

2 METHODS AND MATERIALS

2.1 The Impact of Climate Change on the Frequency and Duration of Ice Phenomena (Ice Drift and Ice Cover)

Data presented in the analysis conducted by the International Commission for the Protection of the Danube River (ICPDR) [6], as well as in the literature [7-10], indicate that the increase in daily temperatures during the winter period in the region in the second half of the 20th century has led to a decrease in the frequency and number of days with ice occurrence.

Analyses have shown a decreasing trend in the total duration of ice cover in Central Europe. For example, on the Oder River along the Germany-Poland border, the ice cover duration decreased by 46 days between 1956 and 2015 [6]. Similarly, for the lower Danube in Romania, the duration of ice cover was reduced by 28 days between 1937 and 2016 [8]. A comparable trend was observed on the lower Drava River in Hungary, where the decrease amounted to 14 days [9].

Fig. 3 presents the results of the analysis of the sum of negative daily average air temperatures from 1900 to 2023, as well as the duration of ice barriers near Novi Sad.

An analysis of ice frequency and analysis of ice cover formation was conducted for the stretch of the Danube River flowing through Serbia, between river kilometers km 995 (Donji Milanovac) and 1425.5 (Bezdan). The study utilized historical ice observation data from two periods: 1900-1970 and 1971-2023. The year 1971 was selected as a reference point due to the completion of the Đerdap I Hydropower Plant and the creation of its reservoir, which significantly altered the river's ice regime. Additionally, a marked increase in thermal and chemical pollution of the Danube was observed beginning in the 1970s.

The results indicate a substantial shift in ice dynamics between the two periods. From 1900 to 1970, ice was recorded almost annually (in 70-90% of the years), while between 1971 and 2023, ice frequency dropped to every

2-3 years (in 30-60% of the years), varying by river segment, with the highest frequency observed in the upstream sections. Complete ice cover during the latter

period was a rare event, occurring once every 5 to 30 years depending on location. The analysis was based on data from 12 surface water monitoring stations [10, 11].

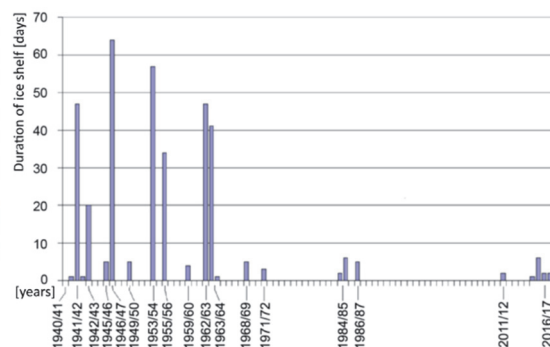
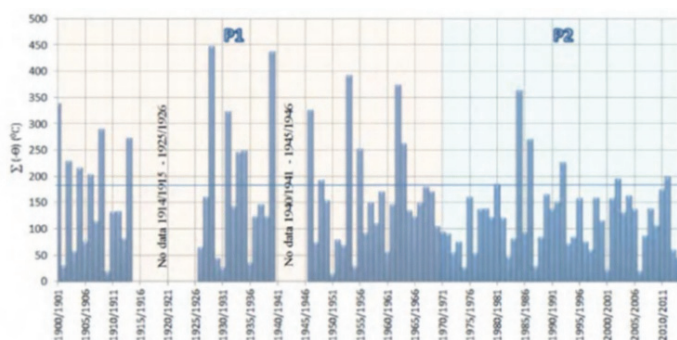


Figure 3 The histogram of the sum of negative daily average air temperatures during the winter period and the number of days with ice barriers on the section of the Danube near Novi Sad (km 1255) [10]

In addition to the data on the frequency of ice phenomena, their duration is also an important characteristic. During the first period (1900-1970), the occurrence of ice floes lasted between 69 and 94 days, while in the second period (1971-2023), the duration was effectively halved. A similar trend is observed for the formation of ice barriers, which now last less than 10 days in the section near Novi Sad [10, 11].

Table 1 The sum of negative daily average air temperatures during the winter period in Novi Sad (data from the winter seasons 2014/2015 to 2023/2024).

Winter season year	Sum of negative daily average air temperatures / °C
2014/2015	-82.0
2015/2016	-49.6
2016/2017	-184.2
2017/2018	-44.2
2018/2019	-38.3
2019/2020	-33.4
2020/2021	-35.2
2021/2022	-35.2
2022/2023	-17.0

The data indicate a trend of increasing daily average air temperatures during the winter period over the past 30 years near Novi Sad, which has resulted in a decrease in the sum of negative daily average air temperatures and, consequently, a reduction in the occurrence of ice barriers along the analyzed stretch of the Danube River through Serbia (Fig. 3 and Tab. 1).

2.2 Modelling Ice Jam Floods

2.2.1 The Critical Value of the Froude Number for Ice Jam Formation

The theoretical foundations for the hydraulic modelling of water flow beneath an ice cover were first defined by Kennedy (1958) and Pariset et al. (1966), with Beltaos [12] later proposing the final form of the equation. The theoretical basis for defining the differential equation in a one-dimensional form along the flow direction (x), as shown in Fig. 4, applicable to large rivers that can be approximated as a rectangular channel, where the water surface width (B) is significantly greater than the water depth (H), has been presented using the concept of limiting-stability relationship used for soil mechanics in article [13]:

$$\frac{d}{dx}(\bar{\sigma}_x t) + \frac{2t}{B}(\tau_{xz}) = s_i \rho g S_w t + \bar{\tau}_i \quad (2)$$

In the previous equation, $\bar{\sigma}_x$ represents the average normal stress (including hydrostatic pressure) in the x -direction, t denotes the thickness of the ice cover relative to the hydrostatic pressure lines below the ice barrier, and B is the channel width. Furthermore, τ_{xz} represents the shear stress between the ice cover and the bank (or the ice on the bank), s_i is the specific gravity of ice, ρ denotes the water density, g is the gravitational acceleration, S_w represents the slope of the water level, and $\bar{\tau}_i$ is the average shear stress induced by the water flow beneath the ice cover. The fundamental assumption of Eq. (1) is that the ice thickness remains constant along the ice jam, which serves as a working hypothesis applicable to the one-dimensional case.

In the further process of defining the terms in the previous equation, the theory of soil mechanics was applied to determine the boundary stresses between the ice cover and the bank (or the ice on the bank):

$$\tau_{xz} = C_i + k_0 \bar{\sigma}_z \quad (2)$$

$$\bar{\sigma}_z = k_1 \bar{\sigma}_x \quad (3)$$

Based on the preceding considerations, the fundamental differential equation can be expressed in the following form:

$$\frac{d}{dx}(\bar{\sigma}_x t) + \frac{2k_0 k_1}{B}(\bar{\sigma}_x t) = \rho_i g t J + \tau_i - \frac{2t C_i}{B} \quad (4)$$

In the equation, the term k_1 represents the lateral pressure coefficient, while C_i denotes the adhesion force of the accumulated ice. For solving the equation, the authors assumed $C_i = 0$. Additionally, the parameter k_0 is defined as $\tan \varphi$, where $\tan \varphi$ is the internal friction angle of the ice blocks. The proposed value for the ice density is $\rho_i = 0.917 \text{ gr/cm}^3$.

With the given assumptions, the general expression for a wide ice barrier is derived in the following form (5).

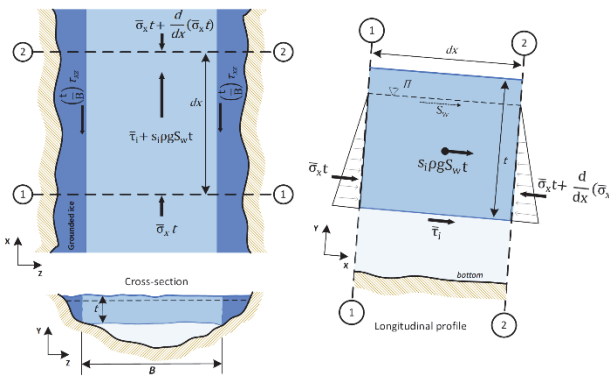


Figure 4 Display forces on a section of ice cover in a rectangular prismatic channel [12]

$$\frac{BV^2}{C^2 H^2} = \mu \frac{\frac{\rho_i}{\rho} \left(1 - \frac{\rho_i}{\rho}\right) \frac{t^2}{H^2} \left(1 - \frac{\rho_i}{\rho} \frac{t}{H}\right)^3}{1 + \frac{\rho_i}{\rho} \frac{t}{H}} \quad (5)$$

As can be concluded, Kennedy (1958) and Pariset et al. (1966) [12] used the Chezy friction coefficient, which represents the combined friction coefficient of the riverbed and the roughness of the underside of the ice cover. In more recent times, the Chezy-Manning coefficient has been more commonly used, expressed as ($C = 1/nR^{1/6}$), where the Manning roughness coefficient (n) in this case accounts for the friction of both the riverbed and the underside of the ice cover.

Under conditions of an ice-covered or jammed flow, the wetted perimeter of the riverbed in the experimental channel is given by $2(H + B)$. However, for wide rivers, the depth H is negligible, allowing an approximation as $2B$. Consequently, the hydraulic radius can be expressed as $R = H/2$. In Eq. (5), V represents the average velocity of the water in front of the ice jam. By solving the equation, Beltaos [2] introduced the coefficient of internal strength, $\mu = k_0 k_1 k_2$, whose value, depending on the strength of the ice, ranges from 1.0 to 2.0, with a commonly accepted value of approximately $\mu \approx 1,28$.

Eq. (5) can be transformed into the dimensionless Froude number for open-channel flow, which represents the ratio of inertial to gravitational forces in the flow, taking the following form:

$$Fr_u = \frac{V}{\sqrt{gH}} \quad (6)$$

$$Fr = f\left(\frac{\mu C^2}{g}, \frac{H}{B}, \frac{t}{H}\right) = \sqrt{\frac{\mu C^2 \left(\frac{H}{B}\right) \frac{\rho_i}{\rho} \left(1 - \frac{\rho_i}{\rho}\right) \frac{t^2}{H^2} \left(1 - \frac{\rho_i}{\rho} \frac{t}{H}\right)^3}{1 + \frac{\rho_i}{\rho} \frac{t}{H}}} \quad (7)$$

Numerous experimental studies have been conducted in laboratories with experimental channels [1] to determine the Froude number for a river section that could be critical

for ice jam formation. Due to the challenges of applying a model based on Froude similarity, these results cannot be used for large rivers where the H/B ratio is less than 0.1. In the referenced literature, the experimental channel is 26.70 m long and 0.4 m wide, with depths ranging from 10 to 30 cm.

Unfortunately, results obtained directly from field measurements on large rivers are rarely found in the literature, as such studies are associated with the risks of conducting measurements under extreme conditions. One such study, based on field observations collected from the St. Lawrence River and the La Grande River in the early 1970s, was conducted by Michel [15]. According to these investigations, the Chezy coefficient (C) ranged from 24 to 40, while the value of μ was between 1.28 and 1.3.

Based on the presented results, it can be concluded that in large rivers where the H/B ratio is less than 0.01-0.02, a Froude number value lower than 0.1-0.12, already poses a challenge for the formation of ice barriers [16]. The literature [17] also highlights research findings from the Danube River in Serbia, demonstrating that low values of $V_{avg} \times B$ and the Froude number, expressed as:

$$Fr = \frac{V_{avg}}{\sqrt{2gR}} < 0.1 \quad (8)$$

at certain river sections lead to the formation of ice jam. As noted in the same literature, the effect of channel curvature, which further facilitates the formation of ice jam, was not considered in this analysis.

2.2.2 Modelling of Flow During Ice Jam Formation

For river sections that are critical for the formation of an ice barrier, the key question arises: what is the maximum river discharge and water level under open-channel flow conditions, without an ice barrier, that would, in the event of ice barrier formation, result in flooding of the protected area?

Flood defence systems on major rivers, such as the Danube, Tisa, and Sava in Serbia, have been designed since the 1970s based on a return period of $Tp = 100$ years, corresponding to an exceedance probability of $p = 1\%$. For such a defined water level, an additional 1.0-1.2 m of freeboard is incorporated into levees, while an 0.8 m freeboard is added to floodwalls in urban areas. The freeboard is determined based on the fact that the flood wave corresponding to a return period of $Tp = 1000$ years ($p = 0.1\%$) is approximately 1.0 m higher than that of $Tp = 100$ years.

The hydraulic calculations used to define flow rates that can cause ice-jam flooding differ from the hydraulic calculations applied to 1D and 2D flow in open channels [18], which are most commonly simulated using software packages such as HEC-RAS (Hydrologic Engineering Center's River Analysis System), developed by USACE (U.S. Army Corps of Engineers). In flow conditions influenced by ice barriers, friction against the ice cover must also be taken into account. In open channel flow, the friction between the water surface and the air is generally neglected, therefore, when an ice barrier is present, the

hydraulic radius is effectively halved ($R = H/2$), as explained in the following text.

Research has shown that flow beneath an ice cover is impeded due to changes in the velocity field, which result from pressurized flow conditions. A direct consequence of this phenomenon is an increase in water levels upstream of the ice barrier and the formation of backwater effects.

Experts [19] and [20] acknowledge that, despite recent research advancements in this field and progress in instrumentation and modelling methods for ice-jam flooding, determining the conveyance capacity of a river channel under an ice cover still requires direct measurements for specific cases. It is recommended that, for rivers frequently experiencing ice cover and ice barrier formation, multiple measurements be conducted under different conditions to develop a hydraulic model tailored to that river.

In these hydraulic analyses, a quasi-uniform and steady flow is typically assumed. However, due to variations in discharge, cross-sectional geometry, river slope, and changes in Manning's roughness coefficient, the flow cannot be characterized as strictly uniform. To address this, certain approximations are made to establish a flow model for a given river section. The calculations take into account the average water surface width (B), the cross-sectional shape and area (A), and a constant discharge (Q). Consequently, an average Manning's roughness coefficient (n_c) is determined, considering both channel friction and the roughness at the bottom of the ice barrier.

In the flow beneath an ice cover, additional friction is generated between the water and the underside of the ice, whereas friction at the water-air interface is negligible. The ice barrier itself rises due to buoyant forces, which increase as the backwater effect develops upstream of the barrier. This backwater does not overtop the ice barrier but gradually lifts it. As a result, the flow now occurs between two boundaries: the riverbed and the ice cover. Consequently, the Manning's roughness coefficient for the entire ice-covered channel can be calculated using the well-known in practical applications, Belokon-Sabaneev formula [21]:

$$n_c = \left(\frac{n_i^{3/2} + n_b^{3/2}}{2} \right)^{2/3} \quad (9)$$

where is: n_c - Manning's roughness coefficient for flow under an ice barrier, n_i - Manning's roughness coefficient for the underside of the ice barrier, n_b - Manning's roughness coefficient for the riverbed under open-channel flow conditions.

The condition for applying this formula is that the water depth in the channel must be greater than $H > 2$ m.

Measurement data [19] indicate that the Manning's roughness coefficient of the ice surface varies, being highest at the initial stage of ice barrier formation (0.04-0.06). However, as the ice undergoes gradual erosion, a granular layer forms at the water-ice interface, significantly reducing its roughness.

Compared to open-channel flow conditions without an ice barrier, the hydraulic radius will decrease by 50%, and the flow capacity of the cross-section will be reduced to

only 60% for the same previous water surface slope. As a result, the water level upstream of the barrier will rise, since the passage of a given discharge requires significantly higher energy, which is compensated by an increase in potential energy in the upstream section [14].

In practical cases, flow can be reasonably well approximated as quasi-uniform by using the Chezy-Manning equation, transformed for a wide channel, where bank friction, and consequently, water depth is negligible compared to the water surface width. Under these conditions, the hydraulic radius ($R = A/P = H$) is equal to the normal depth, which can then be expressed as:

$$h_n = \left(\frac{Qn}{BJ^{1/2}} \right)^{3/5} \quad (10)$$

In flow beneath an ice barrier, additional friction occurs at the underside of the ice cover. For wide channels, where bank friction is negligible compared to the friction with the broad riverbed, the hydraulic radius is given by $R = A/P = H/2$.

Accordingly, for flow beneath an ice barrier, the Chezy-Manning equation can be analogously expressed as:

$$h_{ice} = \left(\frac{2^{2/3} Qn_c}{BJ_{ice}^{1/2}} \right)^{3/5} = 1.32 \left(\frac{Qn_c}{BJ_{ice}^{1/2}} \right)^{3/5} \quad (11)$$

As noted by Beltaos [22], the equilibrium reach is usually much longer than indicated in the Fig. 5. This section allows for the formulation of equations under quasi-uniform flow conditions.

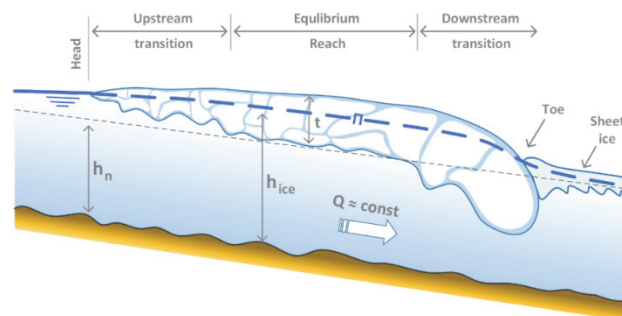


Figure 5 Schematic illustration of an equilibrium jam [22]

Based on the comparison of the equations for normal depth in a flow without an ice cover (h_n) and with an ice cover (h_{ice}), a relationship can be derived between the depth under the ice and the depth with a free surface, where J_{ice} represents the hydraulic gradient (energy slope) beneath the ice cover:

$$\frac{h_{ice}}{h_n} = 1.32 \left(\frac{n_c}{n_b} \left(\frac{J_{ice}}{J} \right)^{1/2} \right)^{3/5} \quad (12)$$

In study [20], research is highlighted on the formation and frequency of ice-jam flooding in relation to climatic parameters. The previous equation is modified into the following form:

$$\frac{h_{ice}}{h_n} \approx \left[1 + \left(\frac{n_i}{n_b} \right)^2 \right]^{\frac{2}{5}} + 0.92 \frac{h}{h_n} \quad (13)$$

where: h - average thickness of the entire ice cover, h_{ice} - mean depth beneath the ice cover (since the Chezy-Manning equation was used, this depth reflects the average friction effects along the observed river section), h_n - depth that would form in the absence of an ice cover, n_i - Manning's roughness coefficient for friction at the underside of the ice sheet, n_b - Manning's roughness coefficient for the riverbed without ice.

3. RESULTS AND DISCUSSIONS

3.1 Analysis of Weather Parameters in Winter 2011/2012

The winter of 2011/2012 was characterized by an exceptionally cold air wave that occurred at the end of

January and persisted throughout February 2012, with relatively constant negative temperatures, as shown in Fig. 6.

The occurrence of ice floes and the formation of an ice cover began on February 6, 2012, as a result of extremely low temperatures, which, at certain times of the day, dropped to $-29\text{ }^{\circ}\text{C}$ at 5 cm above the ground surface, with an average daily temperature of $-18.3\text{ }^{\circ}\text{C}$.

For the formation of the ice barrier, the cumulative sum of mean daily temperatures is a significant factor. By February 6, this value reached $\Sigma t_{da}^{av.} = -83.3\text{ }^{\circ}\text{C}$, marking the formation of the ice barrier in this section of the Danube.

Between January 20 and February 29, the cumulative sum of mean daily temperatures amounted to $\Sigma t_{da}^{av.} = -181\text{ }^{\circ}\text{C}$, which also classifies this period as an exceptionally cold winter.

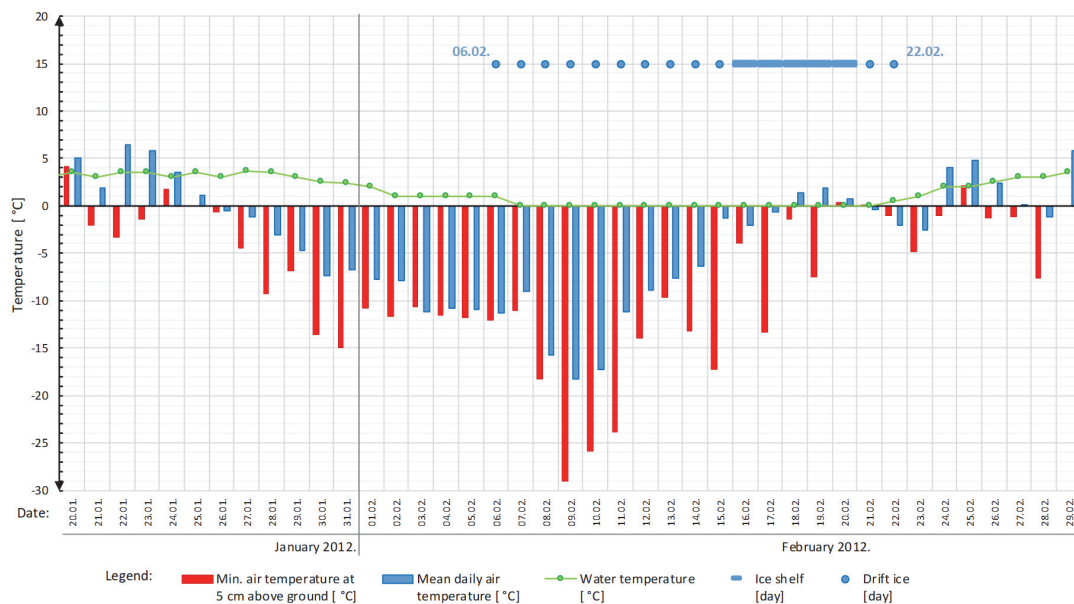


Figure 6 Data from the Novi Sad meteorological station: Minimum air temperatures at 5 cm and mean daily temperatures

3.2 Analysis of Weather Parameters in Winter 2016/2017

In the middle course of the Danube, a cold, dry air mass of Siberian origin appeared at the end of December 2016 and the beginning of January 2017, as shown in Fig. 7. A few days later, a cyclone brought temporarily warmer and more humid weather; however, from January 6 onward, an anticyclone induced a renewed cold spell.

Based on the data presented in Fig. 8, it can be concluded that although a cooling trend was already evident in December 2016, with air temperatures dropping below freezing, a continuous cold spell began on December 29. The formation of ice floes and the development of an ice cover commenced on January 9, 2017, as a consequence of persistently low temperatures, which, at certain times of the day, reached a minimum of $-22.2\text{ }^{\circ}\text{C}$ at 5 cm above the ground surface, with an average

daily temperature of $-14.3\text{ }^{\circ}\text{C}$. The cumulative sum of mean daily temperatures, which is significant for the formation of an ice barrier, reached $\Sigma t_{da}^{av.} = -73.2\text{ }^{\circ}\text{C}$ by January 9, when the ice barrier was formed.

The ice barrier initially formed on January 9 near Novi Sad, at a constricted river profile and the bridge at km 1255. The ice jam gradually moved downstream, eventually stopping near the hydrometric station in Zemun (km 1170), a few kilometers upstream from the confluence of the Sava and the Danube. During this period, an ice barrier extended approximately 70 km upstream, reaching as far as Novi Sad.

According to reports from icebreakers dispatched from Hungary, in accordance with an international agreement with Serbia, the ice thickness in certain river sections reached up to 3 meters.

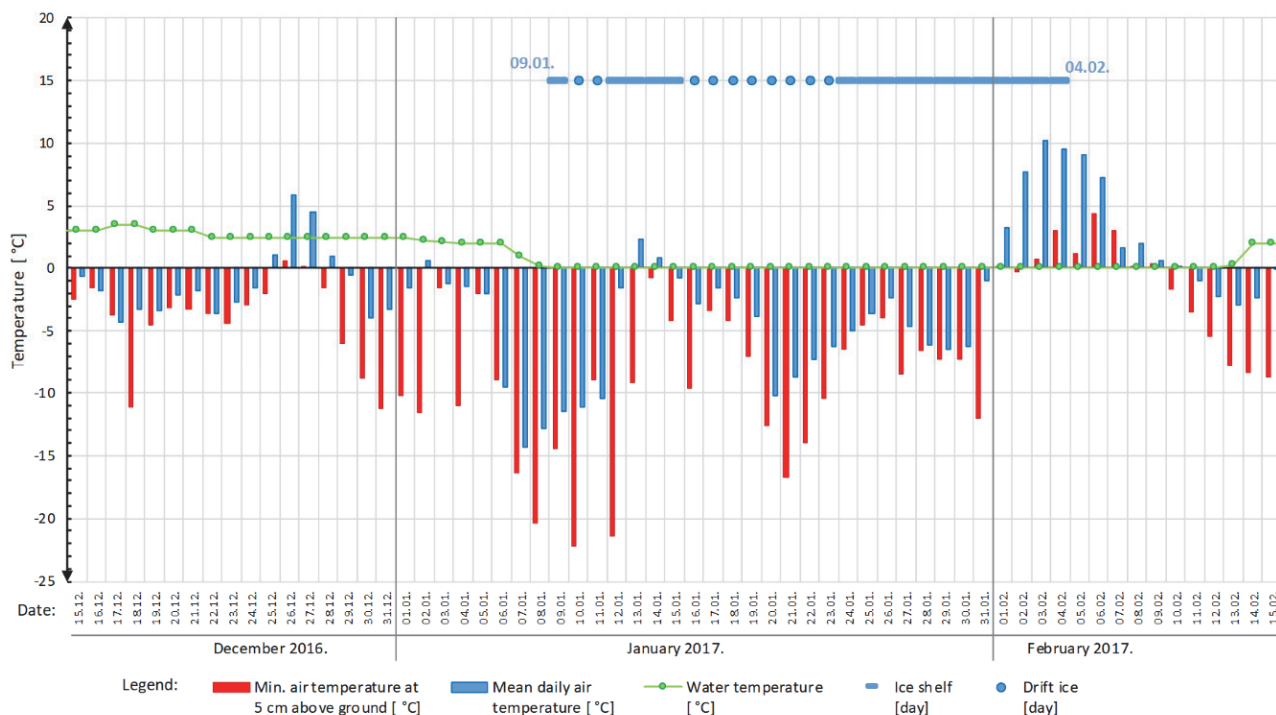


Figure 7 Minimum and mean daily temperatures in January 2017 near Novi Sad (Serbia)



Figure 8 Novi Sad on January 9, 2017 (left) and the Marina in Novi Sad (right) in February 2012. (Source: [6] and <https://www.lupiga.com>)

To perform a hydraulic calculation for the observed river section, it is crucial to understand the genesis of the ice barrier formation. Daily water level variations at the gauging stations along this section (Zemun, Slankamen, and Novi Sad) depend on the temporal progression of the ice barrier movement. As previously mentioned, the ice jam began forming downstream near Zemun on January 14, at the newly constructed Pupin Bridge. As ice floes continued to accumulate, the ice jam expanded upstream, reaching Slankamen on January 24, where it merged with the ice jam extending to Novi Sad, as shown in Fig. 8.

Between December 30 and January 31, the cumulative sum of mean daily temperatures amounted to $\Sigma t_{da}^{av.} = -175.4 \text{ }^\circ\text{C}$. Considering the entire winter of 2016/2017, during which the total cumulative sum of negative mean daily air temperatures exceeded $-180 \text{ }^\circ\text{C}$, this winter can be classified as an exceptionally cold winter. According to the literature [6], for this region of Europe, winters are classified as follows based on the cumulative sum of mean daily temperatures (Tab. 2).

Table 2 Winter classification based on the cumulative sum of mean daily temperatures

Classification	Cumulative sum of mean negative daily temperatures
Mild winter	from $0 \text{ }^\circ\text{C}$ to $-50 \text{ }^\circ\text{C}$
Cold winter	from $-50 \text{ }^\circ\text{C}$ to $-180 \text{ }^\circ\text{C}$
Exceptionally cold winter	from $-180 \text{ }^\circ\text{C}$ to $-450 \text{ }^\circ\text{C}$

3.3 Analysis of Hydrological Parameters in the Winters of 2016/2017 and 2011/2012

As stated in Section 3.2, in order to establish a hydraulic model of quasi-uniform and steady flow, it is necessary for the discharge (Q) to remain approximately constant ($Q \approx \text{const.}$) during the critical period of ice barrier formation. For this reason, the hydrograph $Q(t)$ of the Danube will be analysed for the critical period during both the winter of 2016/2017 and the winter of 2011/2012.

The obtained data indicate that during the formation of the ice barrier in 2017, the assumption of a constant discharge cannot be adopted. However, for the ice barrier in 2012, the discharge along the Danube from Slankamen

to Novi Sad remained constant at $Q \approx 1790 \text{ m}^3/\text{s}$, as shown in Fig. 9. For this reason, the hydraulic analysis will

proceed based on the formation of the ice barrier during February 2012.

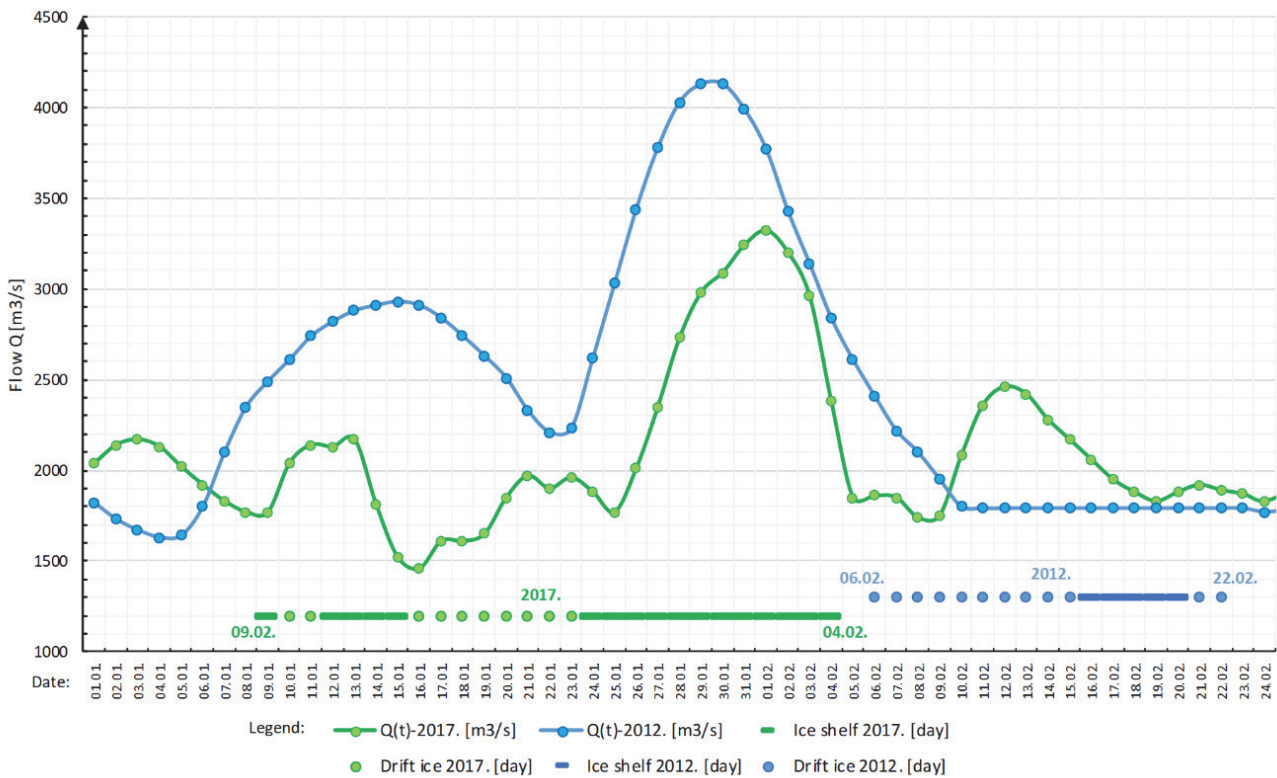


Figure 9 Hydrograph for Novi Sad for the period of January-February 2017 and 2012, including the period of ice barrier formation

3.4 The Impact of the Formed Ice Barrier on Water Levels During the Winter of 2012

It is important to emphasize that during the formation of the ice barrier, the relationship between discharge and water level, $Q(H)$, is no longer straightforward, as the correlation between the water level and discharge during free-flowing conditions and the level during the formation of the ice barrier on a particular section is no longer the same. The discharge capacity of the river channel during the formation of the ice barrier decreases due to increased resistance to flow. For this reason, stage hydrograph ($H(t)$) will be analyzed for the observed period.

In open channels where flow velocities are not high, on the Danube, they are around 1.0 m/s, the kinetic energy per unit weight ($v^2/2g$) is low, and energy losses along a section of the river are primarily expressed through the decrease in potential energy. Therefore, for further analysis, the differences in water levels at two hydrological stations along the observed section (ΔH) will be considered, as shown in Fig. 10.

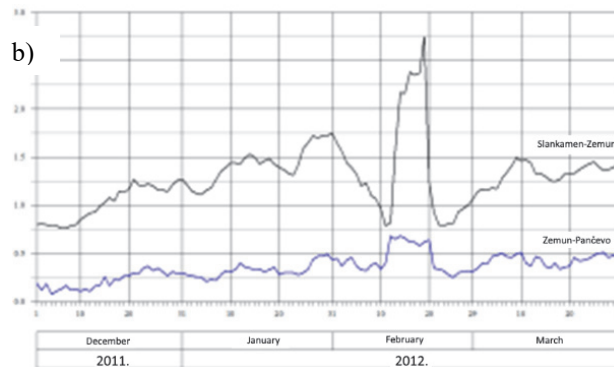
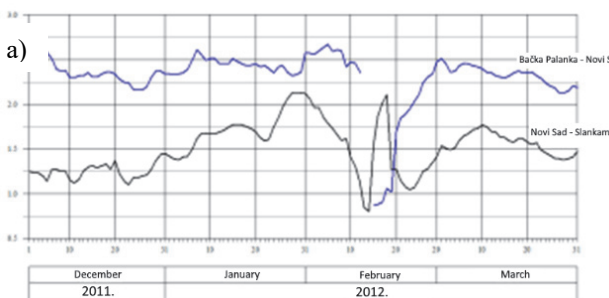


Figure 10 Difference in water levels ΔH (m) at gauging stations along the observed section Novi Sad-Slankamen (the section upstream from Bačka Palanka-Novı Sad (a), and downstream from Slankamen-Zemun (b))



For the analysis of water level variations along the observed section Novi Sad-Slankamen (Equilibrium reach), it is necessary to also include the downstream section Zemun-Slankamen (Downstream transition) and the upstream section Bačka Palanka-Novı Sad (Upstream transition). The reason for this is that changes in hydrological parameters on the downstream section Zemun-Slankamen directly affect the water levels at the boundary profile at Slankamen, and similarly, the difference in levels between Novi Sad and Bačka Palanka indicates a disturbance in the level at Novi Sad, as the formed ice barrier on the Slankamen-Novı Sad section was not reflected at the Bačka Palanka gauging station.

The analysis indicates that the ice jam first formed downstream of Zemun, which raised the water level at that gauging station. As a result, the water level difference between Zemun and Slankamen decreased to just $\Delta H =$

0.76 m on February 11. Due to the congestion of this section, a sudden rise in water levels occurred at Slankamen the next day, creating a level difference with Zemun of $\Delta H = 2.75$ m. This rise in water levels at Slankamen caused an immediate reduction in the level difference between Slankamen and Novi Sad to $\Delta H = 0.80$ m on February 13, and finally, due to the accumulation of ice on the Slankamen-*Novi Sad* section, the water level at Novi Sad increased in the following days, with a level difference to Slankamen of $\Delta H = 2.10$ m on February 17.

It should be noted that the section between Zemun and Slankamen was not included in the hydraulic calculation because the Tisa River flows into the Danube at Slankamen, significantly disrupting the assumption of steady flow. However, no changes were observed on the Slankamen-*Novi Sad* section, so it was assumed that $Q \approx \text{const}$.

3.5 Definition of Flow Resistance in the Presence of a Formed Ice Barrier

The flow rate of the Danube along the given section during the period from February 10 to February 29, 2012, was approximately $Q = 1780 \text{ m}^3/\text{s}$ and can be considered constant. Before the formation of the ice barrier, the water levels were 71.48 m a. s. l. at Slankamen and 72.93 m a. s. l. at Novi Sad, with an average depth along this section of approximately $h_n \approx 6.50$ m, as shown in Fig. 11 and Fig. 12. At the Novi Sad profile, depths were greater due to the reduced channel width, which was only $B = 300$ m (Fig. 13).

An analysis of the ice jam formation indicates that it initially appeared downstream of Slankamen, causing a local water level rise of 1.94 m. The ice jam subsequently propagated upstream toward Novi Sad, where the water level increased by 2.5 m. Considering these factors, it can be concluded that the increased flow resistance due to the

ice jam between Slankamen and Novi Sad resulted in a head loss of $\Delta H = 0.56$ m.

An analysis of the water surface slope prior to the ice jam formation indicates that it was $J = 3.71 \text{ cm}/\text{km}$, whereas after the formation of the ice jam along this section, the slope increased to $J_L = 5.31 \text{ cm}/\text{km}$. The presence of an ice cover downstream of Slankamen and between Slankamen and Novi Sad led to a water level rise of approximately 2-2.5 m for the same discharge, resulting in an average depth of approximately $h_L = 8.50$ m. For further calculations, the ice-covered section will be considered as a Uniform - "Equilibrium" Section [23].

By using the equation derived from the fundamental equation for uniform steady flow, the Chezy-Manning Eq. (12), it is possible to determine the Manning roughness coefficient under ice-covered flow conditions for the entire river channel. The Manning friction coefficient for open-water flow conditions was defined in study [23] through the development of a 1D and 2D hydraulic model of the Danube using the HEC-RAS software package, with a value of $n_b = 0,0225 \text{ ms}^{-1/3}$.

$$\frac{h_{\text{ice}}}{h_n} = 1.32 \left(\frac{n_c}{n_b} \left(\frac{J_{\text{ice}}}{J} \right)^{1/2} \right)^{3/5} \rightarrow$$

$$\frac{8.5}{6.5} = 1.32 \left(\frac{n_c}{n_b} \left(\frac{5.31}{3.71} \right)^{1/2} \right)^{3/5} \rightarrow$$

$$1.31 = 1.32 \left(1.2 \frac{n_c}{n_b} \right)^{3/5} \rightarrow$$

$$1.31 = 1.47 \left(\frac{n_c}{n_b} \right)^{0.6} \rightarrow$$

$$n_c = 0.0186 \text{ ms}^{-1/3}$$

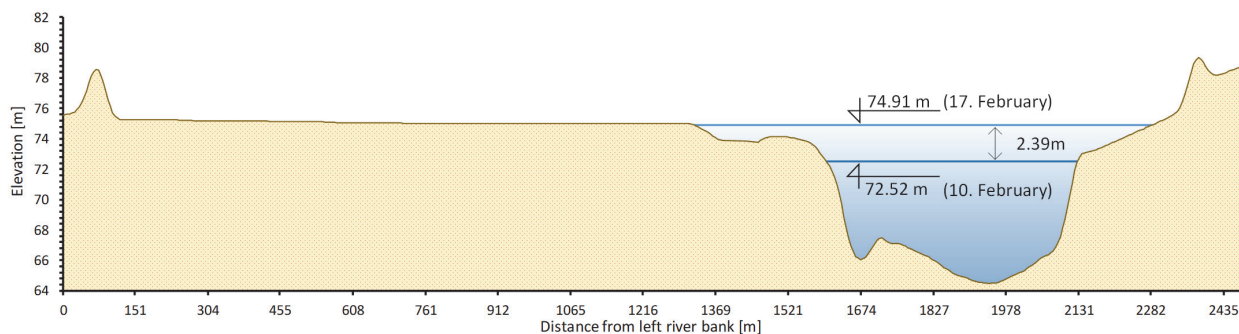


Figure 11 Cross-Section of the Danube between Novi Sad and Slankamen, km 1244, $B = 500$ m

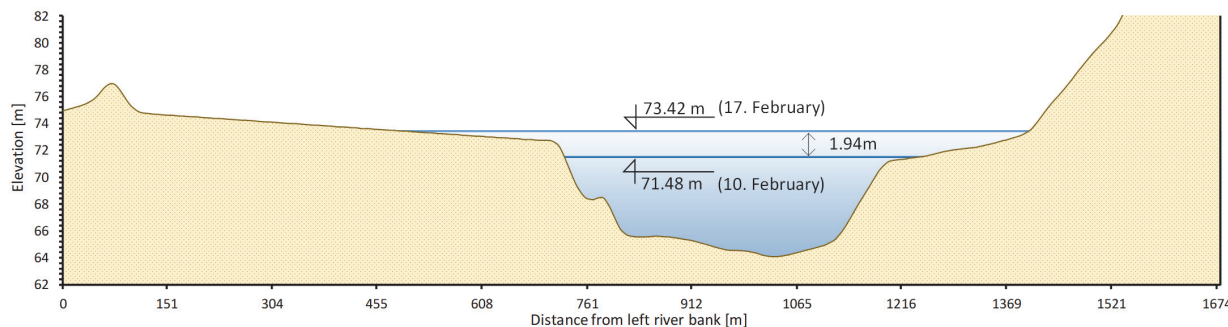


Figure 12 Cross-Section of the Danube at Slankamen, km 1216, $B = 500$ m

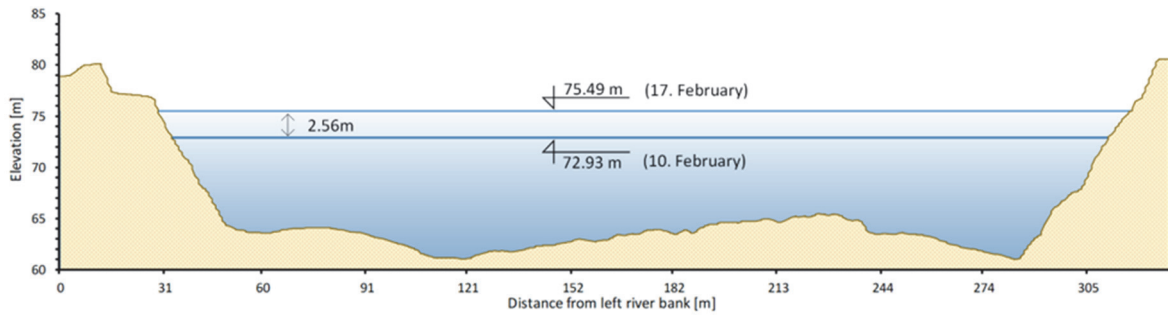


Figure 13 Cross-Section of the Danube at Novi Sad, km 1255, $B = 300$ m

Based on the Belokon-Sabaneev formula Eq. (9), the Manning coefficient for the ice cover is calculated as follows:

$$0.0186 = \left(0.5 \left(n_i^{3/2} + n_b^{3/2}\right)\right)^{2/3} \Rightarrow n_c = 0.0145 \text{ ms}^{-1/3}$$

The obtained results indicate that the roughness coefficient of the ice cover is lower than that of the riverbed ($n_i < n_b$), suggesting that the channel bed exhibits greater irregularities than the ice surface in contact with water. Despite the lower roughness of the ice surface compared to the riverbed, flow resistance is higher due to the wetted perimeter doubling in the presence of ice ($P = 2B$) compared to open-water conditions, where air-water friction is typically neglected ($P = B$). Consequently, the hydraulic radius is reduced by half, from $R = h$ in open-flow conditions to $R = h/2$ under ice-covered flow. This reduction in hydraulic radius indicates that the conveyance of the river channel h in this section is approximately 40% lower when compared to the achieved water depths. A similar result is obtained using Eq. (13), considering that the average thickness of the ice cover beneath the surface was approximately $t \approx 1,0$ m, with reports indicating that ice thickness reached up to 3 m in certain areas:

$$\frac{h_{ice}}{h_n} \approx \left[1 + \left(\frac{n_i}{n_b}\right)^2\right]^{2/5} + 0.92 \frac{h}{h_n} \rightarrow$$

$$\frac{8.5}{6.5} \approx \left[1 + \left(\frac{n_i}{n_b}\right)^{1.5}\right]^{0.4} + 0.92 \frac{1.0}{6.5} \rightarrow$$

$$n_i = 0.014 \text{ ms}^{-1/3}$$

The obtained results are consistent with the findings of numerous researchers who have analyzed a large number of ice-induced floods, as presented in the literature [24].

The Froude number for the analyzed river section is approximately $Fr \approx 0.067-0.07$, and based on the research presented in Fig. 6 in the literature [16] and [17], this section is critical in terms of ice jam formation.

4 CONCLUSIONS

Based on the analysis of the formation of ice barriers, it can be concluded that in the years when the sums of daily

air temperatures are below $\Sigma t_{da}^{av} < -75$ °C during the winter period, we can expect the beginning of the appearance of ice floes in the middle course of the Danube. Critical years for longer occurrence of ice barriers are those with the sum of mean daily temperatures $\Sigma t_{da}^{av} < -180$ °C, these winters are characterized as "exceptionally cold winters". The period of the appearance of ice barriers on the Danube can occur from the beginning of December, like in winter 2001/2002, or during January, like in winter 2016/2017, and even during February, like in winter 2011/2012.

The analysis of the hydrograph $Q(t)$ is necessary to check the stationarity of the flow on the analyzed section in order to be able to use the equations that assume quasi-stationarity. Therefore, the occurrence of the ice barrier in February 2012 has been analyzed in this paper because the assumption of quasi-stationarity was fulfilled.

The obtained results indicate that the total Manning coefficient of friction for this section during the formation of the ice barrier is $n_c = 0.0186 \text{ ms}^{-1/3}$, which is less than the Manning coefficient obtained by the hydraulic model of 1D and 2D flow using the HEC-RAS software package $n_b = 0.0225 \text{ ms}^{-1/3}$. However, in the case of the formation of an ice barrier, the river conveyance is lower because the wetted perimeter for friction in that case is $O = 2B$.

The results of the paper confirm the state, by numerous authors, that ice barriers in large rivers $H/B < 0.01-0.02$ are formed in sections where the value of the Froude number is $Fr = v_{sr}/(2gR)^{1/2} < 0.1$. By the conducted calculations, on the analyzed section of the Danube River, the results of this paper show the value of the Froude number to be $Fr \approx 0.067-0.07$, which agrees with the previous statement.

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