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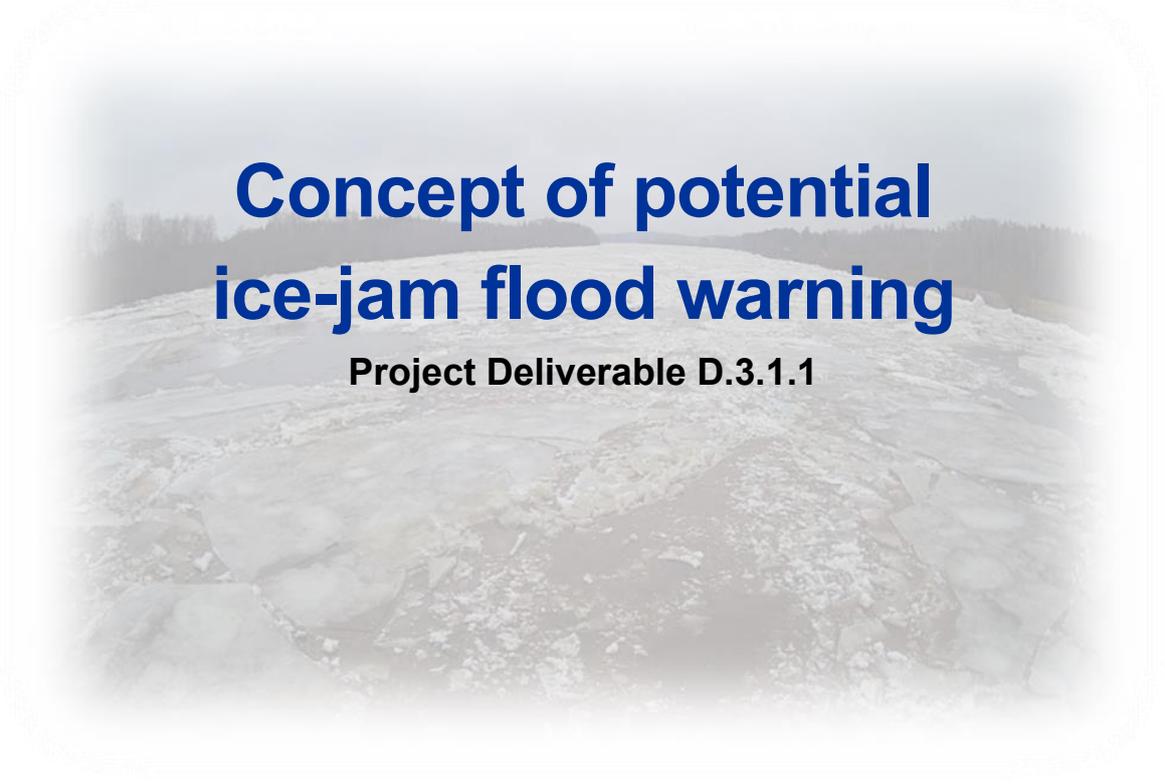


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the European Union

**Latvia – Lithuania**

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**ICEREG**

A photograph of a wide river completely frozen over with large, broken chunks of ice. The background shows a line of trees under a grey, overcast sky.

# Concept of potential ice-jam flood warning

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tarnyba

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## Abbreviations

a.s.l.	above sea level
CMIP	Coupled Model Intercomparison Project
ICEREG	Project LL-00136 “Ice-jam flood risk management in Latvian and Lithuanian regions with respect to climate change”
IJF	ice-jam flood
H	water level (m a.s.l.); $\Delta H$ – water level change
HS	hydrological station
LHMS	Lithuanian Hydrometeorological Service
MS	meteorological station
NDD	negative degree day
PDD	positive degree day
Q	water discharge (m <sup>3</sup> /sec)
SSP2-4.5	moderate climate change scenario
SSP3-7.0	significant climate change scenario
T	temperature
WGS	water gauging station

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# 1. Introduction

In the frame of the project “Ice-jam flood risk management in Latvian and Lithuanian regions with respect to climate change” (ICEREG, LL-00136) financed by the Interreg V-A Latvia–Lithuania Programme 2021–2027, the Concept of the Potential Ice-Jam Flood Warning System was developed on the basis of collected information about historical ice-jam flood events in the project pilot rivers Daugava and Lielupe (Latvia), Mūša and Levuo (Lithuania) as well as the results of the developed Conceptual model of the ice-jam formation (ICEREG project, 2025).

Ice-jams often occur during spring break-up; however, winter ice-jams are also frequent in various rivers in cold regions (De Coste *et al.* 2022). Winter ice-jams can occur during freeze-up and stable ice cover periods and are often caused by brief thaws, rain-on-snow events, and high flow conditions along the river (Beltaos 2002).

Concept of the Potential Ice-Jam Flood Warning System includes the following:

- Guidelines for the ice-jam flood forecasting, and
- Ice-jam flood early warning system.

The examination of historical ice jams information reveals potential relationships between various hydrometeorological parameters. Correlations between those parameters can be used to develop forecasting methods and issue timely warnings. Forecasting guidelines and supportive tools can be created based on this coherence.

To build effective forecasting models, it is advisable to start with the most readily available data – primarily indices indicating the likelihood of ice jam formation. When such conditions arise, special attention should be paid to on-site observations and the development of hydrometeorological conditions. This approach enhances the ability to anticipate situations and issue warnings before critical conditions occur.

Better prediction of river ice and jamming potential would improve estimates of ice-jam flood probabilities that can feed into planning, infrastructure development, and flood-control mitigation programs, ultimately reducing flooding risk. It would also help governments and water managers make more informed decisions on cost effectiveness and more strategically direct ice-cutting operations and artificial ice-cover breakup programs (Dr. Lindenschmidt *et al.* 2020).

However, accurately predicting the exact maximum water level remains challenging and uncertain.

The Concept of the Potential Ice-Jam Flood Warning System has been developed separately in Latvia and Lithuania, considering the difference between the main factors for the ice-jam formation in pilot rivers.

## 2. Ice-jam flood forecasting guidelines

The possibility to prepare guidelines for ice-jam flood forecasting is supported by the availability of high-quality historical observations of ice phenomena and other hydrometeorological parameters. Maintaining and updating such databases is essential for improving the forecasting system in the future. Historical data analysis and monitoring form the foundation for preparing forecasts and warnings.

### 2.1. Ice-jam flood forecasting guidelines for Latvian pilot rivers

Several hydrological parameters characterizing ice-jam floods were used to develop the forecasting guidelines. The maximum water level observed during ice-jams was used as the dependent variable. The main value of interest for forecasting is the maximum water level during an ice-jam.

#### 2.1.1. Hydrological monitoring

Hydrological observations, such as water level, water temperature, and the condition of the water body, are conducted daily. These observations enable timely communication with the public and responsible services and institutions about flood risks. During the cold season, monitoring the formation of ice cover at all stations is essential. Ice-jam monitoring is crucial not only at observation stations, but also along extended river stretches.

In areas where ice-jams occur frequently, seasonal observers monitor the ice regime daily. A significant support tool is the webcams (Fig. 2.1.1.1), which provide images every 10 minutes and offer the option to connect in video mode. This allows for real-time tracking of ice conditions and the ability to inform responsible services and the public promptly. Many of these webcams are equipped to capture usable images even during nighttime hours.



*Figure 2.1.1.1. Camera image, ice movement in Daugava near Zelki hydrological station*

Additional support for surveying longer river stretches includes the use of drones and satellite imagery.

### 2.1.2. Ice-jam flood forecasting tools

1. An **Excel-based tool** has been developed for the pilot territories, using the relationship between the water level before an ice jam and the maximum water level during the ice jam (Fig. 2.1.2.1).

	A	B	C
1	Ievadiet sākuma ūdens līmeni (cm):	508	
2	Prognozētais sastrēguma max līmenis (cm):	736.32	
3	Brīdinājuma līmenis:	0	
4			
5			

Figure 2.1.2.1. Excel-based decision tool: predicted ice-jam max water level

2. **Conditions for different situations** have been compiled as decision-support tools for forecasting.

#### Example

Daugava River at Jēkabpils: interpretation of pre-jam water levels in relation to flood-warning thresholds.

Each hydrological station has predefined and well-established flood warning thresholds. To support early warning and operational decision making, it is essential to estimate the probability that these thresholds may be exceeded during an ice-jam event. The pre-jam water level serves as a key indicator for anticipating the potential rise caused by an ice jam, and thus for issuing early alerts.

Observed relationships between the pre-jam water level and maximum ice jam water level:

< 300 cm	No cases recorded where the maximum water level exceeds 600 cm.
300-400 cm	In approximately 31% of cases, maximum water level exceeds 600 cm.
≥ 400 cm	The probability of maximum water level exceeding the flood threshold is ≥ 70%.
≥ 500 cm	In all cases, maximum water level > 600 cm. Very high risk zone.

Practical interpretation for early warning:

When the pre-jam water level is  $\geq 400$  cm, the likelihood that the ice-jam peak will exceed the 600 cm flood threshold becomes high.

When the pre-jam water level reaches  $\geq 500$  cm, it can be considered almost certain that the flood threshold will be exceeded.

This level should trigger immediate high-risk alerts and preparedness actions.

### 3. Combined tool for river stretches.

In several river stretches, hydrological observation stations exhibit strong correlations between their water level dynamics. This creates the possibility to use observations from individual stations not only for point forecasting, but also to extend predictive capability across longer river sections (Fig. 2.1.2.2).

When the temporal and spatial correlation between stations is high, the water level behaviour at one station can serve as a reliable proxy for conditions upstream or downstream. Such relationships enable:

- Segment-based forecasting, where warnings apply to an entire river stretch rather than a single monitoring point;
- Improved early warning capability, especially in areas with limited station coverage.

This approach is particularly valuable during ice jam formation, when jams often develop simultaneously or propagate within a connected river segment. Strong correlation between stations allows forecasters to assess risk not only locally but also along a broader reach, improving situational awareness and operational decision making.

	A	B	C
1	Zelķi & Jēkabpils Prediction Tool		
2	Start level Zelķi (cm):	500	
3	Start level Jēkabpils (cm):	450	
4	Predicted Max level Zelķi (cm):	800.6092	
5	Predicted Max level Jēkabpils (cm):	643.5001	
6			
7			
8			
9			

Figure 2.1.2.2. Excel-based decision tool: Daugava River, Jēkabpils-Zelķi

## 2.2. Ice-jam flood early warning in Latvia

In Latvia, each hydrological station has unique water level thresholds defined for the **yellow**, **orange**, and **red** warnings. These thresholds serve as the basis for preparing and issuing flood warnings. Initially, the forecasting system automatically determines the warning level for each station based on observed and forecasted water levels, which are then displayed on the map.

## 1. Flood risk information system <https://hidro.meteo.lv/>

The warning thresholds are based on water level return periods or specific water levels defined for flood situations – often determined by local municipalities.

We recommend maintaining the existing warning types (Fig. 2.2.1) but also suggest introducing improved impact descriptions for ice jam floods.



Figure 2.2.1. Different warnings in the Flood risk information system

## 2. Warning system <https://bridinajumi.meteo.lv/>

Flood warnings are issued for different types of flooding. Yellow warnings are typically issued for larger areas and broader river basins, while ice jam forecasts – especially in cases of extreme conditions – are issued for smaller, more localized areas (Fig. 2.2.2).

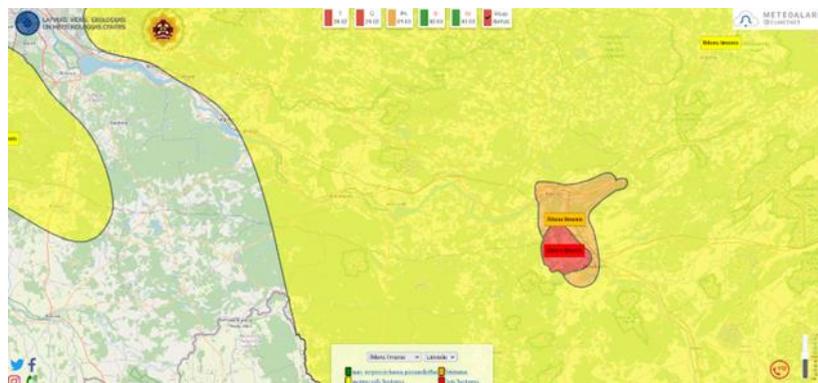


Figure 2.2.2. Territories with different warning levels

Additional information is prepared for social media (Fig. 2.2.3).



Figure 2.2.3. Information for social media

General description of warning levels is as follows:

- Yellow** Hydrometeorological conditions are worsening.
- Orange** Hydrometeorological conditions are becoming dangerous; Forecasted hydrometeorological conditions are not common in the region.
- Red** Hydrometeorological conditions are very dangerous; Very intense hydrological or meteorological conditions are forecasted.

Table 2.2.1. Defined risks for hydrological phenomena of various warning levels and recommendations for action in these cases

Phenomena	SIGNIFICANT INCREASE IN THE WATER LEVEL	FLOODING OF TERRITORIES	FLOOD
Water level rise during floods, ice jams and rain, as well as during storm surge	BE AWARE of the potentially flood-prone areas!	BE PREPARED to protect yourself and your property!	TAKE ACTION to protect yourself and follow the instructions given by the responsible authorities!
	Caution should be exercised when moving in flood-prone areas. On the coastline of the Baltic Sea and the Gulf of Riga, strong winds together with high waves can cause a significant rise in the water level. More information on hydrological conditions is available at <a href="http://hidro.meteo.lv">hidro.meteo.lv</a> . Read more about what to do in the event of a flood here!	Flooding of property and transport infrastructure is possible. There is a risk that power supply, water supply and communications will be disrupted. Evacuation may be necessary. Residents are asked not to visit or move in flood-prone areas, not to endanger themselves and not to hinder the rescue services. On the coastline of the Baltic Sea and the Gulf of Riga, strong winds together with high waves can cause coastal areas and associated low lying areas near rivers and	Widespread life-threatening flooding of property is expected, along with evacuations. Movement is very difficult. Residents are invited to leave the threatened coastal areas and follow all the instructions given by the responsible authorities. There is a very high risk that power supply, water supply and communications will be disrupted. On the coastline of the Baltic Sea and the Gulf of Riga, strong winds together with high waves will cause widespread flooding of the

Phenomena	<b>SIGNIFICANT INCREASE IN THE WATER LEVEL</b>	<b>FLOODING OF TERRITORIES</b>	<b>FLOOD</b>
		lakes to flood, as well as damage dune and coastal infrastructure such as dams or ports. More information on hydrological conditions is available at <a href="http://hidro.meteo.lv">hidro.meteo.lv</a> . Read more about what to do in the event of a flood here!	coastal areas and associated low-lying areas near rivers and lakes, as well as serious damage to infrastructure, property, and defence structures - roads and building foundations may be washed away, dams damaged, sewage system overloaded. As saltwater increasingly enters freshwater ecosystems, risks arise for the organisms living in it and the ecosystem as a whole. More information on hydrological conditions is available at <a href="http://hidro.meteo.lv">hidro.meteo.lv</a> . Read more about what to do in the event of a flood here!

## 2.3. Ice-jam flood forecasting guidelines for Lithuanian pilot rivers

The development of ice-jam flood forecasting guidelines for Lithuanian pilot rivers is based on the analysis of long-term historical observations of ice phenomena, water levels, air temperature, and precipitation. The availability and continuous updating of these datasets are essential for improving ice-jam flood forecasting and early warning capabilities. Historical data analysis combined with real-time monitoring provides the basis for identifying critical conditions leading to ice-jam formation and related flooding.

Ice jams typically form during transitional periods of river ice regime, namely freeze-up and break up, which marks the beginning and the end of the ice cover season. In temperate regions, ice jams may also occur during mid-winter thaws, when unstable ice conditions and rapid hydrometeorological changes prevail.

A conceptual forecasting model was applied to support ice-jam flood prediction in Lithuanian pilot rivers. The maximum water level observed during ice-jam events was selected as the primary dependent variable, as it represents the main parameter of interest for flood risk assessment and warning issuance.

A conceptual model serves as the foundation for an ice-jam flood early warning system. The main parameters of the conceptual model include the river water level prior to ice-jam formation, the rate and magnitude of water level rise, the cumulative sum of negative degree days (NDD) preceding the ice-jam event, the cumulative sum of positive degree days (PDD), as well as the amount of precipitation before ice-jam formation. These parameters reflect both thermal and hydrological conditions that control ice formation, deterioration, and mobility.

Discharge measurements and ice thickness observations are also highly important for ice-jam flood forecasting; however, such data are not always available for all river sections or time periods. The probability of ice-jam occurrence is generally higher during freeze-up conditions, during periods of frazil ice generation and transport, and in river reaches where ice tends to accumulate due to morphological constraints or hydraulic conditions.

### 2.3.1. Hydrological monitoring

Hydrological monitoring in Lithuanian pilot rivers includes continuous observations of water level, water temperature, and ice conditions. These observations are carried out on a daily basis and provide the foundation for timely identification of flood risks and effective communication with responsible services, institutions, and the public.

During the cold season, particular attention is given to monitoring ice regime dynamics, including ice formation, frazil ice generation and transport, ice-jam development, and river ice break up. Changes in water level and water temperature are simultaneously observed in order to enable early assessment of ice-jam flood risk.

Ice conditions are monitored both at hydrological observation stations and along extended river reaches that are prone to ice accumulation. Remote monitoring tools play a significant role in this process, including surveillance cameras installed at selected gauging stations, automated hydrological stations, satellite imagery, and other remote sensing technologies. Camera systems provide near-real-time visual information on ice conditions and water levels, supporting rapid decision-making.



Figure 2.3.1.1. Ice formation in the Neris River. Camera view from the Buivydziai gauging station

To improve the evaluation of ice phenomena formation and enhance preparedness for potential ice jam events, as well as to assess the likelihood of ice cover development, an automated calculator of positive and negative air temperatures was implemented. The occurrence of ice phenomena, including the formation of ice cover in lakes, is assessed based on the cumulative sum of negative air temperatures. This calculator incorporates numerical weather forecasts to provide predictive estimates.

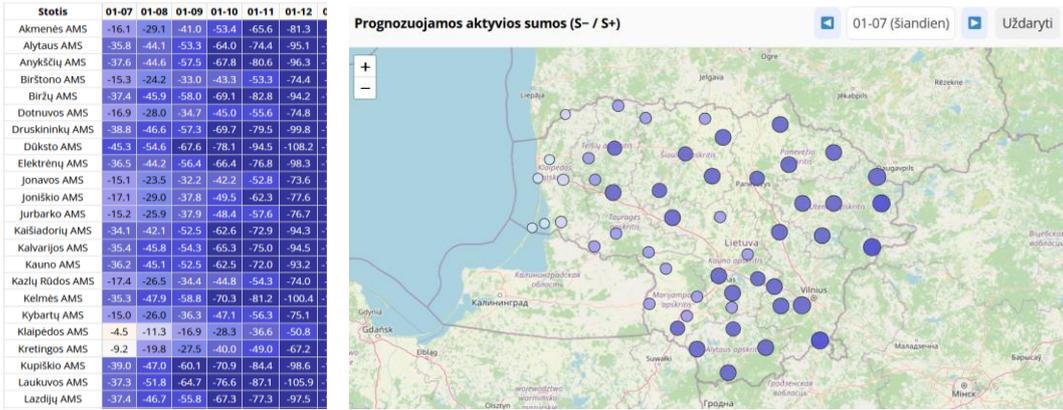


Figure 2.3.1.2. Ice phenomena formation calculator and map of ice phenomena distribution in Lithuania

The outputs of the calculator were used to develop a map that provides a comprehensive visual representation of ice-related phenomena across Lithuania. The map illustrates territories where ice phenomena in rivers are forming or have already formed, as well as lakes undergoing freeze-up. Different colors represent specific ice phenomenon types and lake depth categories, while increasing color intensity indicates more advanced ice development and the formation of ice cover in deeper lakes.

Historical data analysis forms an integral part of hydrological monitoring for ice-jam flood risk assessment. River reaches historically prone to ice jams have been identified based on long-term observations. This information supports hydrodynamic modelling, flood hazard mapping, and the planning of preventive measures, including routine river maintenance and the application of temporary engineering solutions such as barriers or dams. Flood risk is assessed using defined probabilities of recurrence (e.g., 10, 50, and 100-year events), providing a basis for informing the public and responsible authorities.

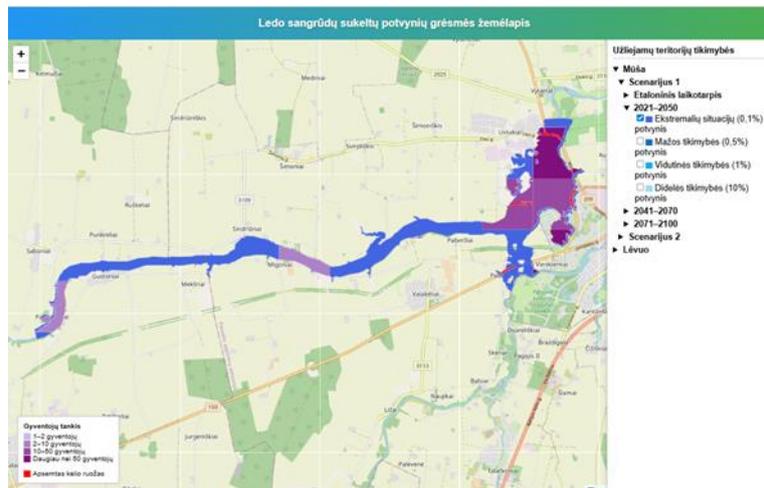


Figure 2.3.1.3. Flood hazard and risk maps of Musa and Levuo (<https://www.meteo.lt/klimatas/hidrologija/ledo-sangrudu-sukeltu-potvyniu-gresmes-ir-rizikos-zemelapiai/>)

The historical ice jam map was developed for informational purposes to raise public awareness of the magnitude and extent of ice jams that have occurred in Lithuania.

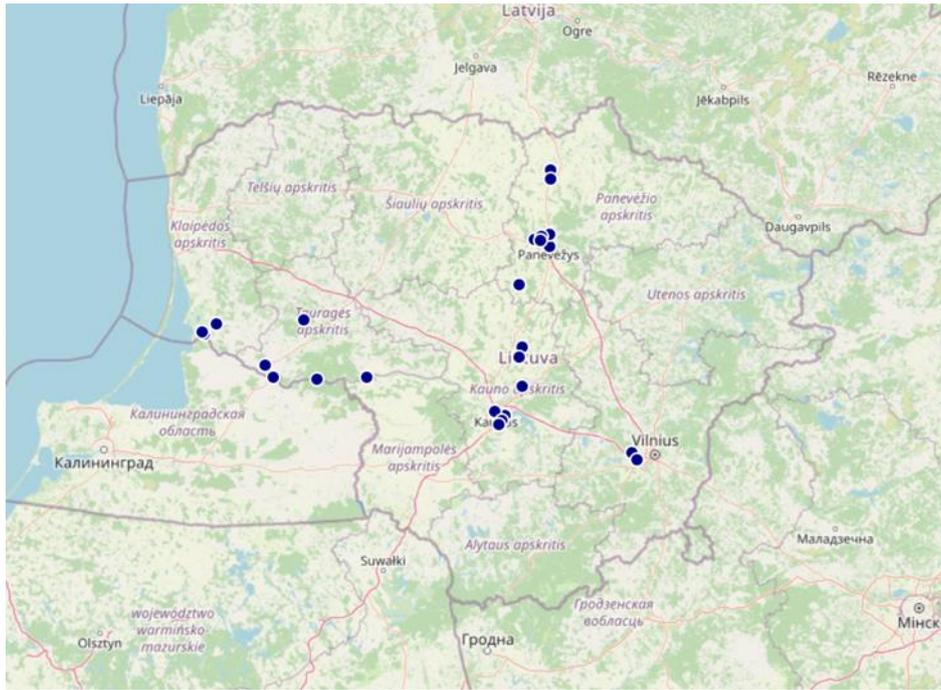


Figure 2.3.1.4. Historical ice jam map (<https://www.meteo.lt/klimatas/hidrologija/ledonesis-ir-ledo-sangrudos/>)

### 2.3.2. Ice-jam flood forecasting tools

Due to the complexity of predicting ice jams, comprehensive monitoring and analysis of all contributing factors are crucial for accurate risk assessment. Depending on the season of formation, underlying causes, river flow conditions, and the level of hazard posed, ice jams are classified into three types:

Table 2.3.2.1. Classification of ice jams

Type	Freeze-up Ice Jams (Frazil/Icing)	Mid-Winter or Spring Break-up Ice Jams
Season	Early winter (beginning of river freeze-up).	Mid-winter or early spring.
Cause of Formation	Rapid drop in air temperature, leading to the formation of frazil ice, slush, and anchor ice, which accumulates in certain areas.	Rising air temperatures, rainfall, and increased runoff. Ice cover breaks up and begins to move.
Ice Type	Frazil ice, slush, anchor ice, and newly forming surface ice.	Thick, compressed ice floes and broken fragments of formerly solid ice cover.
Flow Conditions	Low water discharge typical of cold winter periods; limited runoff.	High water discharge caused by melting snow and/or precipitation.
Hazard Level	Usually causes small, localized floods; minor potential damage to infrastructure.	Often causes major floods with potentially extreme water levels; significant risk to infrastructure, people, and property.

The conceptual model diagram, created using the project results, can serve as a kind of forecasting model. Considering the prevailing conditions (water level, discharge, air temperature, dominant precipitation phase and intensity, as well as ice thickness), it becomes possible to at least preliminarily predict the potential formation of an ice jam.

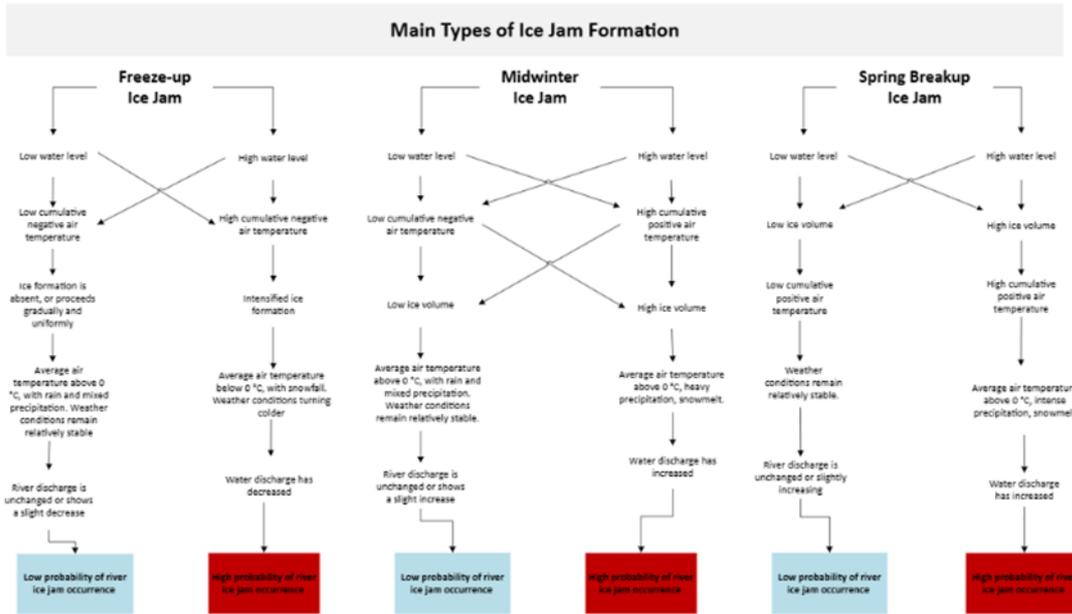


Figure 2.3.2.1. Conceptual model diagram

The critical water level can be used as a reference point, upon reaching which monitoring for potential ice-jam formation begins. The critical water level of the Musa River is 130 cm, and that of the Levuo River is 120 cm. When these water levels are exceeded, the rivers begin to overflow their banks, the nearby fields may become flooded.

For example: If the water level in the Musa River is 90 cm, there are few subzero temperatures, no ice phenomena occur, ice cover is either absent or very thin, the average air temperature is above 0 °C, weather conditions remain relatively stable, and river discharge is unchanged, then the probability of ice-jam formation is low.

Using this model, an ice-jam occurrence calculator was created, which allows for preliminary estimation of ice phenomena appearance, and the probability of ice-jam formation based on key hydrological and meteorological parameters.

Based on the relationship between the water level at the beginning of an ice jam and the maximum water level reached during the ice-jam event, Excel-based calculation tools were developed.

	A	B	C	D	E
1	H_begin (cm)	Hmax_prog (cm)	Rizika (pagal prognozę)	VMS	
2	85	100	Žemas	Mūša - Ustukiai	
3	39	67	Žemas	Lėvuo - Bernatoniai	
4					
5					
6					
7					
8					
9					
10					

An operational Excel-based calculator was developed for the Mūša–Ustukiai WGS river reach to assess potential water-level escalation under ice-jam conditions and to assign a risk class based on the forecasted maximum water level. The calculator retrieves the latest observed water level in real time via an API (H\_begin, cm) and applies an empirical water-level increment ( $\Delta H$ ) approach to estimate the forecasted maximum ice-jam water level (H\_max,prog). The basic principle is:

$$H_{\max, \text{prog}} = H_{\text{begin}} + \Delta H$$

The  $\Delta H$  value is selected according to H\_begin intervals, based on an analysis of historical ice-jam events (H\_begin → H\_max), and ensures the physically consistent condition. For the Mūša–Ustukiai station, the following empirical rules are applied:

- when H begin  $\leq$  130 cm, Hmax,prog =Hbegin +15 cm;
- when H begin  $\leq$  244 cm, Hmax,prog =Hbegin +23 cm;
- when Hbegin  $\geq$ 280 cm, Hmax,prog =Hbegin (no additional ice-jam-induced increase in forecast).

The risk class is determined based on Hmax,prog by comparison with the Mūša–Ustukiai WGS threshold water levels: low water level ( $\leq$  130 cm, within the channel), “Watch” (131–244 cm), “Warning” (245–280 cm), and “Emergency” ( $>$  345 cm, exceeding the 10% probability maximum water level). The calculator is intended for early warning and operational decision-making in ice-jam flood risk management; its purpose is to estimate the potential maximum ice-jam-induced water level rather than to predict the temporal evolution of water levels.

For the Lėvuo–Bernatoniai station, historical ice-jam event data (H\_begin → H\_max) indicate that the additional water-level increase caused by ice jams does not show a clear dependency on the initial water level but is instead characterized by a typical range of increments, with occasional extreme outliers. To ensure robustness and early warning capability, a conservative empirical increment is applied:

$$\Delta H = 28 \text{ cm}$$

Thus, the forecasted maximum ice-jam water level is calculated as:

$$H_{\max, \text{prog}} = H_{\text{begin}} + 28 \text{ cm}$$

This conservative approach is intended to provide earlier indication of potential risk escalation under ice-jam conditions, even when the observed water level has not yet reached critical thresholds.

Risk classification is determined by comparing  $H_{max,prog}$  with the established Lėvuo–Bernatoniai threshold water levels: low water level ( $\leq 120$  cm, within the channel), “Watch” (120–161 cm, from overbank flow to the 10% probability maximum water level), “Warning” (162–222 cm, from the 10% to the 1% probability maximum water level), and “Emergency” ( $> 223$  cm, exceeding the 1% probability maximum water level). As with the Mūša–Ustukaiai calculator, the Lėvuo–Bernatoniai tool is designed for operational risk assessment and early warning rather than for predicting the temporal evolution of water levels.

## 2.4. Ice-jam flood early warning in Lithuania

In Lithuania, the warning system (<https://www.meteo.lt/proгноzes/pavojingi-reiskiniai/>) provides early information on ice-jam and flood risks. Early warning messages are published on the official website (meteo.lt) and sent via email to municipalities, rescue services, and other responsible institutions. Relevant information and updates are continuously shared on social media platforms. The public is also informed about ice-jam formation and associated hazards through educational materials, such as publications, informational leaflets, and community awareness campaigns. Additionally, residents have access to flood risk maps to identify potentially hazardous areas.

Table 2.4.1. Warning levels in the early warning system (IBL)

	Warning	Impact	Action
Green	-	None	Normal/Usual behavior
Yellow	We inform you!	Damage to unprotected objects (avoided)	Protect vulnerable objects and activities
Orange	Be prepared!	General damage (unavoidable)	Follow information carefully. Comply with instructions from responsible institutions
Red	Take measures!	Major damage and/or casualties (usually in large areas), threat to life (unavoidable)	Follow instructions from responsible institutions under all circumstances. Prepare for extreme situations

**Low Risk Level – Ice Formation Alert.** Purpose: To inform the public and institutions about conditions that may lead to the formation of ice jams and potential ice-jam floods. Recommended actions: Monitor hydrological information regularly and check whether your location falls within flood risk or hazard zones.

**Moderate Risk Level – Ice Jam Formation Possible.** Conditions: Favourable for ice jam formation; frazil ice or initial ice movement (break-up) is observed. Purpose: To warn about the beginning of ice jam formation and a potential flood threat. Recommended actions: Continuously follow updated hydrological information, move equipment and belongings away from riverbanks, prepare for possible evacuation.

**High Risk Level – Ice Jam Formed, Major Flood Threat.** Conditions: An ice jam has already formed; there is a significant risk of flooding. Purpose: To immediately notify the public about the existing ice jam and provide continuous updates on rising water levels and the extent of inundated areas. Recommended actions: Closely follow updated hydrological information, Follow the instructions of responsible authorities, Be prepared to evacuate.

Table 2.4.2. Phenomena and recommendations

Hydrological Phenomenon	Recommendations
Ice phenomena	Do not walk on the ice. Thin ice may break.
Ice phenomena	Do not walk on the ice. Stay away from riverbanks during ice break-ups.
Ice jam	Do not walk on jammed ice floes. Prepare for a possible flood.
High water level in river	Do not swim in rivers during high water levels. Prepare for a possible flood.
Flood	Be prepared to protect yourself and your property. Floodwater may inundate real estate and roads. Power, communication, and water supply disruptions are possible. Evacuation may be necessary. Follow the recommendations of the authorities responsible.
Flood	Be prepared to protect yourself and your property. Floodwater may inundate real estate and roads. Power, communication, and water supply disruptions are possible. Evacuation may be necessary. Follow the recommendations of the authorities responsible.

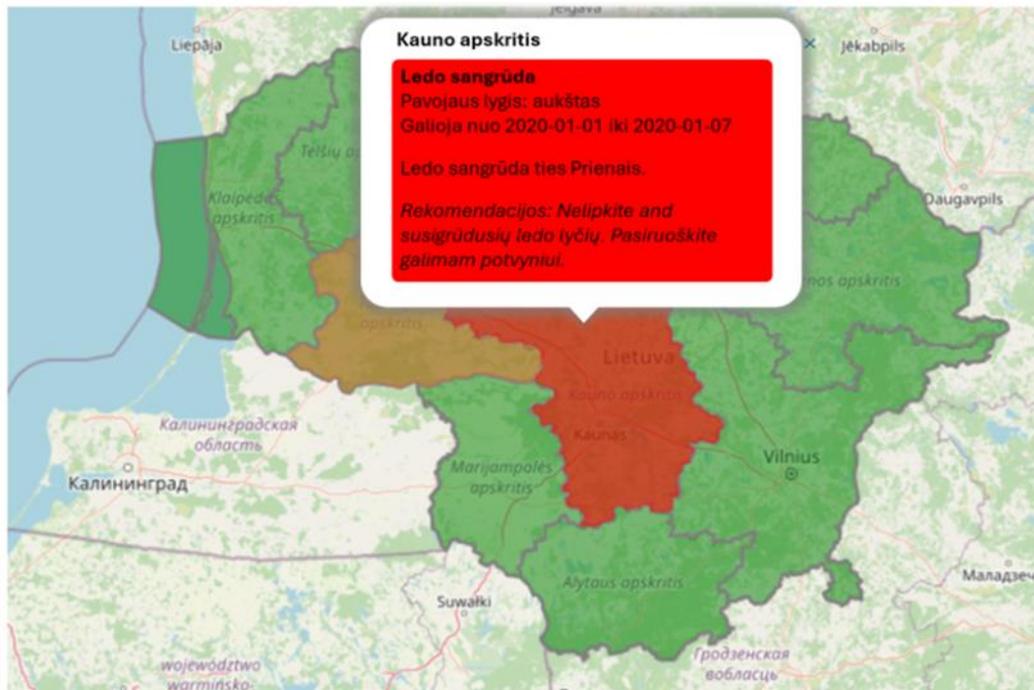


Figure 2.4.1. Example of an Ice Jam Warning. Significant damage and/or casualties (typically over a large area), life-threatening situation (inevitable)

Informing the public is equally important in early warnings. To increase public awareness, brochures about ice jams were developed, including information on their formation processes, the role of early warning systems, and preventive measures.

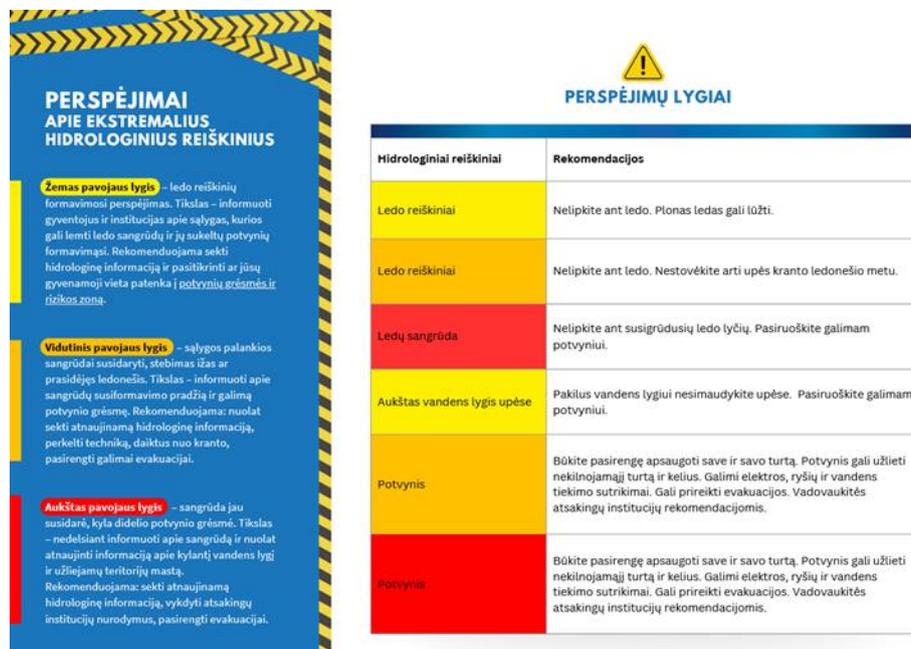


Figure 2.4.2. Example of an Early Warning System Leaflet

### 3. Conclusions

In this study, a first attempt to develop a framework to forecast ice-jam flooding along the project pilot rivers was carried out. The concept was developed to forecast the severity of spring and mid-winter breakup for selected pilot rivers in Latvia (Daugava, Lielupe) and Lithuania (Mūša, Lévu), based on the analysis of long-term historical data, real-time hydrometeorological monitoring, and the results of conceptual modelling of ice-jam formation processes. The study combines the hydrological and hydraulic models and multi-sources of data such as satellite, gauge, and historical studies to develop the stochastic framework.

The results demonstrate that ice-jam flood risk can be effectively assessed using a combination of key hydrological and meteorological indicators, particularly pre-jam water levels, air temperature indices (positive and negative degree days), precipitation, and observed ice conditions. Simple empirical relationships between water levels before and during ice-jam events allow the development of practical, Excel-based forecasting tools that support early warning and operational decision-making.

The study confirms that while precise prediction of maximum ice-jam water levels remains uncertain, early identification of favourable conditions for ice-jam formation significantly improves preparedness and risk mitigation. Continuous hydrological monitoring, including in situ observations, camera systems, and remote sensing, is essential for timely detection of hazardous situations.

Separate forecasting guidelines and warning approaches were developed for Latvia and Lithuania, reflecting differences in river characteristics, dominant ice-jam formation mechanisms, and existing national warning systems. Integration of ice-jam-specific information into existing flood warning frameworks enhances their effectiveness and relevance for local authorities and the public.

In the future, both countries will further strengthen cooperation by regularly exchanging information about issued warnings, fostering a more unified regional understanding of evolving hydrometeorological risks.

Overall, the developed concept provides a practical and transferable foundation for ice-jam flood forecasting and early warning. An important benefit of the ICEREG project is that new knowledge has been gained and new tools have been developed, supporting more informed and data-driven decision-making. However, to ensure long-term robustness of the forecasting framework under changing climate conditions, continued development is essential. This includes ongoing improvement of existing forecasting tools, as accurately predicting ice-jam formation and evolution remains highly challenging. To advance reliability, real-time freeze-up observations and dedicated hydrological forecasting models for each river basin will be required to supply timely and comprehensive modelling data.

## References

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