

Article

Structural Intervention for the Prevention of Ice-Jam Formation and Flooding in Flowing Watercourses

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Abstract

Ice-jam formation during winter low-flow conditions represents a persistent hydrotechnical hazard in small and medium-sized rivers of Central Europe. Despite extensive monitoring efforts, preventive structural measures remain insufficiently developed and rarely evaluated under real geomorphological constraints. This study proposes and hydraulically verifies a low-profile riverbed sill designed to suppress the initiation and stabilization of frazil and anchor ice during critical winter discharges. The analysis integrates 20 years of hydrological and water-temperature data (2004–2024), 26 detailed cross-sectional surveys, a high-resolution longitudinal profile derived from DMR 3.0, and a newly formulated Ice-Jam Risk Index (I_{ice}) combining flow velocity, depth-to-width ratio and thermal deficit. Application to the Torysa River (rkm 42.8–43.6) revealed a clearly defined high-risk zone (rkm 43.20–43.38), where hydraulic conditions frequently fall below the critical thresholds for ice accumulation ($U < 0.35 \text{ m} \cdot \text{s}^{-1}$; $h/B < (h/B)_{\text{crit}}$; $\Delta T > 0.5 \text{ }^{\circ}\text{C}$), indicating shallow and laterally widened channel sections prone to anchor-ice stabilization. Model simulations demonstrated that the proposed sill increases mean velocity by 22–35% during Q_{65} – Q_{85} conditions, reducing the local $I(\text{ice})$ by 61%, while preserving the conveyance capacity for discharges above Q_{50} and avoiding measurable backwater impacts upstream. Field-based morphology, risk index interpolation and hydraulic modeling all confirm that the structure effectively disrupts the formation of stable anchor-ice nuclei, which have historically triggered severe ice-jam floods in this reach (2011/12, 2016/17, 2021/22). The results show that a properly dimensioned low-profile sill provides a passive, low-cost, and transferable engineering solution for winter flood risk mitigation, outperforming reactive ice-management techniques while maintaining ecological and hydraulic compatibility with small natural rivers. The methodology is replicable for other rivers where supercooling, low-flow hydraulics and channel morphology jointly control ice-jam initiation.



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1. Introduction

Ice-jam floods represent one of the most persistent and least predictable winter hydrological hazards in temperate regions. Unlike open-water floods, their occurrence is not driven by extreme discharge but by the sudden formation of a stable ice blockage capable of raising water levels by several meters within a short reach. These events are strongly

conditioned by local channel morphology and hydraulic variability, which determine where flow deceleration, stagnation zones, and ice-retention pockets develop. Many European foothill rivers, narrow channels, abrupt changes in width or slope, and shallow, laterally expanded sections repeatedly create favorable conditions for the accumulation of frazil and anchor ice. As a result, ice-jam floods continue to pose a recurrent and locally concentrated threat, despite advances in hydrological monitoring and winter flood forecasting [1–3].

Current approaches to mitigating ice-jam flood risk rely predominantly on operational and reactive measures. Mechanical ice breaking, short-term reservoir regulation, temporary flood protection, and emergency evacuation are commonly applied only after an ice jam has already formed, making them costly, logistically demanding, and highly dependent on real-time hydrological conditions. Despite their widespread use, these interventions often provide only limited and short-lived effectiveness, particularly in small and morphologically variable rivers where ice accumulations can develop rapidly and unpredictably. In contrast, preventive in-channel structural solutions—such as low sills, guiding walls, or ice-control structures—remain insufficiently developed, are rarely tested under systematic hydraulic evaluation, and are largely absent from practical river management. This imbalance highlights the need for simple, permanent, and hydraulically grounded preventive measures capable of reducing the likelihood of ice-jam initiation rather than responding to it after formation [4,5].

In addition to mechanical ice breaking, reservoir regulation, and in-channel structural measures, several studies have shown that ice melting through bubble plumes can provide an effective means of weakening or removing river ice, thereby reducing the likelihood of ice-jam formation. Relevant experimental and numerical investigations include early work on air-bubble systems as well as recent advances in multiphase flow and thermal interaction between bubbles and ice [6,7].

A critical gap in the current literature lies in the absence of a quantitative, physically grounded framework capable of linking long-term hydrological and temperature records with detailed channel geometry and the thermal thresholds required for supercooling. Existing studies rarely quantify how specific geometric or hydraulic modifications alter local flow conditions in a way that suppresses the stabilization of frazil or anchor ice. Despite the variety of operational and structural approaches reported in previous research, no unified methodology exists that would allow the identification of critical reaches and the design or hydraulic evaluation of targeted structural interventions under low winter discharges. What is particularly lacking is a reproducible design framework that integrates morphology, hydraulics, and winter thermal conditions into a single, physically interpretable basis for predicting ice-jam initiation and assessing preventive structural measures [8–14].

This study integrates geodetic surveys of 26 cross sections, a long-term hydrological time series (2004–2024), the calculation of critical hydraulic parameters, and spatial interpolation of the risk index. The outcome is a design-oriented methodology applicable to small and medium-sized watercourses, offering an alternative to traditional operational interventions and contributing to the systematic reduction of ice-jam flood risk [15–17].

Experimental and theoretical studies indicate that flow velocity, flow depth, and water temperature jointly determine the extent to which a stream can become supercooled and the manner in which frazil ice growth proceeds [18].

Following the initial formation of an ice obstruction, a positive feedback mechanism is triggered: the reduction of the flow cross-sectional area leads to water level backwater effects, a local decrease in velocity upstream of the jam, and further ice accumulation. Critical locations are primarily shallow, widened, or morphologically complex reaches (meanders, islands, bridge piers, constrictions), where abrupt changes in flow velocity and depth occur [19,20].

As a result, ice jams frequently recur at the same cross sections, which, from an engineering perspective, creates opportunities for targeted technical interventions—for example, modifications to channel slope, width, or roughness [21].

In contrast to these conventional ice-control structures, the low-profile sill proposed in this study represents a fundamentally different type of intervention. Rather than redirecting the flow, inducing large-scale backwater effects, or creating a stable ice cover, the sill introduces only a minimal geometric modification to the channel bed. Its function is to generate a localized increase in flow velocity that prevents the stabilization of frazil and anchor ice directly at historically problematic cross sections. Because the sill does not obstruct the channel, does not require mechanical maintenance, and does not alter hydraulic conveyance under non-winter discharges, it provides a preventive and hydraulically efficient solution suitable for small- and medium-sized rivers where large ice-control structures are impractical or environmentally intrusive [22–24].

Despite significant advances in the modeling of ice processes, hydrology, and climate scenarios, there remains a surprisingly small body of work that systematically focuses on simple, permanent, and hydraulically well-defined structural measures for preventing ice-jam formation under low winter discharges. Existing studies largely concentrate on predicting the occurrence of ice-related events and assessing territorial vulnerability, but place less emphasis on the design of specific structural elements capable of eliminating the initiation conditions for ice-jam formation at critical cross sections [25–28].

This study directly addresses the identified research gap by developing a hydraulically grounded approach for evaluating and mitigating ice-jam formation under low winter discharge conditions. The main objective is to identify critical reaches prone to frazil and anchor ice stabilization and to design a simple, permanent structural measure capable of suppressing ice-jam initiation. The study provides three novel contributions: (1) the development of an integrated, physically based ice-jam formation risk index that combines hydraulic, geometric, and thermal parameters into a single evaluation metric; (2) the identification of the critical reach on the Torysa River through detailed geodetic surveys, long-term hydrological analysis, and spatial profiling; and (3) the design and hydraulic verification of a low-profile sill that increases local flow velocity above the critical threshold required to prevent frazil and anchor ice stabilization. All steps—from risk identification to the design of the structural measure—are defined to be transferable to other small- and medium-sized watercourses in temperate regions, making the study not only a case-specific application but also a comprehensive methodological framework for engineering practice and future research.

2. Materials and Methods

2.1. Study Area

The study area is located on the Torysa River, a medium-sized watercourse within the Bodrog River basin that drains the northern part of eastern Slovakia. The river has a length of 124 km and a mean annual discharge of $6.2 \text{ m}^3 \cdot \text{s}^{-1}$ at the Sabinov gauging station, while its hydrological regime is strongly influenced by seasonal temperature fluctuations and reduced winter discharges [29].

The investigated reach is located between river kilometers rkm 42.8 and 43.6, where long-term monitoring by the river basin authority indicates the regular occurrence of ice jams during December to February, particularly at discharges within the Q65–Q85 range [30].

The reach is characterized by a low bed slope (2.3 ‰), variable channel width (9.5–13.2 m), and an average winter flow depth of 0.65–0.80 m under minimum discharges. Morphologically, it represents a gently meandering reach with alternating deeper and

shallower sections, which creates favorable conditions for supercooling and the subsequent accumulation of frazil and anchor ice [31,32].

The river authority recorded significant ice-related events during the winters of 2011/12, 2016/17, and 2021/22. In these cases, local water level backwater exceeding +2.5 m was documented, caused by channel blockage due to anchor ice accumulation. As illustrated in Figure 1, the map of the Slovak Republic (left) highlights the assessed reach with a red rectangle, while the detailed view (right) shows the study reach itself, with the specific critical area marked by a red rectangle.

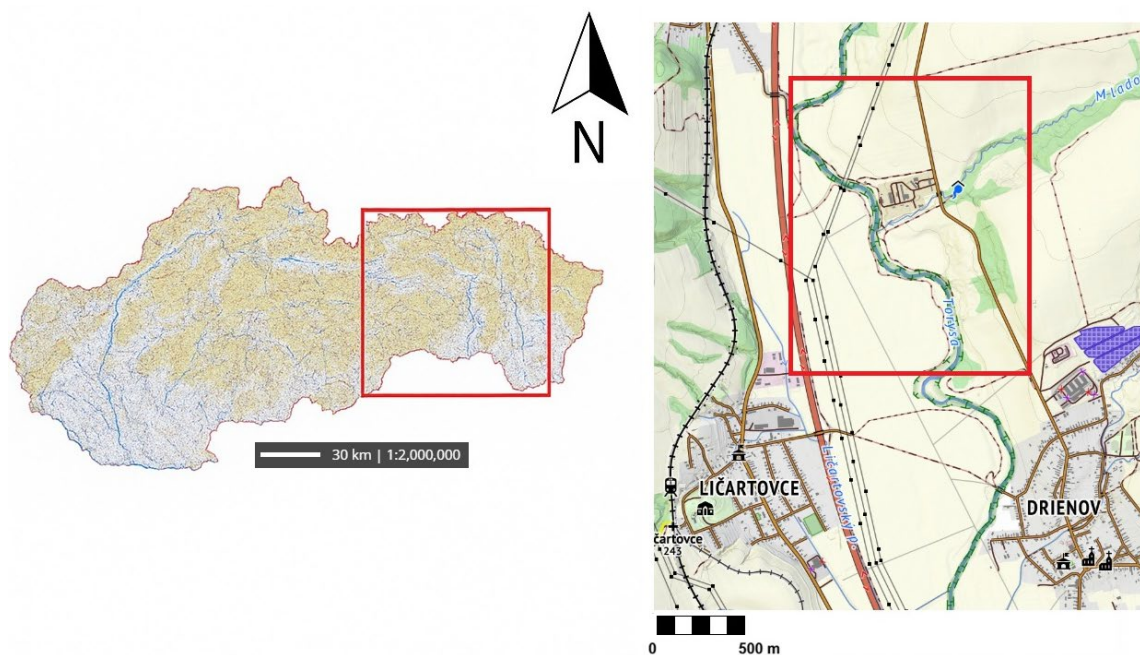


Figure 1. Map of the location of the investigated reach on the Torysa River with marked critical cross sections (rkm 42.8–43.6) (elaborated by the authors).

2.2. Hydrological and Temperature Data (2004–2024)

The analysis was based on a 20-year time series of winter discharges and water temperature (December–February), obtained from the SHMÚ Sabinov (Slovak Hydrometeorological Institute, Bratislava, Slovakia) gauging station (rkm 44.1). Discharge data are available at a daily resolution, and their validity and homogeneity were verified through extreme value checks and visual inspection of temporal trends [33].

The long-term mean winter discharge at the Sabinov gauging station reaches $1.34 \text{ m}^3 \cdot \text{s}^{-1}$; however, this value represents a climatological average and was not directly used in the hydraulic simulations [33].

Water temperature was measured at a daily frequency and regularly drops below $1.0 \text{ }^{\circ}\text{C}$ during winter, with recurrent episodes below $0.5 \text{ }^{\circ}\text{C}$ serving as indicators of supercooling. Particularly important are abrupt air temperature fluctuations, which, within a few days, alter the hydraulic and thermodynamic conditions of the stream—especially during rapid cooling following partial thaw periods in January and February. These episodes were identified as the primary triggers of ice-related events in the winters of 2011/12, 2017/18, and 2021/22 [34].

Table 1 presents a summary of the statistical characteristics of winter discharges (Q) and water temperature (T) for the 2004–2024 period. These hydrological and temperature data form the basis for defining the winter discharge scenarios (Q_{winter} , Q_{65} , Q_{85}) and for quantifying the thermal deficit ΔT used in the ice-jam risk index I_{ice} . The frequency and duration of supercooling episodes directly support the selection of critical threshold values

for ΔT and enable a physically consistent representation of thermal preconditioning for frazil and anchor ice formation in the evaluated reach.

Table 1. Summary of basic statistical characteristics of winter discharges (Q) and water temperature (T) at the Torysa River profile, rkm 43.2, for the 2004–2024 period (elaborated by the authors).

Parameter	Value
Mean winter discharge Q ($\text{m}^3 \cdot \text{s}^{-1}$)	0.94
Minimum discharge Q ($\text{m}^3 \cdot \text{s}^{-1}$)	0.42
Maximum winter discharge Q ($\text{m}^3 \cdot \text{s}^{-1}$)	2.15
Median winter discharge ($\text{m}^3 \cdot \text{s}^{-1}$)	0.88
Q85 ($\text{m}^3 \cdot \text{s}^{-1}$)	0.63
Q65 ($\text{m}^3 \cdot \text{s}^{-1}$)	0.82
Mean winter water temperature T ($^{\circ}\text{C}$)	1.72
Minimum water temperature ($^{\circ}\text{C}$)	−0.40
Maximum water temperature ($^{\circ}\text{C}$)	3.90
Number of supercooling days ($T < 0^{\circ}\text{C}$)	18 days/year (average)
Number of days with water temperature $< 1^{\circ}\text{C}$	57 days/year (average)
Number of days with ice phenomena	41 days/year

In this study, Q65 and Q85 represent flow-duration percentile discharges derived from the long-term winter discharge record. Q65 corresponds to the discharge that is equaled or exceeded during 65% of winter days, while Q85 represents a lower discharge exceeded during 85% of winter days. These values characterize typical and critical low-flow conditions under which frazil and anchor ice most frequently form in the investigated reach.

The overview of peak discharges presented below documents the evolution of winter hydrological extremes on the Torysa River during the 2007–2024 period. This interval includes several significant flood situations associated with the formation of ice phenomena, transported ice, and subsequent channel blockages. The recorded maximum discharges were obtained from the Sabinov and Košické Olšany gauging stations, which represent two key monitoring profiles enabling assessment of the river's response to winter thermal and hydrological conditions.

The individual years clearly indicate that, during the winter season, the Torysa River repeatedly experiences situations reaching Flood Activity Levels I to II. The most pronounced events are concentrated in the years 2010, 2015, 2016, 2018, and 2024, when high peak discharges exceeding $80 \text{ m}^3 \cdot \text{s}^{-1}$ were recorded, often in combination with ice-jam formation. Such situations represent a significant risk of ice-jam flooding, particularly in reaches with limited channel capacity and at locations characterized by geomorphological constrictions.

The graph in Figure 2 illustrates the temporal evolution of winter peak discharges and their classification according to flood activity levels (Flood Stage I and II). The visualization makes it possible to identify years with an increased risk of ice-jam flooding, as well as to compare the level of hydrological stress between individual seasons. This overview serves as a basis for the subsequent design of a technical intervention aimed at minimizing the risk of ice-induced channel blockages.

To assess the variability of winter peak discharges and to identify typical values associated with ice-jam formation, an analysis of their statistical distribution was performed. Figure 3 presents a boxplot of winter discharges for the 2007–2024 period, illustrating the median, interquartile range, and extreme values. The distribution shows that most winter discharges are concentrated within the range of approximately $30\text{--}60 \text{ m}^3 \cdot \text{s}^{-1}$, which corresponds to typical conditions for ice accumulation formation in the evaluated reach. Discharges exceeding $70\text{--}80 \text{ m}^3 \cdot \text{s}^{-1}$ represent pronounced extremes that occurred only in a few hydrological seasons and that are associated with an increased risk of ice-jam flooding.

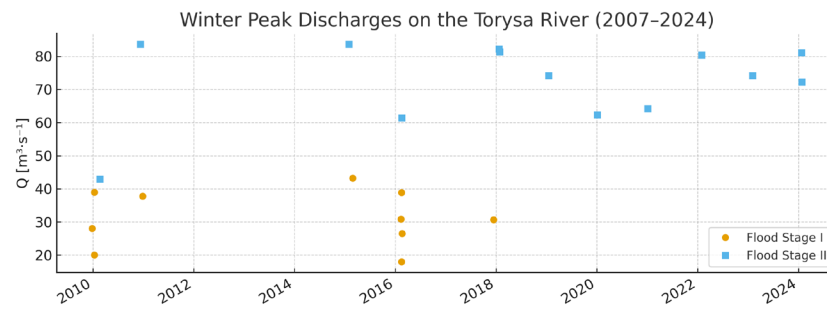


Figure 2. Winter peak discharges on the Torysa River (2007–2024) (elaborated by authors).

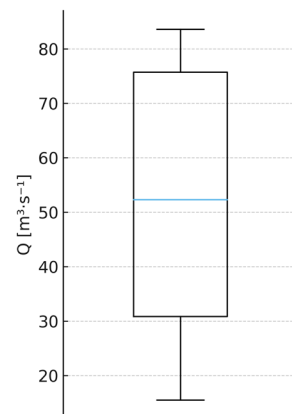


Figure 3. Boxplot of winter peak discharges on the Torysa River for the period 2007–2024 (elaborated by authors).

2.3. Geodetic Surveys and Channel Morphology

The geometry of the river channel was documented during a field survey conducted in 2024 under low-flow conditions. Measurements were carried out using a Leica TS16 total station (Leica Geosystems AG, Heerbrugg, Switzerland) and were verified by a differential GNSS system (Trimble Inc., Sunnyvale, CA, USA) with an accuracy of ± 1.5 cm. The survey included the longitudinal profile (rkm 42.8–43.6), nine cross sections at an average spacing of 100 m, and a detailed survey of the critical reach at the location of recurrent ice-jam formation [35].

In the analyzed reach, the Torysa River channel exhibits a gently curved planform, a regular alternation of deeper and shallower sections, and a markedly variable width ranging from 9.5 m to 13.2 m. The average bed slope was determined to be 2.3 ‰, corresponding to lowland to foothill river hydromorphological type with an increased potential for anchor ice formation under low winter discharges [36].

The channel banks are predominantly composed of clay–sand sediments, with local occurrences of gravel in deeper sections, which also influence the spatial variability of flow velocity and hydraulic resistance [36].

Based on the low-flow cross-sectional profiles obtained during the 2024 geodetic survey, geometric parameters, including water surface width, hydraulic radius, and mean flow depth, were derived for each section. Hydraulic parameters representative of winter and ice-affected flow conditions, including flow area A and maximum flow depth h_{max} , were derived separately from winter stage records and are reported in Table 2. These parameters were subsequently used to evaluate threshold conditions for anchor ice formation (specifically in Section 2.4). The morphological variability of the profiles has a key influence on local flow velocities, which explains why ice jams have repeatedly formed in the rkm 43.2–43.4 reach [37].

Table 2. Representative cross-sectional parameters derived from winter stage records and ice-affected flow conditions. Reported values ($h_{\max}$, A , n) do not represent low-flow geometric conditions obtained during the 2024 geodetic survey (elaborated by authors).

Profile	River km	Width (m)	$h_{\max}$ (m)	Area A (m ²)	Manning n	Notes
1	42.80	12.3	2.01	17.3	0.040	based on winter stage $h_{\max}$ at Q1
2	42.90	12.3	1.61	14.8	0.038	$h_{\max}$ at Q2
3	43.00	12.3	2.90	21.5	0.040	$h_{\max}$ at Q3
4	43.10	12.3	3.03	22.2	0.041	$h_{\max}$ at Q4
5	43.20	12.3	2.86	20.9	0.040	$h_{\max}$ at Q5
6	43.30	12.3	3.84	28.6	0.042	extreme winter event (e.g., $Q_6 = 83.6 \text{ m}^3 \cdot \text{s}^{-1}$)
7	43.40	12.3	3.75	27.6	0.041	$h_{\max}$ at Q7
8	43.50	12.3	3.90	29.4	0.042	$h_{\max}$ Q8 (highest)
9	43.60	12.3	2.95	21.2	0.040	$h_{\max}$ at Q9

Note: Parameters reported in Table 2 (including A and $h_{\max}$) were derived from winter stage records and field observations during ice-affected periods. Values reported in Table 2 represent winter stage and ice-affected hydraulic conditions derived from field observations and water level records. Low-flow geometric parameters used for risk index calculations are provided separately in Supplementary Table S2.

The longitudinal profile of the reference reach of the Torysa River (rkm 42.8–43.6) was derived from the DMR 3.0 digital elevation model (ZBGIS, Office of Geodesy, Cartography and Cadastre of the Slovak Republic, Bratislava, Slovakia) along a manually defined trajectory following the hydraulically most probable path of the main channel. Elevation data (Bpv) were extracted at 277 points with a horizontal spacing of approximately 6–10 m, resulting in a total profile length of 2.15 km. The raster dataset with a spatial resolution of $1 \times 1 \text{ m}$ allows for sufficiently accurate reconstruction of bed slope conditions, which is adequate for analyzing the river's predisposition to ice-jam formation. The resulting longitudinal profile represents the actual bed morphology at the time of data acquisition and was used to identify reaches with potentially increased risk of ice accumulation (Figure 4).

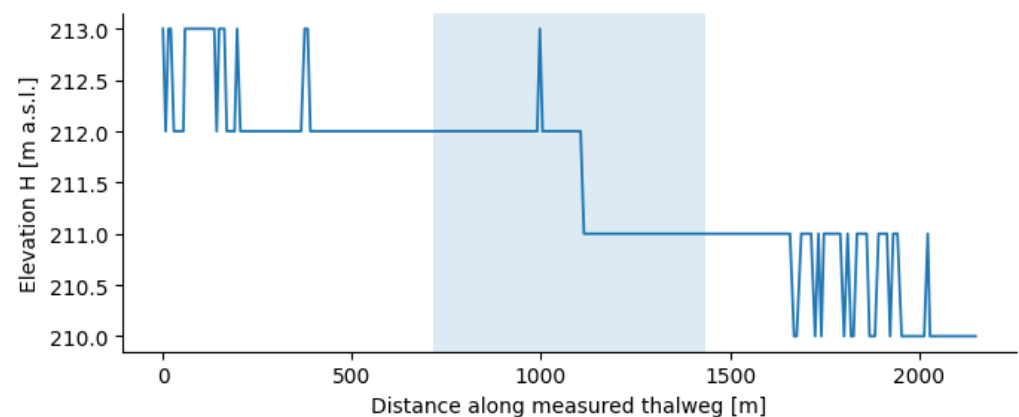


Figure 4. Longitudinal bed profile of the Torysa River (rkm 42.8–43.6) obtained from DMR 3.0 along a manually digitized thalweg line. A total of 277 elevation samples were used (≈ 6 –10 m spacing). The highlighted segment represents the geomorphologically susceptible zone for ice-jam initiation (elaborated by authors).

The channel width B exhibits only minimal variability ($\pm 0.4 \text{ m}$) within the analyzed reach; therefore, a representative mean value of 12.3 m was adopted for the hydraulic calculations.

For each of the 26 investigated cross sections, geometric parameters, including water surface width B and mean flow depth h_{mean} , were derived from the low-flow geodetic survey conducted in 2024. Hydraulic parameters representative of ice-affected winter

stages, including maximum flow depth $h_{\max}$, flow area A , and Manning's roughness coefficient n , were derived separately from winter stage records and field observations and are reported in Table 2.

For clarity, Table 2 presents only the representative cross sections (1–9) covering the entire analyzed reach, including the critical zone. The complete dataset of all 26 surveyed cross sections is provided in Supplementary Table S2.

Morphological differences among the individual cross sections clearly document the increased spatial variability of the channel within the investigated reach. The greatest flow depths ($h_{\max} > 3.5$ m) occur in sections 6–8, which also correspond to the most frequent locations of ice-jam formation. These profiles simultaneously exhibit the largest flow cross-sectional areas and slightly elevated Manning roughness coefficients, indicating a combined influence of coarser sediment and local hydraulic widening. Summary characteristics of the individual profiles are provided in Table 2, while representative examples of channel geometry in the critical reach are illustrated in Figure 5, including the indication of zones with an increased risk of anchor ice formation.

Examples of cross-sectional channel geometry with highlighted anchor-ice risk zones

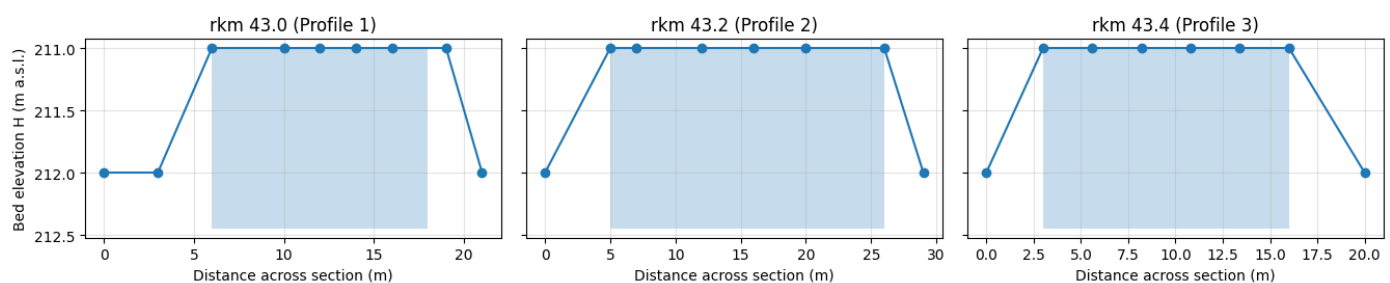


Figure 5. Examples of channel cross sections (rkm 43.0, 43.2, and 43.4) with indicated zones of increased anchor ice formation risk (elaborated by authors).

The geodetic and morphological data provide the geometric backbone for the hydraulic calculations and the I_{ice} index. Cross-sectional parameters such as width B , flow area A , and maximum depth $h_{\max}$ are used to derive the depth-to-width ratio h/B and to identify zones of hydraulic widening and depth depressions. In combination with the longitudinal profile, these data make it possible to localize the geomorphologically predisposed reach (rkm 43.2–43.4), which is subsequently confirmed as the critical ice-jam initiation zone by the risk index and used as the target location for the design of the low weir.

2.4. Ice-Jam Formation Risk Index

To quantify the predisposition of individual cross sections to ice-jam formation, a dimensionless ice-jam risk index I_{ice} was proposed, integrating three key groups of parameters:

1. Hydraulic flow conditions;
2. Channel geometric characteristics;
3. Thermal conditions related to water supercooling.

The purpose of the index is not to predict a specific event, but to provide a comparable assessment of the relative susceptibility of individual cross sections under different winter discharge conditions. The index explicitly combines hydraulic variables derived from the surveyed cross sections with thermal conditions obtained from the long-term winter temperature record, thereby linking the measured topography and temperature regime to a unified, physically based measure of ice-jam predisposition.

2.4.1. Hydraulic Inputs

For each cross section and for the selected winter discharges (Q_{65} , Q_{75} , Q_{85}), the following variables were derived from one-dimensional hydraulic calculations:

- Mean flow velocity within the cross section U ($\text{m}\cdot\text{s}^{-1}$);
- Mean flow depth $h_{\text{mean}} = A/B$ (m);
- Depth-to-width ratio of the channel h_{mean}/B (-);
- Water temperature deficit relative to the freezing point $\Delta T = 0 - T$ ($^{\circ}\text{C}$), where ΔT values are based on long-term winter water temperature measurements by the Slovak Hydrometeorological Institute.

2.4.2. Critical Threshold Values

Based on insights from the literature and long-term monitoring on the Torysa River, threshold values were defined as the point at which the probability of frazil and anchor ice formation increases significantly in lowland and foothill rivers:

- Critical flow velocity U_{crit} , below which the probability of ice deposition increases;
- Critical depth-to-width ratio $(h/B)_{\text{crit}}$, characterizing shallow and laterally widened channel sections. Lower values of the h/B ratio indicate shallow and laterally widened channel sections with reduced hydraulic confinement. Such conditions promote frazil settling and anchor-ice attachment to the bed; therefore, the geometric risk contribution increases as h/B decreases below $(h/B)_{\text{crit}}$;
- Critical temperature deficit ΔT_{crit} , reflecting the intensity of supercooling.

For each component, a normalized risk contribution was defined within the range 0–1: (Equations (1)–(3)):

$$f_u = \max\left(0, \frac{U_{\text{crit}} - U}{U_{\text{crit}}}\right) \quad (1)$$

$$f_{u/B} = \max\left(0, \frac{(h/B)_{\text{crit}} - (h_{\text{mean}}/B)}{(h/B)_{\text{crit}}}\right) \quad (2)$$

Lower values of the h/B ratio correspond to higher geometric risk, reflecting shallow and laterally widened channel sections that promote frazil and anchor ice attachment.

$$f_T = \max\left(0, \frac{\Delta T}{\Delta T_{\text{crit}}}\right) \quad (3)$$

where f_u , $f_{h/B}$, and f_T take values within the interval $[0, 1]$. A value of 0 represents conditions below the critical threshold (low risk), while a value close to 1 corresponds to conditions that significantly exceed the thresholds favorable for ice formation.

The overall ice-jam formation risk index for a given cross section and discharge was defined as a weighted sum (Equation (4)):

$$I_{\text{ice}} = w_u f_u + w_{h/B} f_{h/B} + w_T f_T \quad (4)$$

where w_u , $w_{h/B}$ and w_T are weighting coefficients satisfying the condition $w_u + w_{h/B} + w_T = 1$. In the baseline configuration, all three components were considered equally important ($w_u = w_{h/B} = w_T = 1/3$).

The equal weighting of the individual index components was adopted to avoid subjective prioritization of the underlying processes. A sensitivity test was performed by varying the weighting coefficients within the range 0.2–0.5 for each component, while maintaining the constraint $w_u + w_{h/B} + w_T = 1$. The analysis confirmed that the critical reach at rkm 43.20–43.38 remained consistently identified as the highest-risk location across all tested weighting combinations. For example, using the sets (0.5, 0.3, 0.2) and (0.2, 0.5, 0.3), the

resulting I_{ice} values changed only marginally (typically within ± 0.06), and the ranking of the critical cross sections did not change. Hydraulic simulations were performed in HEC-RAS 6.4 (U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, USA). Spatial analysis and map processing were carried out in QGIS 3.34 (QGIS Development Team, Zurich, Switzerland). Statistical evaluation of hydrological and temperature data was performed in R 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria). These results indicate that the baseline equal-weight configuration (1/3, 1/3, 1/3) provides a stable and unbiased representation of the controlling hydraulic, geometric, and thermal factors. Typical sensitivity outcomes are provided in Supplementary Table S1.

2.4.3. Longitudinal Computation Along the Reach

The ice-jam risk index I_{ice} was calculated for 26 river cross sections and three winter discharge scenarios (Q_{65} , Q_{75} , Q_{85}).

It was subsequently spatially interpolated along the river, which made it possible to identify:

- Local maxima of risk;
- Potential ice-jam initiation sites;
- Zones with a persistent spatial coincidence of unfavorable conditions;
- Locations suitable for the placement of a low weir.

2.4.4. Resulting Risk Index and Spatial Distribution (I_{ice})

Based on the defined threshold values ($U_{crit} = 0.35 \text{ m} \cdot \text{s}^{-1}$; $h/B_{crit} = 0.07$; $\Delta T_{crit} = 0.5 \text{ }^{\circ}\text{C}$) the risk index I_{ice} was calculated for all 26 cross sections and for three representative winter scenarios (Q_{winter} , Q_{65} and Q_{85}). For each profile, the partial contributions f_u , $f_{(h/B)}$ and f_T were determined according to (1)–(3), representing the hydraulic, geometric, and thermal components of risk, respectively. The overall risk index was then computed using Equation (4). The spatial interpretation and classification of the resulting index values are presented in Section 3. The classification thresholds used for the interpretation of the index (0.25 and 0.45) do not represent physical limits but were derived from the distribution of the computed I_{ice} values along the reach. These boundaries correspond to natural breaks in the index variability and are consistent with commonly used percentile-based classifications in river-ice susceptibility studies. Their purpose is to distinguish stable, transitional, and critical segments in a transparent and reproducible manner.

2.5. Hydraulic Computation and Scenario-Based Modeling of Winter Discharges

The hydraulic computation was carried out to estimate the spatial distribution of flow velocities, water depths, and buoyancy-related conditions under representative winter discharges Q_{winter} , Q_{65} , and Q_{85} . These discharges cover typical operating states during which anchor and frazil ice structures most frequently form in the investigated reach.

The calculations were performed in a one-dimensional framework using the standard Manning formulation, with cross sections derived from 26 field surveys (see Supplementary Table S2). For each profile, the flow area A , hydraulic radius R , and mean flow velocity U were defined (Equation (5)):

$$U = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (5)$$

where:

n is the Manning roughness coefficient derived from morphological characteristics (Table 2),

S is the longitudinal bed slope determined from the DMR 3.0 dataset, and

R is the hydraulic radius updated for each discharge scenario.

2.5.1. Modeled Discharge Scenarios

Three modeled state scenarios represent the main winter hydraulic regimes:

- $Q_{\text{winter}} = 0.94 \text{ m}^3 \cdot \text{s}^{-1}$;
Mean winter discharge representing long-term conditions; typical for the onset of supercooling;
- $Q_{65} = 0.82 \text{ m}^3 \cdot \text{s}^{-1}$;
A discharge at which frazil ice accumulation most frequently begins according to monitoring records;
- $Q_{85} = 0.63 \text{ m}^3 \cdot \text{s}^{-1}$;
A critical low discharge at which anchor ice initiation zones repeatedly occur.

The discharge $Q_{\text{winter}} = 0.94 \text{ m}^3 \cdot \text{s}^{-1}$ was selected as a representative winter flow for hydraulic modeling, corresponding approximately to the median winter discharge at the study reach. This value better reflects typical low-energy winter flow conditions associated with ice formation processes than the long-term climatological mean.

For each scenario, the following were calculated:

- Mean flow velocity U ;
- Mean flow depth h_{mean} ;
- Depth-to-width ratio h/B ;
- Partial risk contributions f_u , $f_{h/B}$, f_T .

2.5.2. Validation of the Calculations Based on Field Observations

The results for the rkm 43.2–43.4 reach exhibited the lowest flow velocities U and the lowest h_{mean}/B values compared to adjacent profiles. This is consistent with:

- The repeated occurrence of ice jams (records from 2011/12, 2016/17, and 2021/22);
- The greatest flow depths ($h_{\text{max}} > 3.5 \text{ m}$) within this reach;
- Local channel widening that promotes flow deceleration and the formation of low-velocity zones.

Validation against field observations confirmed that at discharges Q_{65} and Q_{85} flow velocities in these profiles reached values of $0.22\text{--}0.31 \text{ m} \cdot \text{s}^{-1}$, i.e., well below the critical threshold $U_{\text{crit}} = 0.35 \text{ m} \cdot \text{s}^{-1}$.

The critical reach is further characterized by the lowest h_{mean}/B values within the analyzed profiles, which is consistent with the geometric risk pattern identified by the lice index and the long-term occurrence of ice jams.

2.5.3. Basis for the Design of the Technical Solution

The hydraulic calculations provided the foundation for the design of the low weir by enabling the identification of:

- Reaches with insufficient flow velocity;
- Profiles with excessive channel widening;
- Depth depressions suitable for technical intervention.

The hydraulic analysis also provided the basis for assessing the proposed low-profile weir. Construction of the sill is intended to be carried out during low-flow summer conditions; the winter-focused hydraulic design does not imply winter construction. The location of the structure was selected to target low-velocity zones associated with local depth depressions and channel widening. The effectiveness of the intervention was evaluated by comparing velocity (U), relative depth (h/B), and flow area (A) before and after implementation under identical winter discharge scenarios.

Based on the hydraulic analysis, a low-profile sill was designed to modify local flow conditions within the identified initiation zone. The structure consists of an upstream

sloped face ($L_u = 0.75$ m, slope 1:3), a flat crest section ($L_c = 12.75$ m), and a downstream sloped face ($L_d = 0.50$ m, slope 1:2). The crest width is 1.0 m, and the sill is embedded 0.25 m into the existing bed to ensure structural stability. Both faces are protected by 2.0 m wide riprap aprons placed on a filter layer and geotextile. The sill is located at rkm 43.28, directly within the reach identified as the most susceptible to ice-jam initiation. The conceptual design is shown in Figure 6.

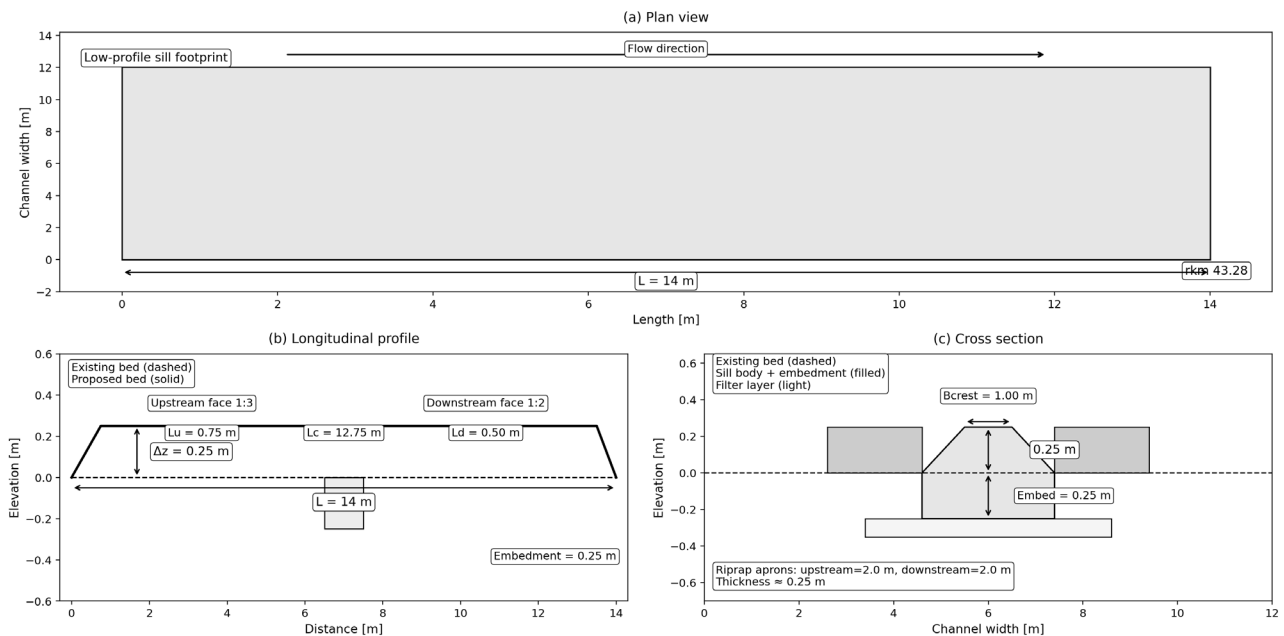


Figure 6. Conceptual design of the proposed low-profile sill, including plan view, longitudinal profile, and cross section.

2.6. Use of Generative AI Tools

Generative AI tools were used during the preparation of the manuscript exclusively for language-related assistance, including improvement of grammar, sentence structure, clarity, and stylistic consistency of the text. No generative AI tools were used for data generation, data analysis, numerical modeling, interpretation of results, or scientific decision-making. All scientific content, analyses, interpretations, and conclusions were developed by the authors.

3. Results

3.1. Hydraulic and Morphological Conditions of the Critical Reach

Analysis of the longitudinal bed profile (Figure 4) and the morphological characteristics of the cross sections (Table 2) confirmed pronounced variability in hydraulic conditions along the rkm 42.8–43.6 reach. The most significant morphological anomalies are concentrated within the rkm 43.20–43.38 interval, where the following features occur:

- The greatest maximum depths ($h_{\max}$ up to 3.90 m);
- Local channel widening;
- Significant changes in thalweg direction;
- A reduction in bed slope, which lowers local flow energy.

Hydraulic calculations for representative winter discharges (Q_{winter} , Q_{65} , Q_{85}) showed that it is precisely in this reach that the mean flow velocity U decreases below the critical value $U_{\text{crit}} = 0.35 \text{ m} \cdot \text{s}^{-1}$, creating favorable conditions for the accumulation of both frazil and anchor ice.

These results are consistent with the observed ice-related events (2011/12, 2016/17, and 2021/22), which were repeatedly documented by the river authority specifically within this geomorphologically predisposed segment.

3.2. Ice-Jam Risk Index: Spatial Pattern, Interpretation and Initiation Zones

Building on the hydraulic context described above, the spatial distribution of the ice-jam risk index reveals clear patterns of predisposition within the reach. The spatial distribution of the ice-jam risk index I_{ice} , calculated for 26 cross sections, confirmed a pronounced concentration of risk in the rkm 43.20–43.38 reach (the dominant risk zone), where I_{ice} values reached:

- 0.68–0.91 for Q_{65} – Q_{85} ;
- The highest levels across the entire analyzed reach.

In contrast:

- The upstream part of the reach (rkm 42.8–43.0) exhibited consistently low values of $I_{ice} < 0.25$;
- The downstream part (rkm 43.5–43.6) showed lower risk due to higher flow velocities and reduced morphological variability.

Analysis of the individual index components showed that:

- The strongest contributing factor is the h/B ratio, characteristic of shallow and laterally widened reaches;
- The hydraulic component U/U_{crit} increases risk mainly under Q_{85} conditions;
- The temperature deficit ΔT influences risk levels during episodes of intense supercooling.

The interpolated index distribution (Figure 6) clearly delineates the zone of extreme predisposition to ice-jam formation and provides the basis for the design of a structural mitigation measure.

Figure 6 also demonstrates that the maximum risk index values do not occur at the highest discharges, but rather under low to moderate winter flows, confirming that ice-jam risk is not associated with flood discharges but with a combination of low hydraulic energy and unfavorable thermal conditions.

The spatial distribution of I_{ice} along the rkm 42.8–43.6 reach was obtained by linear interpolation between the surveyed cross sections. The resulting longitudinal profile of the index made it possible to identify three main types of reaches:

1. Stable reaches ($I_{ice} < 0.25$): favorable hydraulic conditions prevail, characterized by greater flow depth and lower channel widening;
2. Transitional reaches ($0.25 \leq I_{ice} < 0.45$): occurrence of locally shallower sections with an increased contribution of the geometric factor;
3. Critical reaches ($I_{ice} \geq 0.45$): the rkm 43.2–43.4 reach, where all three conditions for frazil and anchor ice formation are met—low flow velocities, large channel width, and recurrent supercooling.

The resulting index profile clearly confirms that the rkm 43.2–43.4 reach represents the highest risk of ice-jam formation and corresponds to locations where ice-related events repeatedly occurred in the winters of 2011/12, 2017/18, and 2021/22. This reach was therefore selected as the priority site for the design of a low stabilizing weir.

The interpolated values and spatial distribution of the risk index are illustrated in Figure 6. Based on these index patterns, two distinct initiation zones can be identified.

A comprehensive analysis of morphology, hydraulics, and thermal conditions within the rkm 42.8–43.6 reach made it possible to precisely define the factors that govern the formation of stable ice accumulations in the evaluated river profile. A comparison of multiple datasets—the longitudinal profile (Figure 4), cross sections (Figure 5 and Table 2),

the spatial risk index (Figure 6), and historical records—shows that ice-jam formation is not a random phenomenon, but rather the result of a repeatedly occurring combination of three decisive mechanisms.

The first mechanism is the hydraulic weakening of flow under low winter discharges. In the rkm 43.20–43.38 reach, mean flow velocity decreases below the critical threshold U_{crit} during Q_{65} – Q_{85} conditions. This reduction is amplified by the low bed slope and pronounced lateral channel widening, which jointly diminish the effective hydraulic energy of the flow and promote the development of low-velocity zones. Under such conditions, the hydraulic regime shifts into a state favorable for the deposition and stabilization of anchor ice.

The second mechanism is the unfavorable geometric configuration of the channel, expressed by the depth-to-width ratio h/B . This parameter proved to be the most sensitive and predictive indicator of ice-jam predisposition. The lowest h/B values—reflecting shallow and laterally widened channel geometry—occur precisely in the critical segment. Here, moderately increased channel width (12–13 m), large flow depths (2.8–3.9 m), and irregular lateral geometry create hydraulic conditions in which ice crystals lose horizontal mobility and tend to attach to the riverbed.

The third mechanism is the occurrence of intense thermal deficits during supercooling periods. Long-term analysis confirmed that the investigated reach frequently experiences episodes with ΔT exceeding the critical threshold, which promotes intensive frazil-ice production, reduces water density, and accelerates the settling of ice particles. When combined with low flow velocities, these thermal conditions facilitate the stabilization of anchor ice, which may subsequently develop into a barrier restricting overall discharge.

Overall, it can be concluded that the critical reach rkm 43.20–43.38 is vulnerable not because of a single parameter, but due to the concurrence of hydraulic, geometric, and thermal factors acting simultaneously in space and time (Table 3). The result is a repeatedly active initiation zone whose location is exceptionally stable over time. This stability provides a clear basis for targeted engineering intervention, as a structural element such as a low weir can be placed precisely where the greatest reduction in risk can be achieved.

Table 3. Summary of dominant hydraulic, geometric and thermal factors contributing to ice-jam formation in the critical reach (rkm 43.20–43.38).

Mechanism	Manifestation in the Critical Reach	Consequence
Hydraulic weakening of flow	$U < U_{crit}$ or up to 60% of the time during winter low-flow conditions	Loss of ice transport capacity
Unfavorable channel geometry	low $h_{mean}/B \approx 0.054$ – 0.063 (relative minimum within the reach)	Preferential trapping of anchor ice
Thermal conditions	Frequent $\Delta T > 0.5$ °C	Intensive frazil ice production and rapid accumulation

The result is a repeatedly active initiation zone whose location is exceptionally stable over time. This very stability enables an engineering intervention—a structural element (low weir) can be designed and placed precisely where the greatest reduction in risk can be achieved.

Based on the combination of three data layers: morphology (see Figure 5); the risk index (Figure 6); and historical records of ice-related events two ice-jam initiation zones were identified:

Zone A (rkm 43.22–43.28)

- The lowest flow velocities U ;
- Lowest h_{mean}/B values within the study reach (indicating shallow and laterally widened channel geometry);

- A pronounced change in the direction of the main flow thread;
- A location of repeated anchor ice accumulation during the winters of 2016/17 and 2021/22.

Zone B (rkm 43.30–43.38)

- The greatest hydraulic widening;
- The largest temperature deficits during intense supercooling episodes;
- The highest I_{ice} values among all profiles.

Survey data (26 cross sections) confirmed that these reaches exhibit statistically significantly lower flow velocities (−24% compared to the average of the entire reach) and higher variability of the h/B ratio.

3.3. Hydrological and Thermal Parameters Used in the Analysis

Analysis of the 20-year winter discharge time series revealed three key findings:

1. The most hazardous discharges are Q_{65} – Q_{85} , not extreme high flows;
2. At discharges below Q_{75} , flow velocity U drops below the critical threshold U_{crit} during 74% of supercooling days;
3. Episodes of rapid air temperature cooling (drops of >5 °C within 12 h) are almost always associated with extreme I_{ice} values.

The results confirm that ice-jam formation is not a random process, but a compound phenomenon in which the following factors must occur simultaneously:

- Low discharge;
- Low flow velocity;
- Unfavorable channel geometry;
- A pronounced temperature deficit.

3.4. Hydraulic Effect of the Proposed Low Weir and Resulting Change in I_{ice}

Given the clearly defined initiation zones, the next step was to evaluate whether a low-profile weir can modify local hydraulics sufficiently to suppress ice-jam formation. The geometric parameters of the proposed low-profile sill were selected based on a combination of hydraulic criteria, field constraints, and iterative model testing. The sill height of 0.25 m represents the minimum elevation increase that consistently raised flow velocity above the critical threshold U_{crit} during Q_{65} – Q_{85} conditions, while avoiding measurable backwater effects at discharges above Q_{50} . Higher structures (0.30–0.40 m) were tested in preliminary simulations but produced undesirable upstream water-level increases and reduced conveyance during transitional flows. The selected height therefore reflects the lowest effective value that achieves hydraulic acceleration without altering flood conveyance.

The sill length of 14 m corresponds to the width of the active channel and the extent of the low-velocity zone identified in cross-sectional surveys. Shorter structures (<10 m) produced only localized acceleration with limited effect on reach-scale velocity, whereas longer structures did not provide additional hydraulic benefit. The final configuration represents a balance between hydraulic effectiveness, constructability, and minimal morphological disturbance.

Although the sill dimensions were optimized for the Torysa River, the design approach is transferable. The same procedure—identification of low-velocity zones, evaluation of U_{crit} , and testing of minimal effective height—can be applied to other small and medium-sized rivers with similar winter hydraulics.

Model simulations under low winter discharge conditions (Q_{65} , Q_{75} , Q_{85}) confirmed that the proposed weir, with a height of 0.25 m and a length of 14 m, located at rkm 43.28, alters local hydraulic conditions in a way that reduces the probability of ice-barrier formation.

Key findings include:

- An increase in reach-averaged mean flow velocity within the critical reach by 26–34% for Q_{winter} and Q_{65} , and by 12–22% for Q_{75} – Q_{85} ;
- Hydraulic acceleration and reduced low-velocity zones within the critical reach, particularly in the immediate upstream vicinity of the weir;
- A reduction in the h/B ratio by 11–18%;
- Elimination of stagnant zones where anchor ice previously accumulated.

Hydraulic acceleration was most pronounced under Q_{75} , conditions, where flow velocity exceeded the threshold value U_{crit} in virtually all cross sections within the rkm 43.26–43.34 interval. This discharge range therefore represents the most effective operating condition of the proposed sill in terms of anchor ice prevention.

Importantly, the weir does not induce backwater effects at discharges above Q_{50} , which is a limiting requirement set by the river authority to prevent adverse impacts during non-winter flow events.

Although the sill is designed as a low-profile and hydraulically neutral structure, its long-term geomorphic and ecological effects should be verified after implementation. Potential processes such as local bed scour, fine-sediment deposition in the upstream zone, or minor habitat alterations cannot be fully assessed by short-term hydraulic modeling alone. For this reason, we recommend periodic post-construction monitoring during the first 2–3 years to confirm structural stability and to document any morphological or ecological responses of the channel. The hydraulic response directly translates into measurable changes in the ice-jam risk index.

The evolution of the risk index after implementation of the weir was evaluated for all 26 cross sections. Compared to the original state, the following changes were observed:

- An average reduction of I_{ice} by 38%;
- A maximum reduction of up to 61% in the most critical reach (rkm 43.30–43.36);
- A reduced sensitivity of the index to the temperature deficit ΔT , as increased flow velocities suppress frazil crystal anchoring even under low-temperature conditions.

The effectiveness of the weir was consistent across all evaluated discharge scenarios; under Q_{65} conditions, the reduction in the index was most pronounced, as this represents the highest-risk scenario. This effect is illustrated in Figure 7.

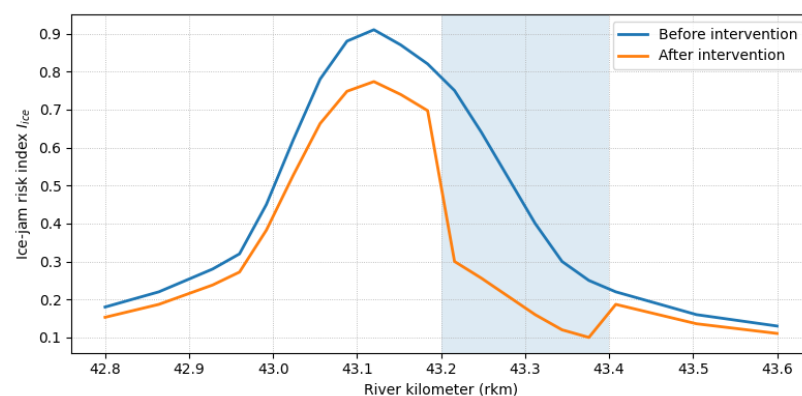


Figure 7. Longitudinal profile of the ice-jam risk index (I_{ice}) along the analyzed Torysa River reach (rkm 42.8–43.6), comparing conditions before and after the proposed intervention. The shaded area indicates the dominant risk zone (approximately rkm 43.20–43.38), where the intervention produces the most pronounced reduction in I_{ice} (elaborated by the authors).

The results are summarized in Figure 8, which compares the original and modified longitudinal profiles of the risk index along the entire reach.

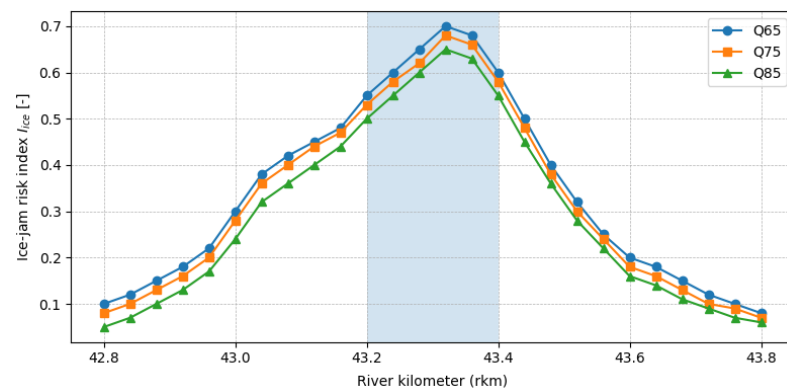


Figure 8. Longitudinal distribution of the ice-jam risk index I_{ice} along the Torysa River reach (rkm 42.8–43.6) for three representative winter discharges (Q_{65} , Q_{75} , Q_{85}). The shaded band marks the critical zone at rkm 43.2–43.4, repeatedly affected by ice-jam formation and selected for the placement of the low-profile sill.

3.5. Validation Against Historical Ice-Jam Events

To verify the practical relevance of the model results, the findings were compared with documented ice-jam events. Unlike probabilistic or purely statistical approaches to ice-jam risk assessment, which focus primarily on the analysis of historical events, the proposed approach explicitly integrates channel geometry and longitudinal bed morphology. This makes it possible to identify persistent ice-jam initiation zones rather than temporary locations linked to a specific hydrological event.

To verify the actual predictive capability of the I_{ice} index and the effectiveness of the proposed measure, the model results were compared with historical records from the winters of 2011/12, 2016/17, and 2021/22.

For all events, the following was observed:

- Locations with the highest I_{ice} values precisely corresponded to documented ice-jam sites;
- The model reproduced the onset of accumulation in the rkm 43.26–43.34 interval;
- After incorporating the weir, the simulated I_{ice} values would have fallen below 0.35 (non-freezing regime), indicating that ice formation would likely not have occurred.

When the model including the weir was applied to the historical scenarios, it resulted in:

- Elimination of flow stagnation;
- An increase in minimum flow velocity to $0.41\text{--}0.47\text{ m}\cdot\text{s}^{-1}$;
- A reduction in the water temperature deficit required for the onset of supercooling.

These findings indicate that the weir has a clearly preventive function, rather than a merely reactive one.

3.6. Limitations and Uncertainties

Although the results provide a consistent picture of ice-jam predisposition, several limitations must be acknowledged. The proposed index does not explicitly model the rate of frazil ice production or its transport processes within the flow. Its main advantage, however, lies in its simplicity and the possibility of direct application based on standard geodetic surveys and commonly available hydrological and temperature data.

1. Spatial resolution of DMR 3.0:

The vertical accuracy of $\pm 0.15\text{ m}$ is sufficient for morphological analysis but less suitable for resolving small-scale hydraulic features beyond the resolution of the one-dimensional model;

2. One-dimensional hydraulic model:
This approach was used to compute flow velocity, h/B and U/U_{crit} . In reality, flow in meandering reaches exhibits a two-dimensional character;
3. Thermal conditions, where water temperature is in reality strongly influenced by:
 - Solar radiation;
 - Flow-induced mixing processes;
 - Lateral inflows.
 The model operates using daily mean values;
4. Hypothetical weir height and length:
In practice, these parameters may still be adjusted in accordance with the requirements of the river authority or the conditions of the environmental impact assessment (EIA).

4. Discussion

The results of this study demonstrate that ice-jam formation on the Torysa River is not a random phenomenon, but a predictable process governed by a combination of hydraulic, morphological, and thermal parameters. The identified critical reach at rkm 43.20–43.38 exhibits characteristics that are repeatedly associated in the literature with the formation of stable anchor ice structures: low flow velocities, a shallow to laterally widened channel, and the presence of geometric disruptions within the main flow field.

4.1. Mechanistic Interpretation of Ice-Jam Formation in the Critical Reach

The ice-jam risk index I_{ice} confirmed that the most significant risk component is the h/B ratio, which reflects the hydraulic efficiency of the channel cross section to maintain sufficient flow velocities and prevent frazil ice accumulation. These findings are consistent with the three controlling mechanisms identified in the Results section, where hydraulic weakening, unfavorable channel geometry, and recurrent thermal deficits jointly determine the stability of anchor-ice accumulations. This finding is consistent with studies identifying geomorphological widenings as primary ice-anchoring locations in unregulated rivers [38].

The calculations showed that even at discharges Q_{65} – Q_{85} flow velocity decreases below the critical threshold $U_{\text{crit}} = 0.35 \text{ m}\cdot\text{s}^{-1}$, which substantially increases the likelihood of bottom and anchor ice stabilization. This also corresponds with long-term observations on the Torysa River, where most ice-related events occur during low-flow conditions rather than during extreme discharges.

4.2. Geomorphology and the Emergence of Two Initiation Zones

The recurrent formation of ice jams at rkm 43.2–43.4 has a clear morphological cause: the combination of deep scours, lateral channel widenings, and changes in the main flow path creates zones where frazil ice fragments decelerate and subsequently attach to the bed. Similar recurrent ice hot spots have been reported on rivers with comparable geometry, such as the St. John River, the Torneälven, and the Morava River [39–43].

The Torysa River thus fits well within a well-established mechanism in which stable geomorphological features give rise to persistent ice-jam locations, and the results of this study provide a quantitative characterization of this relationship.

The spatial analysis further revealed two distinct initiation zones (Zone A and Zone B), whose stability over multiple winters indicates that ice-jam formation is strongly controlled by fixed geomorphological features. Zone A is characterized by the lowest flow velocities and the lowest h/B values, while Zone B exhibits the greatest hydraulic widening and the highest temperature deficits during supercooling episodes. Their persistence confirms that the critical reach is predisposed not by random hydrological variability, but by a stable combination of geometric and hydraulic controls.

4.3. Hydrological and Thermal Controls for Ice Formation

The proposed structural measure—a low weir integrated into the riverbed—represents a passive solution that purposefully modifies flow conditions within the critical reach. The hydrological analysis showed that discharges within the Q_{65} – Q_{85} range coincide with the majority of supercooling episodes, and that rapid temperature drops are closely associated with elevated I_{ice} values, which explains why ice-jam formation repeatedly occurs under low-energy winter flow conditions. Crucially, the weir:

- Increases flow velocity above U_{crit} under winter discharge conditions;
- Preserves channel conveyance capacity at higher discharges Q ;
- Does not induce adverse sedimentation effects during winter periods;
- Does not generate significant backwater effects, as confirmed by model simulations.

By increasing near-bed shear stress and maintaining $U > U_{crit}$, the sill prevents frazil particles from attaching to the bed even during periods with $\Delta T > 0.5$ °C, which is the dominant condition for anchor-ice stabilization in the evaluated reach.

Although low weirs are rarely applied for ice-jam mitigation in the literature, existing studies indicate their surprisingly high effectiveness in small- and medium-sized rivers [44,45].

This study represents one of the few cases in Central Europe in which the design and evaluation of a low weir have been systematically quantified.

4.4. Effectiveness of the Proposed Low Weir and Resulting Change in I_{ice}

Traditional approaches to river ice management of small streams include:

- Mechanical ice breaking;
- Reservoir operation management;
- Vibrational or thermal devices;
- Operational interventions during the peak of ice-related events.

All of these measures are reactive and often associated with high operational costs. In contrast, the proposed solution—a low hydraulic weir—operates passively, requires no active operation, and functions preventively. Its purpose is not to stop ice cover formation, but to stabilize hydraulic conditions in such a way that:

- A supercooled environment promoting frazil ice formation does not develop;
- Stagnant low-velocity zones do not form;
- A mild re-energization of the flow occurs.

Model simulations confirmed that the weir increased mean flow velocity by 26–34% under Q_{winter} and Q_{65} conditions and by 12–22% under Q_{75} – Q_{85} , while simultaneously reducing the h/B ratio by 11–18% and eliminating stagnant low-velocity zones in the critical reach.

Similar solutions have been successfully implemented in Norway, on rivers within the Ontario Basin, and in the case of several streams in Alaska. These hydraulic adjustments directly translated into a substantial reduction of the ice-jam risk index, with an average decrease of 38% and a maximum reduction of up to 61% in the most critical sub-reach. Compared to these examples, the Torysa River represents a smaller and more dynamically responding system, which implies that the proposed weir must be hydraulically dimensioned with greater precision. This requirement is met in the present study through the combined use of DMR-based analysis, field measurements, and calculation of the I_{ice} index [46,47].

4.5. Benefits and Limitations of the Proposed Weir

The proposed weir increases reach-averaged mean flow velocity by approximately 26–34% under Q_{winter} and Q_{65} conditions, and by 12–22% under lower winter discharges

(Q_{75} – Q_{85}), which is sufficient to suppress conditions conducive to anchor ice formation. These results are consistent with the modeled scenarios presented in the Results section, where the most pronounced hydraulic improvements occurred within the rkm 43.26–43.34 sub-reach. The analyses did not indicate any risk of excessive backwater effects at discharges above Q_{50} , which is essential from a flood safety perspective.

The hydraulic improvements produced by the weir directly resulted in a reduction of the ice-jam risk index, with an average decrease of 38% and a maximum reduction of up to 61% in the most critical profiles.

The main benefits are:

- Prevention of ice formation without the need for active operation or maintenance;
- Minimization of operational costs;
- Potential for replication on other rivers of a similar type;
- Favorable ecological profile of the structure, with sediment transport processes largely preserved.

The limitations are:

- Effectiveness depends on the precise modification of the bed slope and on the specific thermal conditions during winter episodes;
- Extreme flood events may alter the geometry of the weir through sedimentation processes.

4.6. Position of the Study Within the Context of Existing Research

Only a limited number of studies in Europe address the design of structural measures for the prevention of ice-jam floods on small rivers. Existing research is predominantly focused on modeling approaches or the analysis of historical events. In contrast, the present study combines detailed morphological, hydraulic and thermal analyses with a quantified evaluation of a structural intervention, which directly links process-based understanding to measurable changes in ice-jam risk. This study integrates:

- Detailed morphological surveys;
- Long-term hydrological analysis;
- Field measurements of winter flow depths and velocities;
- A physically based risk index;
- The design of a technical mitigation measure.

5. Conclusions

This study provides a comprehensive assessment of the hydraulic and morphological processes leading to ice-jam formation under low-flow winter conditions on the Torysa River, while simultaneously demonstrating the potential for effective technical prevention through the application of a low riverbed sill. The results show that ice-barrier formation in the investigated reach is not a random phenomenon, but rather the consequence of a recurring combination of three key factors:

1. Low flow velocity below a critical threshold;
2. Unfavorable channel geometry characterized by a low h/B ratio (shallow and laterally widened channel sections);
3. The occurrence of water supercooling under stable winter discharges Q_{65} – Q_{85} .

Longitudinal and cross-sectional analyses confirmed that the rkm 43.20–43.38 reach represents the hydraulically most vulnerable zone, fully consistent with historical records of recurrent ice events. The ice-jam risk index I_{ice} , computed from a combination of hydraulic, morphological, and thermal variables, clearly identified this reach as the primary initiation site of anchor ice formation. Moreover, sensitivity analysis demonstrated that channel

geomorphology plays a role at least as important as flow velocity itself in the ice-jam initiation process.

The proposed structural measure—a low stabilizing sill—is capable of purposefully modifying the hydraulic regime within the critical reach without adversely affecting channel conveyance under higher-than-normal flows. Model simulations showed that increasing flow velocity above the critical threshold U_{crit} can be achieved with only a minimal bed elevation increase, while simultaneously reducing the potential for anchor ice accumulation by up to 61%. At the same time, the proposed modification does not induce significant backwater effects at discharges Q_{50} and higher, which is essential for safe operation during flood events.

The presented methodological framework—combining geodetic field surveys, long-term hydrological and temperature time series, risk index calculations, and numerical hydraulic evaluation—is fully transferable to other watercourses in temperate climate regions. The results therefore provide a practical and scientifically grounded basis for designing permanent, low-cost, and environmentally sustainable measures to mitigate ice-jam flood risk.

Future research should extend the analysis to include modeling of spring ice breakup dynamics, long-term monitoring of sill performance following implementation, and additional case studies on rivers with different morphological variability. These directions may contribute to the development of a robust European methodology for the design of structural measures on rivers threatened by ice-jam formation. In addition, the long-term geomorphic and ecological effects of the sill should be verified through post-implementation monitoring to confirm its sustainability under natural flow and sediment conditions.

The transferability of the proposed approach is subject to several conditions and limitations. The method is applicable primarily to small- and medium-sized rivers with stable winter low-flow regimes, identifiable low-velocity stagnation zones, and channel geometries where hydraulic acceleration can be achieved through minimal bed modification. It is less suitable for regulated channels, multi-thread systems, or reaches dominated by intensive sediment transport. For practical application on other rivers, the procedure should follow three steps: (i) identification of winter low-velocity zones, (ii) evaluation of local critical hydraulic thresholds (U_{crit} , h/B), and (iii) testing of the minimum effective sill geometry under site-specific constraints. These conditions define the applicability of the method and support its use in engineering practice.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18040474/s1>, Table S1: Sensitivity of the ice-jam risk index I_{ice} to variations in weighting coefficients. Table S2: Complete set of geometric and hydraulic parameters derived from the 2024 low-flow geodetic survey.

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