ICEREG

Conceptual model of the ice-jam flood formation

Project Deliverable D1.2.1

2025

Contents

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.); ΔH - 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^3/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 Conceptual Model of the ice-jam formation was developed on the basis of collected information about historical ice-jam flood events in the project pilot rivers Daugava and Lielupe (Latvia), Muša and Levuo (Lithuania).

This conceptual model for ice-jam formation includes key parameters used in the research of the occurrence of this phenomenon. The conceptual model is a mechanism that helps analyse and interpret data (meteorological, hydrological and morphological parameters) by identifying relevant variables, asking research questions and defining the relationship between the key parameters of the ice-jam formation process.

The conceptual model proves that the formation of ice jams is a complex process that depends on a variety of interacting factors. Understanding these factors is essential for predicting and mitigating the effects of ice jams on rivers, particularly in areas prone to seasonal freezing and thawing. It is helpful in preparation of early warnings about ice-jam formation.

Due to the fact that formation of ice jams is a complex process, it is very challenging to predict them. Consequently, the best thing to do is provide early warnings about ice-jam formation for the wider public.

The research of the ice-jam formation has been done for the pilot river stretches that were identified by the project and described in the “Report on Latvian–Lithuanian ice-jam flood sensitive areas” (D.1.1.1). These pilot river stretches are the following:

Latvia

- Daugava River: between river tributaries Nereta and Aiviekste;
- Lielupe River: from the confluence of Musa and Memele rivers to the junction with Sesava River.

Lithuania

- Muša River: between settlements Gustoniai to Ustukiai;
- Levuo River: from the Pamarliškiai to Bridge in Skaistgiriai.

2. Main factors for the ice-jam formation process

The decay, fracture, transport, and removal of the river ice cover, that is, the entire process commonly called a breakup, is complicated and varies greatly between rivers, between stretches of the same river, and between winters (Beltaos, 1995). River ice breakup is a crucial process in hydrology. It refers to the disintegration and movement of river ice during seasonal transitions, particularly from winter to spring. There are two main types of river ice breakup: thermal and mechanical.

Thermal breakup occurs gradually as rising air temperatures and solar radiation cause river ice to melt in place without significant disruption. The ice thins, weakens, and breaks slowly, with little risk of ice jamming or flooding. This uniform and predictable process leads to minimal environmental or infrastructural impact.

Mechanical or **dynamic breakup** occurs more suddenly and violently, often triggered by rising water levels from snowmelt or rainfall. The rapid increase in discharge causes the river to break up ice and push large chunks downstream, which can accumulate and form ice jams, blocking the flow. This unpredictable process frequently results in flooding, posing significant risks to infrastructure and nearby communities.

Therefore, if hydrodynamic forces dominate, the ice cover dislodges, breaks up, moves, and creates potentially flood-generating ice jams (Burrell et al., 2023). Ice jams are blockages to channel flow that cause a temporary rise in water levels higher in stage than floods during ice-free conditions with equivalent flow (Lindenschmidt et al., 2018). This process can be called winter and spring versions of flash floods (Niziol, 2020). Ice jams have three critical components: occurrence, severity (i.e., water level), and timing of breakup (Madaeni et al., 2020). Figure 2.1 presents a scheme of river ice-jam formation and water level rise created by Rokaya et al. (2018).

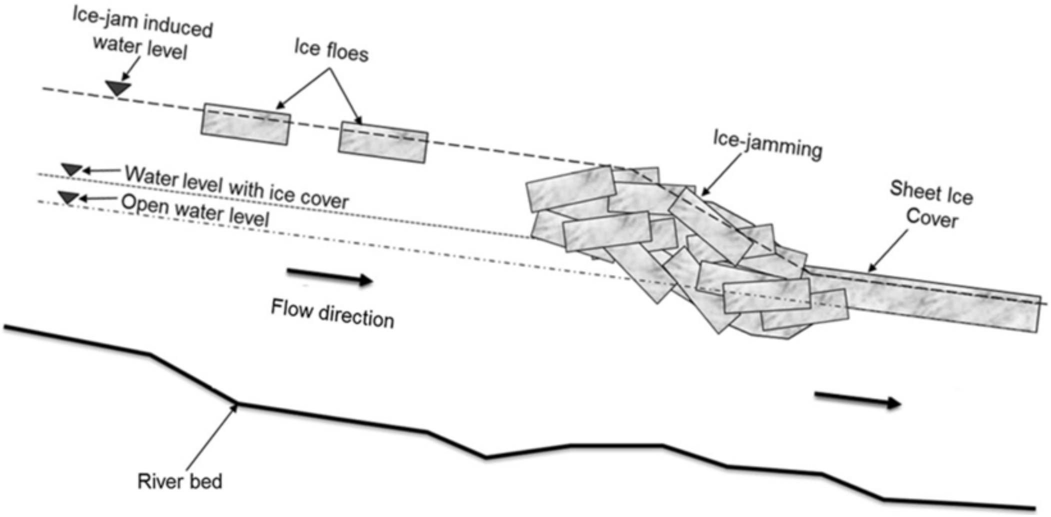


Figure 2.1. Schematic view of river ice jam and associated water levels (Rokaya et al., 2018)

Ice jams are most common at breakup but can also occur at freeze-up, when cold weather cools river water, forming frazil ice crystals and slush that clump together into frazil ice. These ice particles float or accumulate near the surface; some frazil crystals can settle and attach to the bottom or submerged surface objects, forming anchor ice. In certain conditions, anchor ice can float to the surface when it detaches, often carrying rocks, vegetation, or other debris. Accumulating ice pieces are carried downstream until they encounter an obstacle (such as narrow sections of the river, bends, or bridges) or when the velocity of the flow decreases. This may cause their accumulation, blocking the flow of water and, eventually, ice jam formation.

Table 2.1. The main aspects of breakup and freeze-up jams

Aspect	Breakup jams	Freeze-up jams
Season	Late winter or early spring during thawing conditions	Early winter when rivers begin to freeze
Trigger	Rising temperatures, rain, and increased runoff that break and mobilize ice cover	Rapid cooling, forming frazil ice and slush that accumulates in certain areas
Ice type	Large, thick chunks of consolidated ice from pre-existing ice cover	Frazil ice, slush, anchor ice, and new ice forming on the water surface
Flow conditions	High flows due to snowmelt or rainfall increase the river discharge	Low flows typical of cold winter conditions with limited runoff
Severity	More severe, with the potential for catastrophic flooding and rapid downstream release	Typically less severe, but can still cause localized flooding and infrastructure issues
Duration	Shorter, because rising temperatures and water flow can clear jams quickly	Longer, as cold conditions stabilize the jam until river ice consolidates

Therefore, **ice jams typically form during the transitional periods of freeze-up and breakup**, marking the beginning and end of the ice-cover season. In temperate regions, they can also occur in midwinter during events known as "midwinter thaws" (Beltaos, 2008). Ettema (2007) distinguished (i) freeze-up jams, which may develop at any stage of winter, depending on prevailing weather conditions; (ii) breakup jams, which generally occur later in winter or early spring; and (iii) a sequence of breakup jams followed by freeze-up jams. Breakup jams are typically the most severe and pose the greatest risk. Depending on the season, ice-jam flooding can occur for a wide range of durations (Kovachis et al., 2017). In many cases, the flooding caused by an ice jam can be intense but persists for a relatively short period. This is particularly true of spring breakup ice jams.

The formation of ice breakup and jamming phenomena are primarily governed by stream morphology, flow hydrograph, and ice properties (Beltaos and Prowse, 2001). Important climatic parameters for ice-cover growth and decay are air temperature and precipitation, solar radiation, cloudiness, humidity, and wind speed. These factors also control the flow hydrograph once the runoff characteristics of the watershed are specified. Moreover, the type of precipitation, liquid or solid, plays a prominent role, often dictating whether a breakup event will occur at all.

Ettema (2007) classifies factors associated with specifically ice jam formation into three broad groups: (1) thermal, (2) hydrological, and (3) mechanical conditions.

1. Thermal conditions govern ice formation and ice deterioration, snowmelt, and runoff.

Ice volume and its eventual deterioration depend on air temperature and wind, as do volumes of snowmelt and runoff (Ettema, 2007). When ice-jam flood levels are calculated by hydrodynamic models, the volume of ice in an ice jam is one of the most critical parameters affecting water levels and the extent of flooding, both in the longitudinal and transverse to river directions (Lindenschmidt et al., 2018). The thicker, denser, and more resistant the ice cover is during a breakup, the greater the probability of a mechanical breakup (Boucher, 2014). Thus, all variables that prevent the ice cover from melting and that control the mechanical properties of the ice cover are important.

Overall, the length of the ***frost season*** usually has a significant effect. Colder frost season may lead to thicker and denser ice covers and result in abundant frazil production, accelerating the formation of hanging dams.

Ultimately, ***abundant snow precipitation***, especially in the weeks preceding the breakup, may slow down the thermal degradation of the ice cover. According to Prowse et al. (2007), shortwave radiation is the most critical factor influencing the mechanical strength of ice (which in turn defines the type of breakup, i.e., thermal or mechanical).

2. Hydrological conditions are associated with the volume of snow and/or rainfall dropped on a watershed and the evolution of runoff hydrographs for watersheds (Ettema, 2007).

River discharge magnitude and temporal distribution influence water depth, jam equilibrium thickness, and flood level. Meanwhile, ***river flow velocity*** influences jam formation in two ways (Madaeni et al., 2020). When the velocity is low enough, the submerging ice floes aggregate under the existing ice cover, forming ice jams (i.e., hanging dams). Higher water velocities increase the external forces acting on ice covers, leading to collapse. Ice blocks then aggregate, forming new thicker and more competent jams (called wide-channel jams).

3. Mechanical conditions are related to ice cover breakup, transport, and accumulation (Ettema, 2007). The ways whereby an ice cover breaks up, moving ice is conveyed along a river, and moving ice may accumulate in a river. Factors to be considered here are:

i. channel morphology, insofar as these variables affect magnitude and distribution of flow velocities and depths, and thereby jam thickness,
ii. flow resistance, as exerted by the jam underside roughness and channel bed roughness,
iii. ice volume, as it affects the jam thickness and upstream extent,
iv. strength characteristics of a jam,
v. water temperature insofar as it affects jam strength.

River channel morphology primarily influences the location of an ice jam (De Munck et al., 2017). That is why some rivers are more susceptible to ice-jam flooding. Unlike some other types of natural hazards, flooding along river systems is generally a reoccurring event; floods are most likely to occur on rivers that have experienced flooding in the past (Kovachis et al., 2017).

Ice jamming is often caused by the constriction of the channel by ***natural or anthropogenic obstacles*** such as existing ice blocks, slope breaks, shallow reaches, bottom bars, meanders, confluence of rivers, river narrowing, islands, bridges, etc. (De Munck et al., 2017; Madaeni et al., 2020). Bridge piers are the most common man-made obstacles (Boucher, 2014). Natural constrictions are often associated with the presence of geological obstacles (e.g., rock outcrops) that force the passage of water into a bottleneck. The presence of islands, as well as sharp meander bends, can also be identified as possible obstacles to the free circulation of the ice.

Finally, the ice cover itself, owing to the nonuniform patterns of decay along a river, may be seen as an obstacle to the circulation of ice rafts drifting downstream. Depending on the thickness of the “ice wall” (e.g., hanging dams) and as a function of water velocities and ice discharges from upstream, the magnitude of the blockage by the ice cover might vary considerably between years. Ultimately, ice-jamming sites tend to be located where a combination of the upper-mentioned obstacles is found.

Although floods are generally predictable, ice-induced floods resulting from the formation and release of ice jams are highly variable and difficult to predict (Lindenschmidt et al., 2018; Rokaya et al., 2018). Climate change presents additional challenges that could impact river ice dynamics and lead to more frequent ice jams.

3. Parameters of the ice-jam formation process and its variations in pilot river stretches

Similarly as in other rivers, formation of ice jams in the project pilot river stretches is influenced by a variety of morphological, hydrological, and meteorological factors. Ice-jams occur when ice blocks the flow of water, causing localized flooding and changes in the river dynamics.

3.1. Daugava River from Nereta to Aiviekste

Morphological conditions

The sinuosity of Daugava River between tributaries Nereta and Aiviekste rivers is not high. River channel has a sinuous form with the coefficient 1.24 and the flow direction here changes several times.

Channel width varies from 60 m to 400 m due to a number of islands in the stream, and this coefficient equals approximately 6.7.

Near Jekabpils, the gradient of the riverbed increases significantly. It is only 0.05 m/km in the Daugavpils-Livani section, and rises to 0.25 m/km near Jekabpils, while in the rapid section in Jekabpils territory it reaches 2.0 m/km. The flow velocity here reaches 1.5-2.0 m/s in summer, while in spring it increases to 3 m/s and above. On the territory of Jekabpils City, the Daugava River is braided into several channels, the longest of them is Saka. There are three islands within Jekabpils territory: Saka Island, Daugavsala Island and Adamsons Island. The mainstream of Daugava flows here between Saka Island and Daugavsala Island. These are the last rapids in Daugava before the Plavinas Reservoir. After the creation of the Plavinas Reservoir, ice-jams often occur in the river stretch between hydrological stations Jekabpils and Plavinas (Gruberts, 2024).

This section of the river is very complex. Its configuration, depth distribution and changes in flow velocity are reflected in the extremely complex hydrological regime, and especially the ice regime.

Meteorological conditions

Concentrations of anchor ice in combination with frazil and slash ice at the rapid Daugava stretch between Saka and Daugavsala islands fill the channel and lead to ice-jam formation. These phenomena are more often observed in the Saka channel that is much narrower than the main Daugava channel.

Ice blockage in the upper part of the Saka Island most likely leads to flooding in Jekabpils city, in such cases HS Jekabpils registers maximum values of ice-jam water level. Water level rise under these circumstances is very rapid.

Alternatively, ice-jam blockage in the bottom part of the Saka Island leads to floods in Saka Island itself. If the ice-jam head is located near Zelki bridge, then the highest flood water marks can be registered in HS Zelki.

The freeze-up period data analysis shows quite close relationship between the NDD 30-days sum and the length of the period with ice phenomenon before the ice-jam (Fig. 3.1.1).

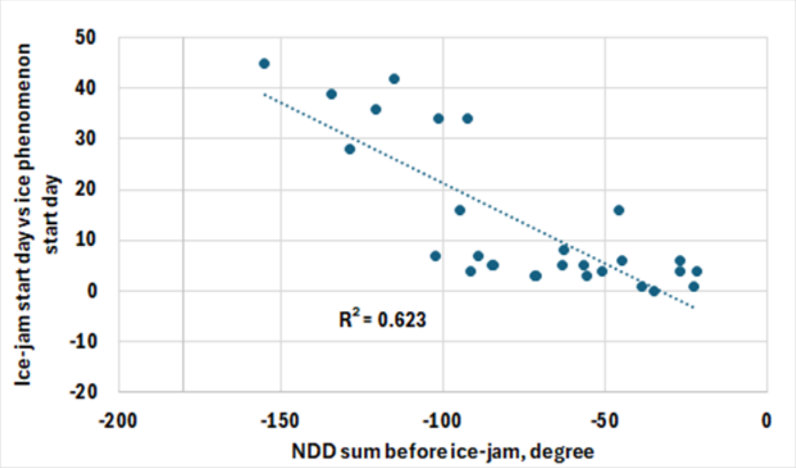


Figure 3.1.1. NDD 30-days sum vs period with ice phenomenon before ice-jam formation

In the formation of ice phenomenon during freezing, presence of precipitation in the snow form is essential (Fig. 3.1.2). It is clearly seen that during the quite cold winter, even though there is a large amount of precipitation, ice-jam doesn't form due to early ice cover set-up. In case ice cover is incomplete, snow enters the water forming the slush ice and leading to ice-jam formation. Moreover, frazil ice floe and ice masses accumulation period can be prolonged when river discharge is increased and air temperature is only few degrees below 0 °; as a consequence, full river ice cover can not form, slush and frazil ice develop intensively and accumulate in the river. Such frazil ice accumulations can also have a negative impact later on the break-up process, like in spring 2010 (Fig. 3.1.5).

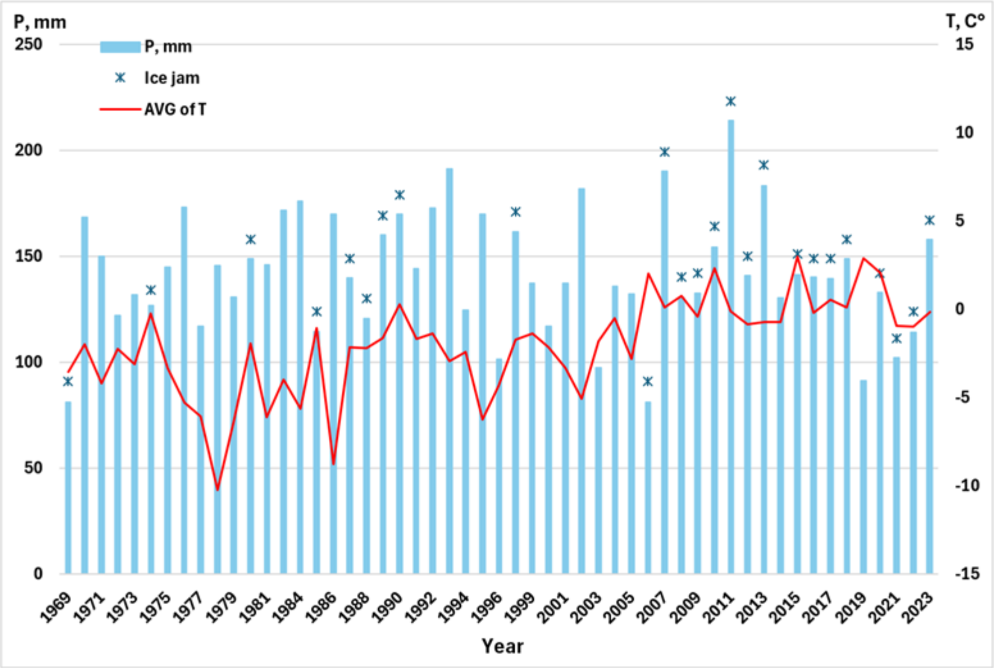


Figure 3.1.2. Combination of precipitation and air temperature values for winters with and without ice-jams, MS Zilani

The break-up period should be divided into two separate groups, one of which is related to the spring hydrometeorological conditions, and other – to the thawing during winter season.

The ice-jam formed at Zelki during the 1988-1989 winter thawing period is shown on Figure 3.1.3. During the relatively cold period, the ice cover was complete but then the air temperature increased, and the frazil ice combined with the slash ice from the upstream section led to ice-jam formation.

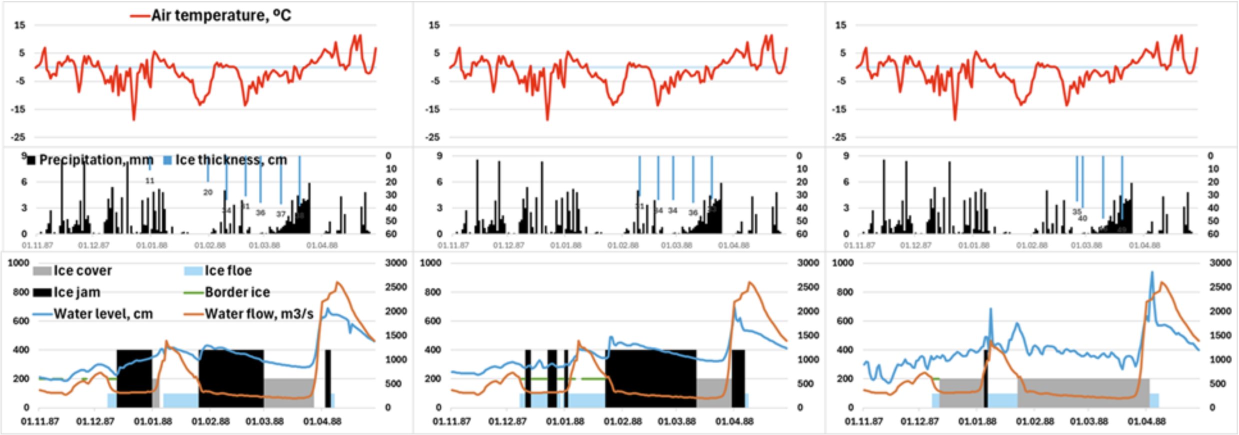


Figure 3.1.3. Integrated graphs of the meteorological (MS Zīlāni) and hydrological parameters (HS Jersika – left, HS Jēkabpils – centre and HS Zeļķi – right) of the Daugava River, 1988

Figure 3.1.4. illustrates the freeze-up process of the Daugava River in the winter 1969/1970, with an ice-jam caused by unstable air temperature and ice floes in

November – December. Incomplete ice cover and snow lead to ice-jam formation in Jekabpils and in Zelki as well. Moreover, ice-jam released in Jekabpils goes downstream to Zelki, like it was in 1969, January 10.

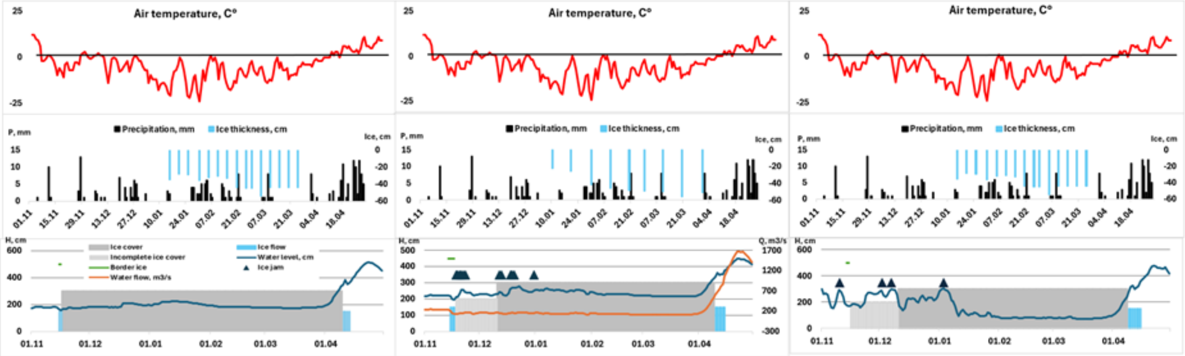


Figure 3.1.4. Integrated graphs of the meteorological (MS Zīlāni) and hydrological parameters (HS Jersika – left, HS Jēkabpils – centre and HS Zeļķi – right) of the Daugava River, 1969

Winters of 2009/2010 (Fig. 3.1.5) and 2022/2023 (Fig.3.1.6) are characterised by quite long ice-jam periods in January; however, the ice regime afterwards was substantially different. In 2010, the next two months were cold, so the complete ice cover with some slash ice in water had been observed till spring.

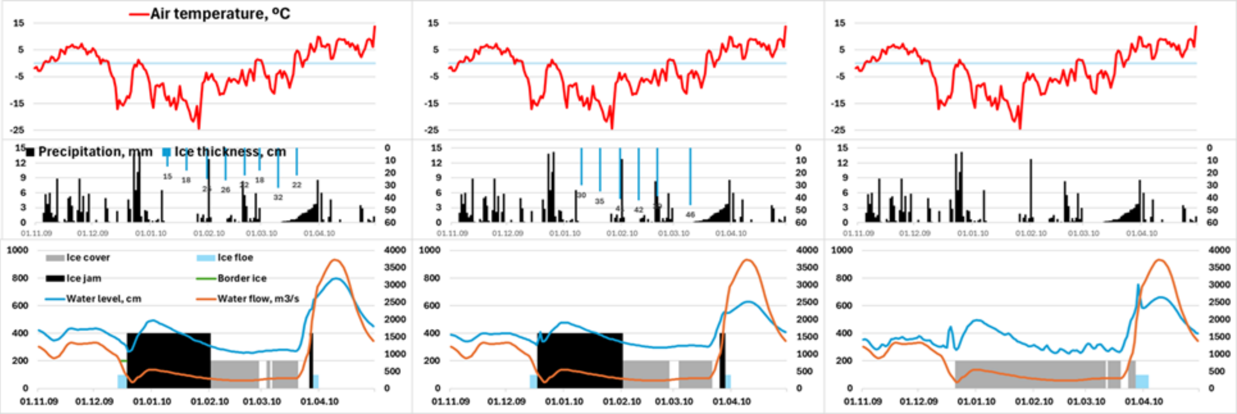


Figure 3.1.5. Integrated graphs of the meteorological (MS Zīlāni) and hydrological parameters (HS Jersika – left, HS Jēkabpils – centre and HS Zeļķi – right) of the Daugava River, 2010

Due to the very warm period in the first days of January 2023, Daugava river was free from the ice cover in almost all its length; water flow was significantly increased, and the water was cool. Only a few cold days were needed for extremely intensive frazil and slush ice formation along the river. The big winter flood in January 2023 was caused by huge amounts of frazil, slush and anchor ice that moved with flow velocity about 0.7 – 1.0 m/s and crowded the river in the rapid section near Saka channel and Daugavsala island. After ice-jam releasing due to warm weather, the ice floe continued.

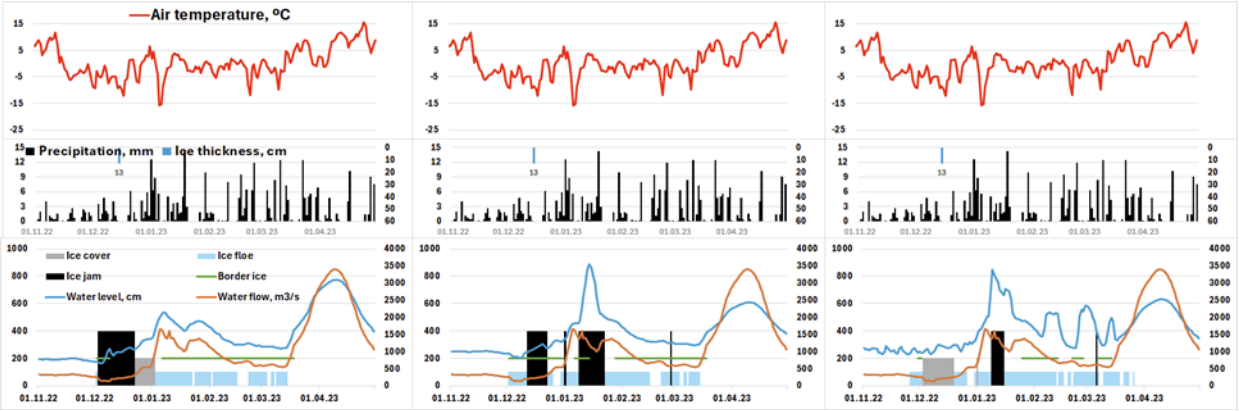


Figure 3.1.6. Integrated graphs of the meteorological (MS Zīlāni) and hydrological parameters (HS Jersika – left, HS Jēkabpils – centre and HS Zeļķi – right) of the Daugava River, 2023

Hydrological conditions

The correlation matrix method was used for the analysis of the ice-jam events in the Lielupe and Daugava rivers. Several hydrological parameters characterising ice-jams in the Daugava and Lielupe rivers were used in this procedure. Maximum water level observed during the ice-jam was used as a dependent variable. For independent variables, the following parameters have been analysed:

- Water level before the ice-jam,
- Water level rise,
- Stream velocity,
- Cross-section area under ice,
- Ice-jam length,
- Ice-jam volume,
- Sum of negative degree days (NDD) before the ice-jam,
- Sum of positive degree days (PDD) before the ice-jam,
- Amount of precipitation before the ice-jam.

The anchor ice that appears in the rapid sections of Saka channel and in the main Daugava channel between two islands Saka and Daugavsala rises to the water surface when the flow velocity is relatively high. Floating frazil and slush ice, together with the anchor ice, crowded the Daugava River channel, forming an ice-jam. These ice conditions are usually observed under the freeze-up process. Figure 3.1.7 shows the hydrological factors (water discharge and water level) that play the most significant role in ice-jam formation during this period. Evidently, the water discharge has to be not less than 330 m^3/sec, but the flow velocity – 0.60 m/sec and higher.

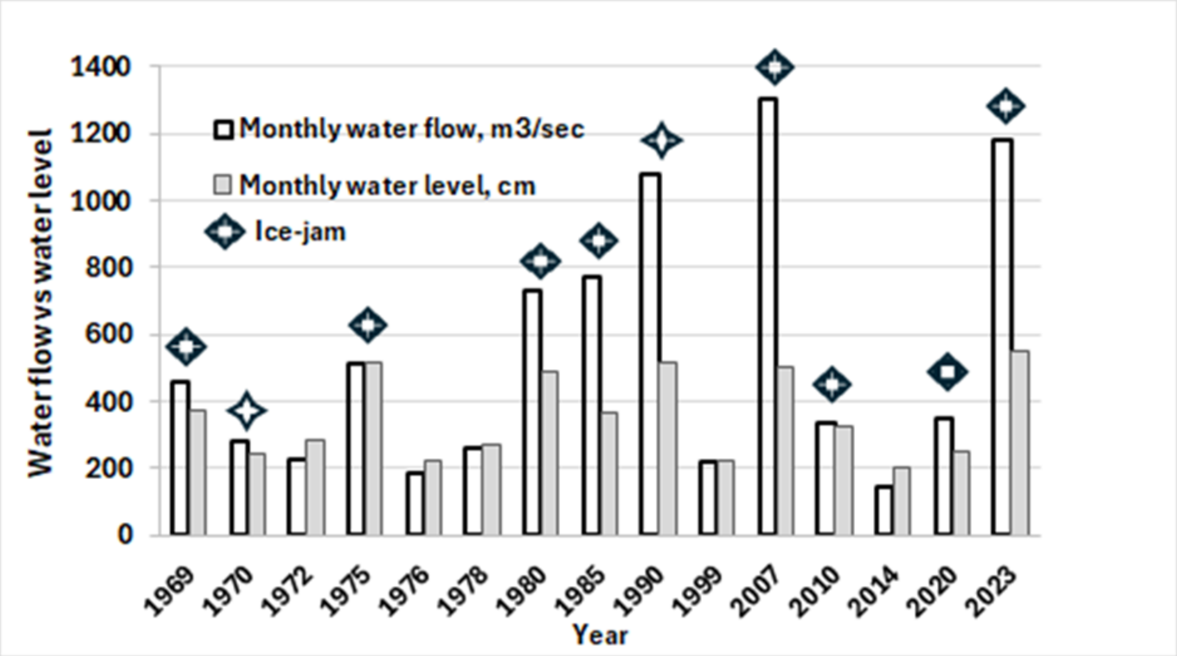


Figure 3.1.7. Water flow and water level during freeze-up, with and without ice-jam, HS Jekabpils

There is a close relationship between the water level elevation before ice-jam and its maximum during ice jam (Fig. 3.1.8 and 3.1.9). For the freeze-up period, the correlation coefficient between those data series is 0.88, but for the break-up period it is 0.78.

It can also be noted that a shorter ice-floating period was observed at lower flows, but significantly longer one at high flows, which results in a larger amount of ice accumulated in this section of the river.

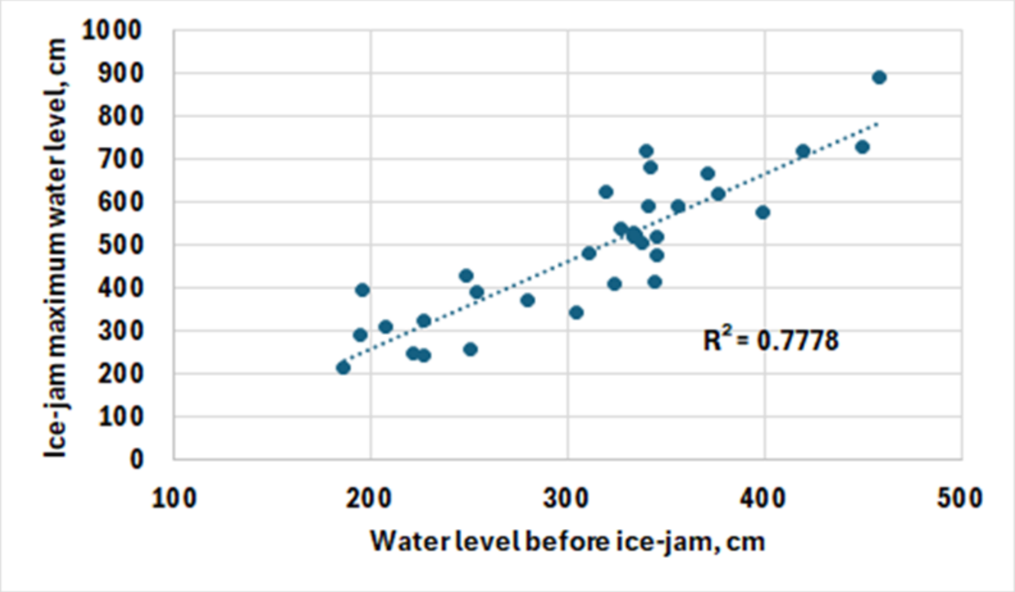


Figure 3.1.8. Relationship between water level before the ice-jam and its maximum during the ice-jam in river freeze-up, HS Jekabpils

In years when ice formation and ice-jamming starts in the high water period, it is more likely that the ice-jam maximum water level will reach flood warning thresholds. If the water level before the ice-jam is higher than 350 cm, then expected water level rise at the HS Jekabpils can in many cases be greater than 150-250 cm or even higher.

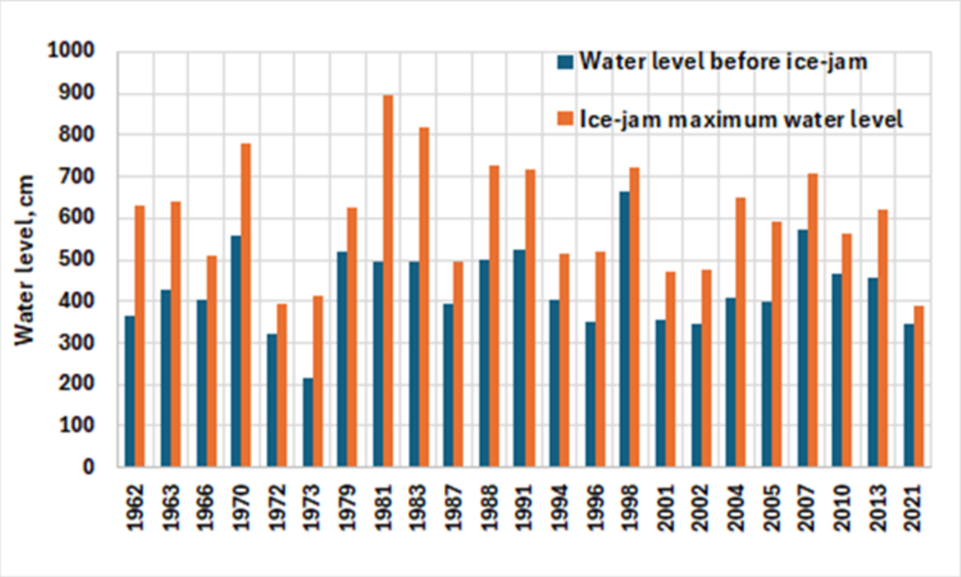


Figure 3.1.9. Relationship between water level before the ice-jam and its maximum during the ice-jam in river break-up, HS Jekabpils

In the break-up process, the highest ice-jam maximum at the HS Jekabpils was reached when water level before the ice-jam was 400 cm or higher. In years when the starting water level was 300-400 cm, ice-jam maximum water level that is reached later varies a lot. This shows that hydrometeorological conditions development in such cases is crucial. If the water level before the ice-jam is lower than 300 cm, it is more likely that the water level rise will be less significant.

Water level rise due to ice-jam near HS Zelki is often much higher than that in HS Jekabpils - up to 725 cm. If the water level before the ice-jam was lower than 250 cm, then the ice-jam maximum water level will more likely be under the warning level (Fig. 3.1.10.) If the water level near HS Zelki in the period when ice-jam starts is 300 cm or higher, then the observed ice-jam maximum will most likely be 600 cm or higher and will lead to flooding.

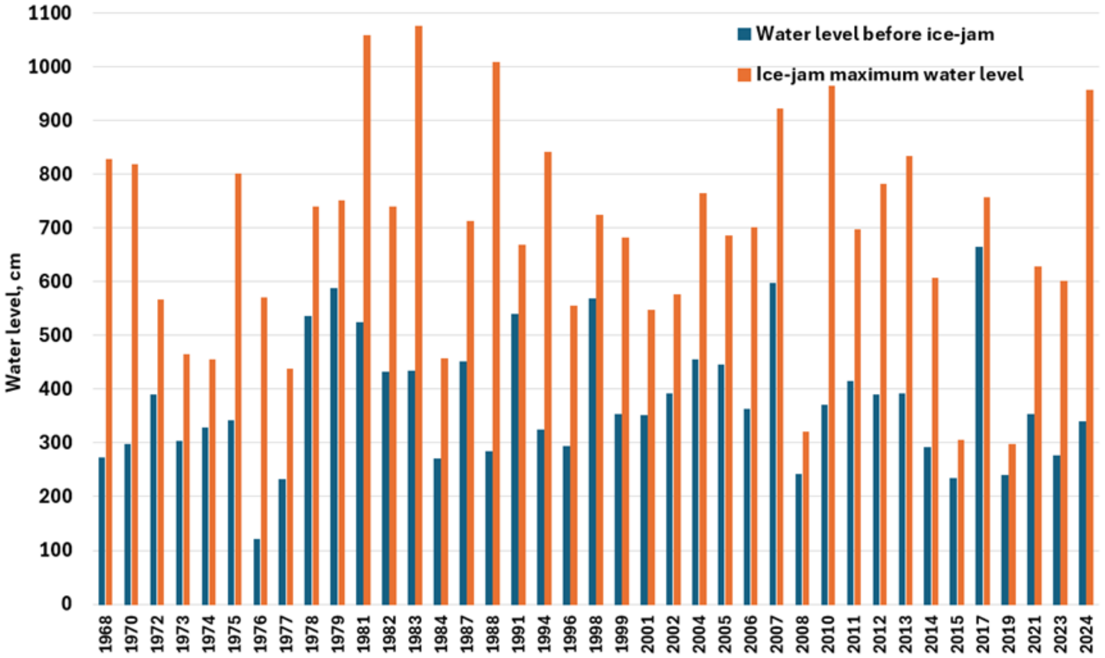


Figure 3.1.10. Relationship between water level before the ice-jam and its maximum during the ice-jam in river break-up, HS Zelki

Main factors for the ice-jam formation in the Daugava River stretch between tributaries Nereta and Aiviekste:

1. *River morphology:*
   - presence of narrowest sections;
   - islands;
   - rapids.
2. *Meteorological conditions:*
   - sum of NDD - in a mild winter, unstable air temperature with a small sum of NDD leads to a quite short time lapse between the beginning of ice floe and the ice-jam start day: 1-10 days if the sum of NDD is not less than -70 and 30-40 days if it is -130 … -150;
   - precipitation in the snow form during the freeze-up process - snow that comes into a cooling water accumulates and leads to ice-jam formation, usually the sum of precipitation before the ice-jam is about 100 mm and higher;
   - length of the water cooling period (before ice cover) that depends on air temperature fluctuation.
3. *Hydrological conditions:*
   - Water flow before the ice-jam ≥330 m^3/sec promotes the anchor ice rising from the bottom at the rapid section of Daugava River. In combination with frazil and slush ice it is crowding channels and forming ice-jams;

- Water level before the ice-jam being lower than 300 cm in HS Jekabpils and lower than 250 cm in HS Zelki, the ice-jam maximum water level is not expected to be significant, but ≥400 cm in HS Jekabpils and ≥300 cm in HS Zelki lead to flooding of territories;
- changes of surface water gradient after construction of the Plavinu Reservoir is a very important and permanent cause of the ice-jam formation in this pilot stretch of the Daugava River.

3.2. Lielupe River from Musa–Memele rivers' junction to Sesava River

Morphological conditions

The sinuosity of the Lielupe River between the Musa – Memele rivers junction and Mezotne village is not high. The river channel has a sinuous form with the coefficient equal to 1.1.

However, channel width variation is extremely high due to a number of islands within the stream and high depth variation as well. This coefficient equals 4.1.

Several places can be seen as most sensitive from the ice-jam formation point of view. The first one is the junction of Musa and Memele rivers, where Ķirbaka and other small islands are located. The second section is near Mežotne Palace and HS Mezotne, where the river becomes wider. Here the ice-jam usually lasts 1–2 days and then the ice moves on till the third place – Stalgene. Here, ice-jam forms both in the river bed narrowing at the Stalgene Bridge and at the mouth of Garoze (right bank tributary). At the Stalgene section, ice-jam persists for quite a long time, and under these conditions both the river floodplain and the fields are inundated.

Meteorological conditions

Air temperature plays the most significant role in the river freezing and ice breaking processes. Lielupe River ice regime analysis results show several ice floes during the freeze-up period (November–December) due to unstable air temperature and, as a result, several ice-jams that usually don't cause high floods. The sum of negative degree days (NDD) for these ice-jams does not exceed -300 (Bauska NS); by comparison, the sum of NDD before the break-up might be close to -1000. There is a certain relationship between the sum of NDD and the ice-jam volume (Fig. 3.2.1).

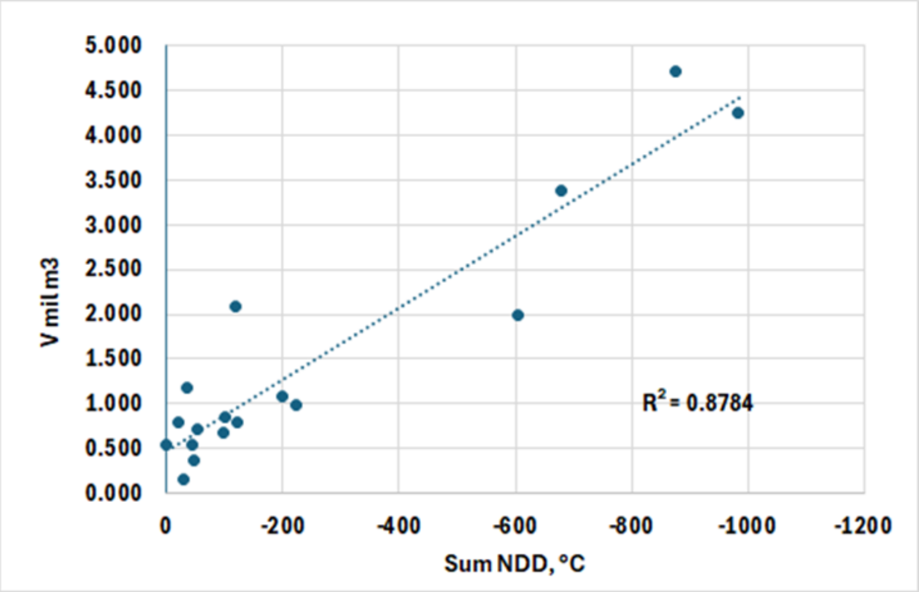


Figure 3.2.1. Relationship between ice-jam volume and sum of NDD, HS Lielupe – Mezotne

The scatter of observation points on Figure 3.2.1 is related to the relatively large uncertainty of the ice-jam volume values that were calculated taking into account the observation data from HS Bauska and HS Tabokine. While HS Bauska is located not far away from the HS Lielupe–Mezotne, the length of the Memele River stretch from the HS Tabokine to the junction with Musa River is about 70 km.

The most significant factors for the ice break-up process are both the count and the sum of positive degree days (PDD). Analysis results of the observed ice-jams near the Mežotne Palace show that more than 90% of the ice-jams occurred during rapid springs, when the count of the PDD was less than 50–55 days but the sum of PDD was below 80 (Fig. 3.2.2). In 1980, the count of PDD was 18 and the sum was >29,6.

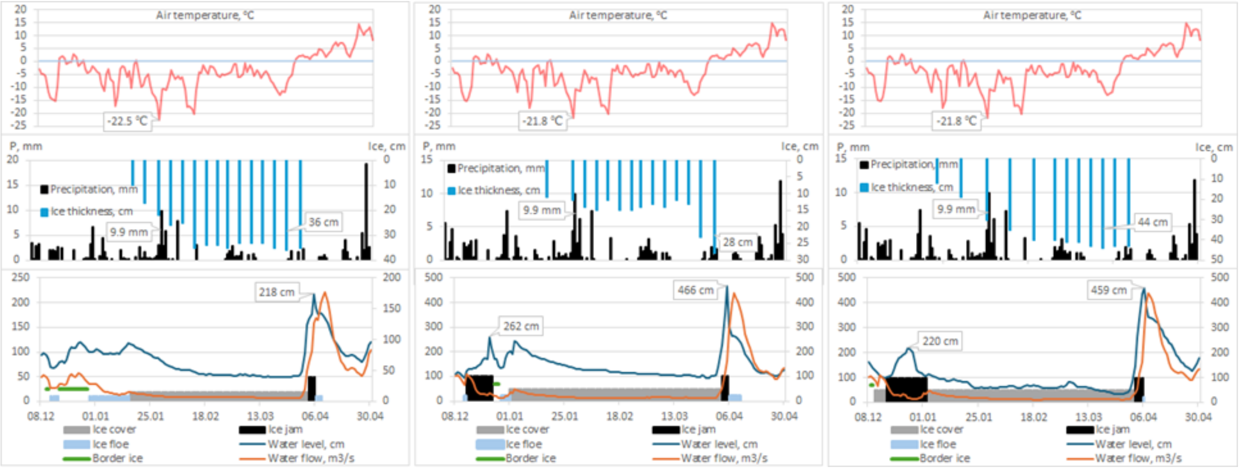


Figure 3.2.2. Integrated graphs of the meteorological (MS Bauska) and hydrological parameters (HS Bauska – left, HS Mežotne – centre and HS Stalgene – right) of the Lielupe River, 1980

In winter 1979/1980, the first ice-jam in the Lielupe River was observed during the freeze-up process in the middle of December 1979, after ice moved from the Musa River. Due to the rapid spring that started in the end of March 1980, the ice floe caused the second ice-jam, much higher than the first one.

If the ice break-up process lasts a long time and air temperature varies from negative to positive values, ice-jams are usually not observed (Fig. 3.2.3). In 2020, the count of PDD was 86 and the sum was >260.

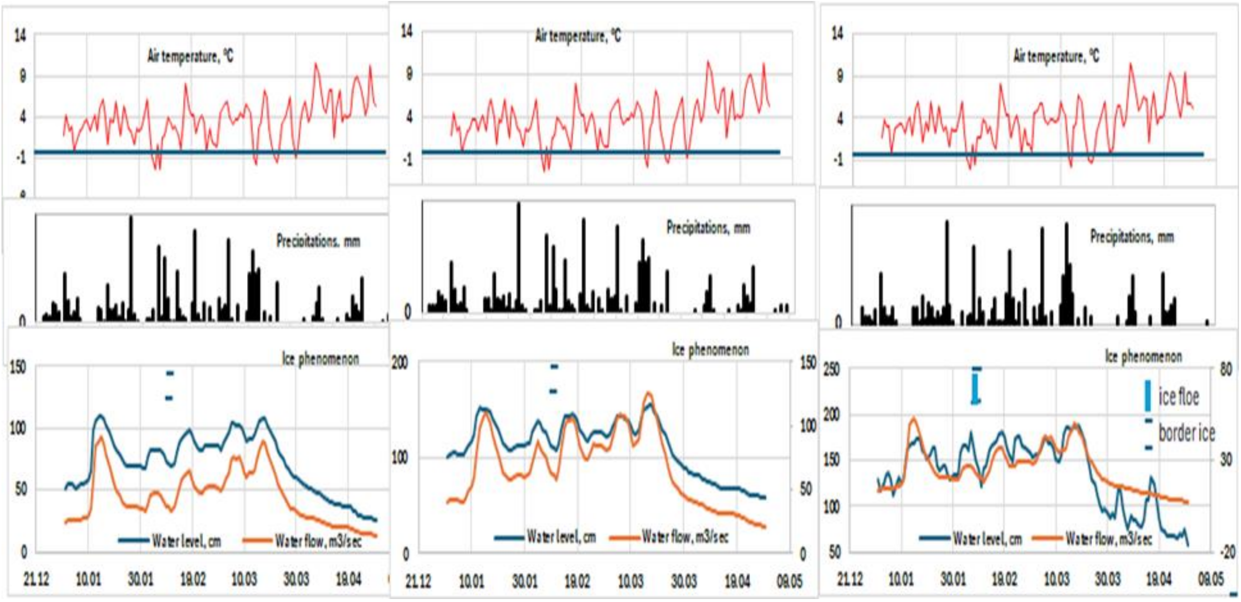


Figure 3.2.3. Integrated graphs of the meteorological (MS Bauska) and hydrological parameters (HS Bauska – left, HS Mežotne – centre and HS Stalgene – right) of the Lielupe River, 2020

Figure 3.2.3 illustrates variations of the air temperature, precipitation, water level, water discharge and ice phenomena along the Lielupe River, starting from the HS Musa–Bauska. Year 2020 had hydro-meteorological conditions typical for warm winters without full ice cover and ice phenomena in the form of border ice and ice floe. For almost the whole season, the air temperature was above 0℃ but the amount of precipitation varied from 14 mm in April 2020 (about 60% below the norm) to 37 mm in February 2020 (about 9% above the norm).

Sum of the PDD affects the ice-jam formation in spring, as well as in winter during thawing (Fig. 3.2.4).

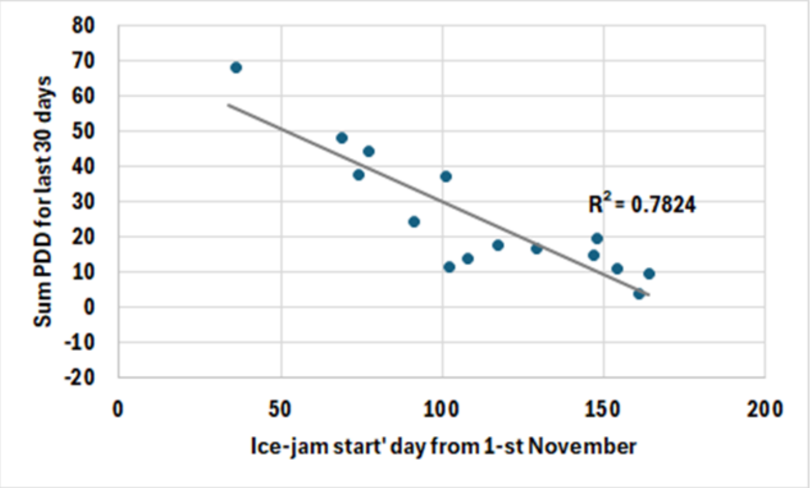


Figure 3.2.4. Relationship between ice-jam starting day and the sum of PDD for 30 days before the ice-jam, HS Mezotne

This relationship is valid if the ice period is 30 days or longer. For HS Stalgene, an ice-jam is usually formed after ice-jam disappears in Mezotne. Therefore, for HS Stalgene the ice-jam starting date is a few days later.

Precipitation plays an important role in the ice-jams formation during the freeze-up period. In cooling water, when the air temperature decreases below 0℃, border ice appears along river banks and frazil ice forms within the stream. Precipitation in the form of snow facilitates appearing of the slush ice and then the slush ice-jam formation. As usual, it starts first in the upper stretches of river and goes downstream with ice-jam formation. In the Lielupe River, such an upper stretch is the Musa River.

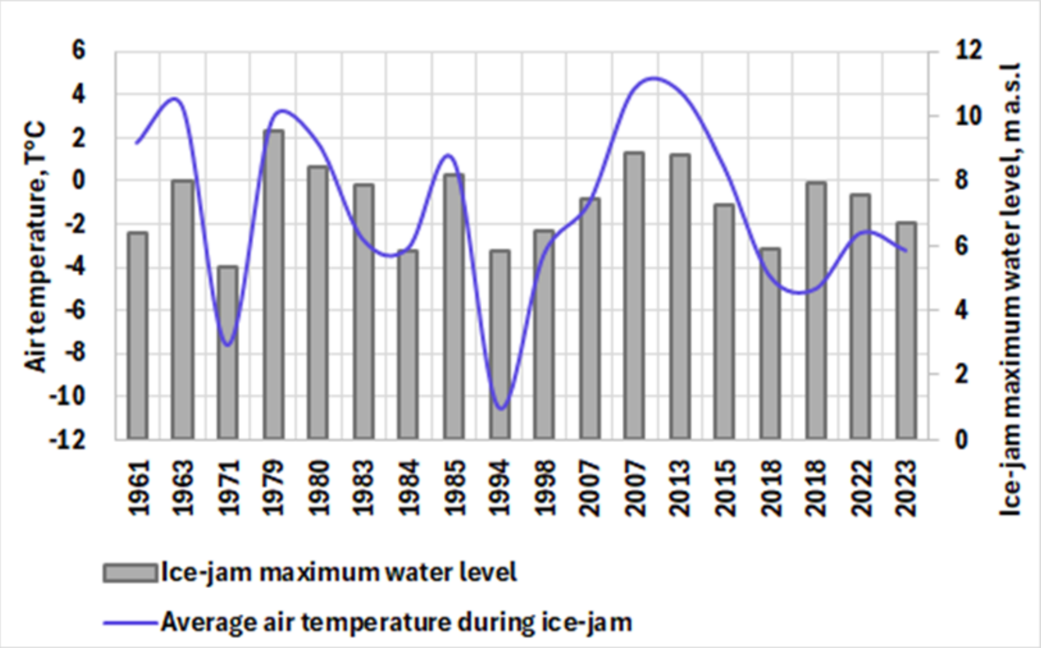


Figure 3.2.5. Relationship between average air temperature during the ice-jam and the maximum water level of the ice-jam, HS Mezotne

The maximum water level of the ice-jams corresponds quite closely to the average air temperature during the ice-jam (Fig. 3.2.5). The correlation coefficient between these two data series is 0.76.

Hydrological conditions

Analysis of the ice-jam events in the Lielupe River shows that, similarly to the Daugava River, the water level before the ice-jam is the crucial factor determining the ice-jam flood maximum water level (Fig. 3.2.6).

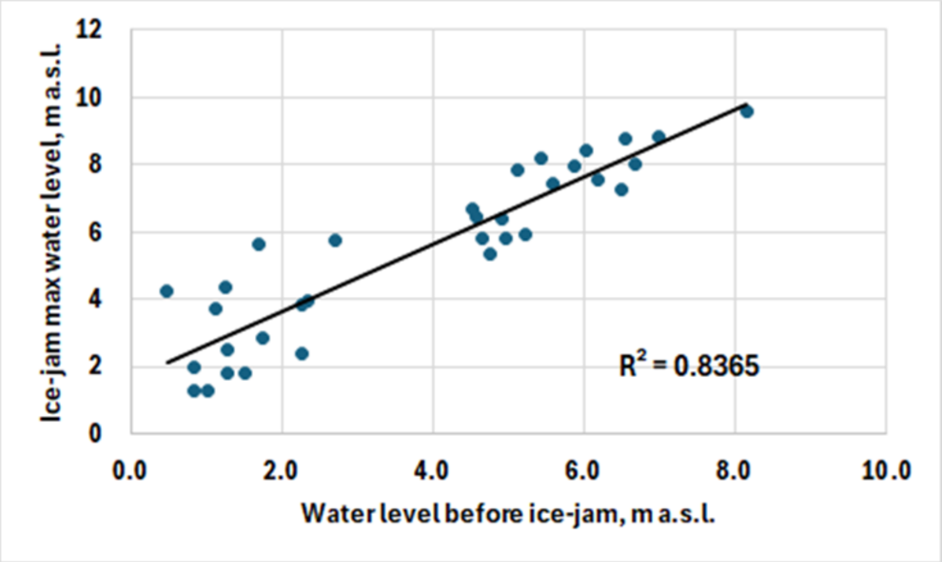


Figure 3.2.6. Dependence of the ice-jam maximum water level on the water level before the ice-jam, HS Mezotne

As is the case with the Daugava River, also in the Lielupe River both water discharge and water level are very important factors in the ice-jam formation (Fig. 3.2.7). Evidently, the water discharge has to be not less than 100 m^3/sec for transportation of the frazil and slush ice along the Lielupe River from the upstream river stretch to the Mezotne Palace location downstream.

Similarly to the previously discussed Daugava River analysis, also for the Lielupe River correlation between the water level before the ice-jam and ice-jam maximum water level is quite close. When ice formation and ice-jamming starts in the high water period it is more likely that ice-jam maximum water level will be high and will lead to flooding. Due to warmer and wetter autumn-winter periods, it is expected that ice formation under the conditions of increased river flow will become more frequent.

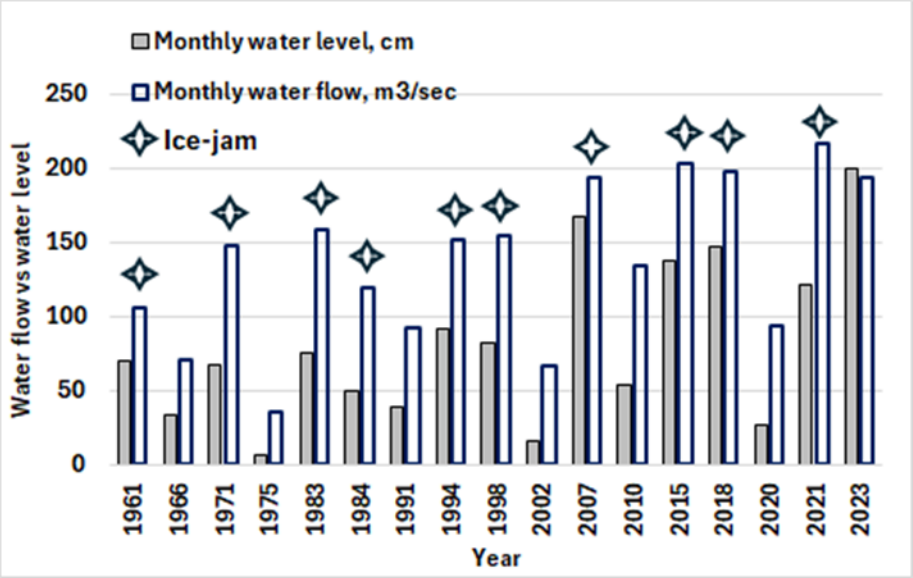


Figure 3.2.7. Water flow and water level during freeze-up with and without ice-jam, HS Mezotne

Main factors for the ice-jam formation in the Lielupe River stretch from the junction of Musa and Memele rivers to Sesava River:

1. *River morphology:*
   - Islands;
   - presence of narrowest sections;
   - rapid depth variations from one section to another;
   - Stalgene bridge constructions.
2. *Meteorological conditions:*
   - sum of NDD – during the freeze-up period (November–December), due to unstable air temperature, the sum of NDD doesn't exceed -300, hence ice-jams don't cause the high floods. In spring, the sum of NDD before the break-up might be close to -1000.
   - days count and sum of PDD – in the ice break-up process more than 90% of ice-jams occurred in the case of rapid spring, when the count of the PDD was less than 50–55 days but the sum of PDD was below 80.
   - average air temperature during ice-jam leads to ice and snow melting thereby affecting the maximum water level of ice-jams.
3. *Hydrological conditions:*
   - Water level before the ice-jam lower than 100 cm in HS Mezotne causes insignificant ice-jam maximum elevation, but if it is ≥200 cm the territory will be inundated.
   - Water discharge has to be not less than 100 m^3/sec for transportation of the frazil and slush ice along the Lielupe River.

3.3. Muša River between settlements Gustoniai to Ustukiai

Morphological conditions

The Muša river stretch from Gustoniai to Ustukiai features a relatively straight channel with gentle, smoothly curved meanders (sinuosity coefficient 1,33). The river also includes multiple branching systems formed by clusters of small islands. These islands reduce the width of the river in certain areas and can act as natural barriers favouring ice jam formation. The river width varies significantly, ranging from 15 meters at its narrowest to 70 meters at its widest, with an average width of 30–40 meters. Depths also fluctuate, primarily between 1–2 meters, though some sections reach up to 4 meters. The riverbed has a gradual slope of 0,35 meters per kilometer, and the flow speed varies between 0,1–0,4 meters per second.

Due to some sharp bends and the presence of an important logistical bridge at Ustukiai, ice jams can form, posing a risk to the nearby communities of Gustoniai and Pasvalys, as well as seasonal residences along the river.

Meteorological and hydrological conditions

At the beginning of the analysis, LHMS grouped ice jams into three types: freeze-up ice-jams, mid-winter and break-up spring ice-jams. But due to the small number of cases it was decided to use all cases (without classifying).

For Muša – Ustukiai HS, the best and most correlations were obtained without classifying ice jams into types (Freeze up, Mid-Winter, Spring) and examining only events where ice thickness data were known. The analysis was performed based on 17 events: 1972 (3 events), 1978, 1980 (3 events), 1986 – 1988, 1993 (2 events), 1994, 1998, 1999, 2010, and 2013.

Table 3.3.1. The correlation matrix method results of hydrological and meteorological parameters in Muša river (Ustukiai HS). Correlation coefficients equal or above 0,70 and equal or less than -0,70 were determined as significant

Hydrological / morphological parameters	**H at the beginning of ice-jam**	**H max of ice jam**	**Q max of ice jam**	**Stream velocity**	**Ice thickness**	**Ice jam Volume**
H max of ice jam	0,99	-				
Q max of ice jam	0,95	0,93	-			
Stream velocity	0,90	0,87	0,81	-		
H rising days	–0,56	–0,51	–0,53	–0,58		
Ice thickness	0,48	0,45	0,55	0,35	-	
Ice jam Volume	0,66	0,64	0,73	0,51	0,95	-
Sum of negative air T month before ice-jam	0,77	0,73	0,76	0,66	0,87	0,89
Sum of positive air T month before ice-jam	–0,41	–0,40	–0,38	–0,32	–0,66	–0,57

Hydrological / morphological parameters	H at the beginning of ice-jam	H max of ice jam	Q max of ice jam	Stream velocity	Ice thickness	Ice jam Volume
Monthly air T°C vs norma month before ice-jam	–0,53	–0,50	–0,51	–0,54	–0,63	–0,63
Monthly air T°C vs norma during ice-jam	0,47	0,50	0,49	0,31	0,23	0,31
Positive air T days during last 30 days	–0,44	–0,42	–0,43	–0,39	–0,73	–0,65
Sums of positive air T during last 5 days	0,82	0,78	0,86	0,81	0,35	0,49
Positive air T days during last 5 days	0,70	0,66	0,70	0,67	0,46	0,57
Sums of positive air T during last 2 days	0,85	0,80	0,89	0,85	0,33	0,47
Positive air T days during last 2 days	0,87	0,83	0,87	0,82	0,54	0,68

For Lithuanian data analysis, additional meteorological parameters were included. The reason for this is the methodology of ice phenomena prediction based on temperature counts that are used in Lithuania:

- Positive air T days during the last 30 days before the ice jam;
- Sums of positive air T during the last 5 days before the ice jam;
- Positive air T days during the last 5 days before the ice jam;
- Sums of positive air T during the last 2 days before the ice jam;
- Positive air T days during the last 2 days before the ice jam.

This study analyzes the correlation matrix of hydrological and meteorological parameters involved in ice jam formation at the Ustukiai WGS. A chronological approach is used to describe the sequence of events leading to ice jam formation, with an emphasis on parameter importance based on correlation coefficients.

As it is known, ice jams occur when floating ice accumulates and obstructs river flow, leading to significant hydrological disruptions and flooding. The formation of ice jams depends on a combination of meteorological and hydrological factors. This analysis aims to examine these factors based on statistical correlations, identifying key contributing parameters and their chronological sequence in the formation of ice jams.

The correlation matrix of hydrometeorological parameters was analyzed to determine the relationships between variables influencing ice jam formation. The analysis focused on key parameters such as water level, discharge, stream velocity, air temperature variations, and ice thickness. Correlation coefficients were used to assess the strength and direction of relationships, with parameters arranged in chronological order based on their influence on ice jam initiation, growth, and culmination.

Initial conditions: temperature and ice growth

Prior to ice jam formation, sub-zero temperatures persist for an extended period, leading to ice growth. The **sum of negative air temperatures in the month before ice jam formation** shows a significant correlation with **ice thickness**. This correlation suggests that colder preconditions result in thicker ice cover, providing a necessary foundation for subsequent ice jam development. **The best correlation with ice jam volume** is the sum of negative air T month before ice-jam (correlation coefficient 0,89). The worst correlation (coefficient 0,65–0,68) is with positive air T (days during the last 30 days and days during the last 2 days). The volume of ice depends on the sum of the negative air temperatures, as colder temperatures lead to faster and more intense ice formation. At sub-zero temperatures, water begins to freeze, and the longer and lower the temperature stays, the more ice is formed. This means that prolonged periods of low temperatures or very low temperatures can increase the volume of ice in a short time.

Years with high sums of negative air temperatures (e.g., 1980, 1986, 1987, 2010) tend to have larger ice jam volumes, while years with low negative air temperature sums (e.g., 1998, 1999) show relatively small ice jam volumes, reinforcing that warmer winters lead to less ice formation (Fig. 3.3.1).

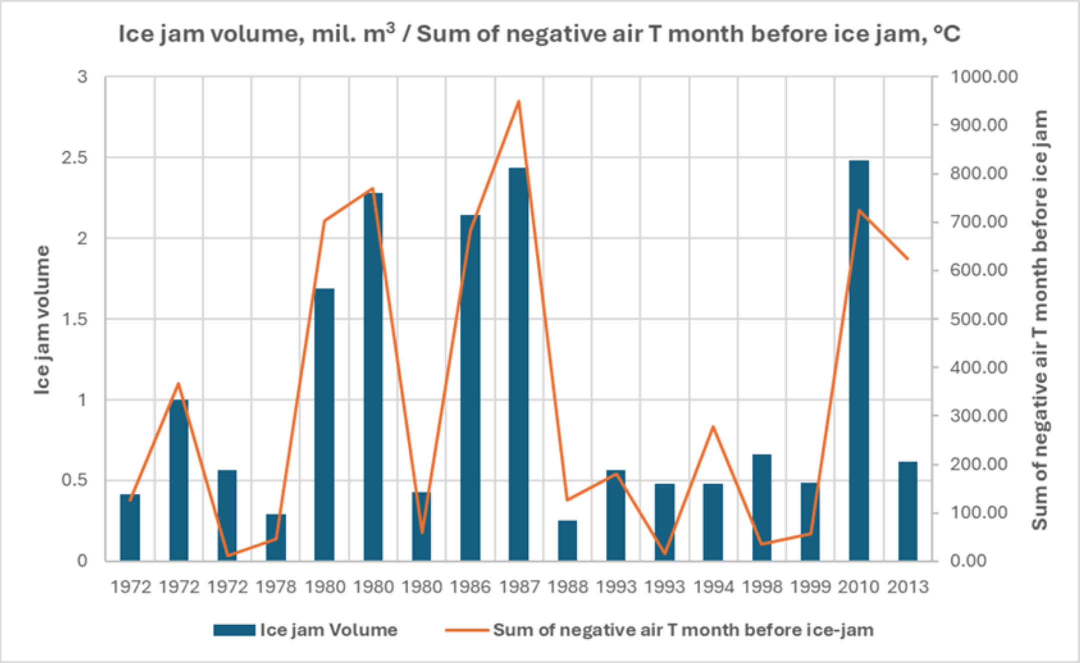


Figure 3.3.1. Relation between cold air temperatures and ice jam volume in Muša – Ustukiai HS

When the sum of negative temperatures is high (above 600°C), the ice jam volume is also higher, often exceeding 2.0 mil. m³. For lower negative air temperature sums (below 200°C), ice jam volume varies widely, indicating that other factors (e.g., river flow, precipitation) might also influence ice formation (Fig. 3.3.2).

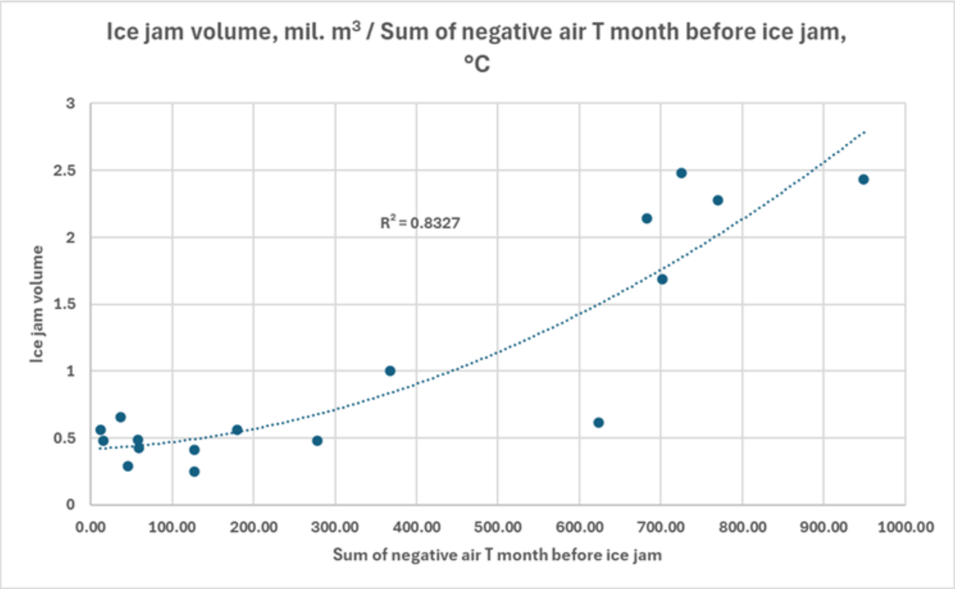


Figure 3.3.2. Scatter plot visualizing the relationship between Sum of negative air temperature (°C) before ice jam formation and Ice jam volume (mil. m³)

The best correlation with ice thickness shows the sum of negative air T for one month before ice-jam (0,87), as well as positive air T days during the last 30 days (0,73). When temperatures are consistently below freezing point, ice formation is more likely to occur and accumulate over time. The colder it gets, the thicker the ice can become, as the freezing process continues uninterrupted.

As for positive air temperatures, warmer temperatures in the daytime lead to ice melting or weakening. This can lead to formation of ice jams as the ice breaks apart and moves downstream, potentially causing blockages. In summary, the combination of prolonged cold periods followed by warmer temperatures can significantly influence ice thickness and the likelihood of ice-jams. The strong correlation values indicate that these temperature patterns are reliable predictors of ice conditions.

When the sum of negative temperatures exceeds 600°C, ice thickness is generally above 0,45 m, confirming that colder and prolonged freezing periods contribute to thicker ice formation. For lower sums of negative air temperatures (below 200°C), ice thickness varies between 0,08 m and 0,18 m, indicating that shorter cold periods result in thinner ice (Fig. 3.3.3).

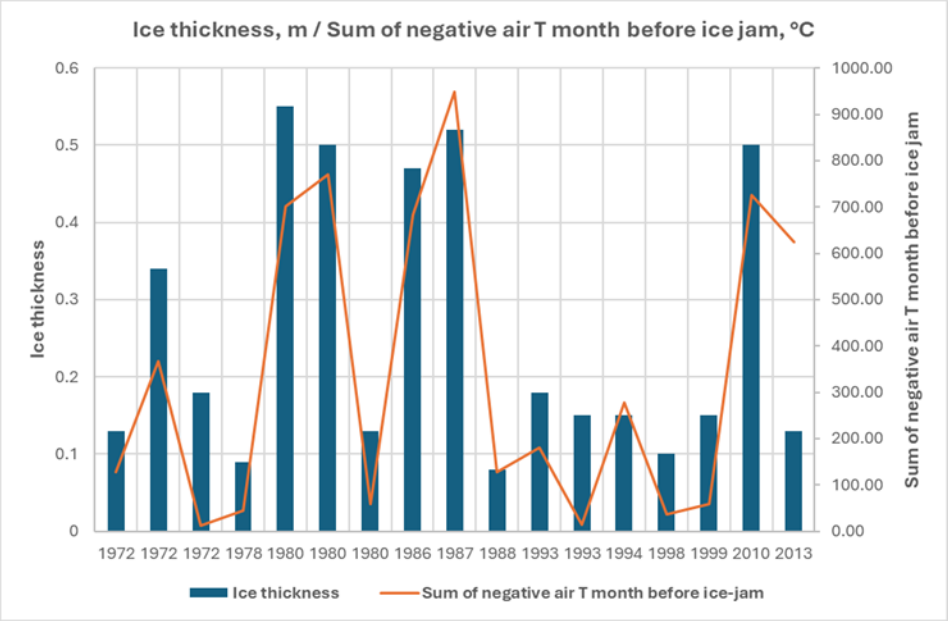


Figure 3.3.3. Relationship between sum of negative air temperature (°C) before ice jam formation and ice thickness (m) in Muša-Ustukai HS

The Scatter plot trendline with R-value of 0,76 indicates a strong positive relationship between negative air temperature and ice thickness. The spread of points shows some variability, but the trend remains clear (Fig. 3.3.4).

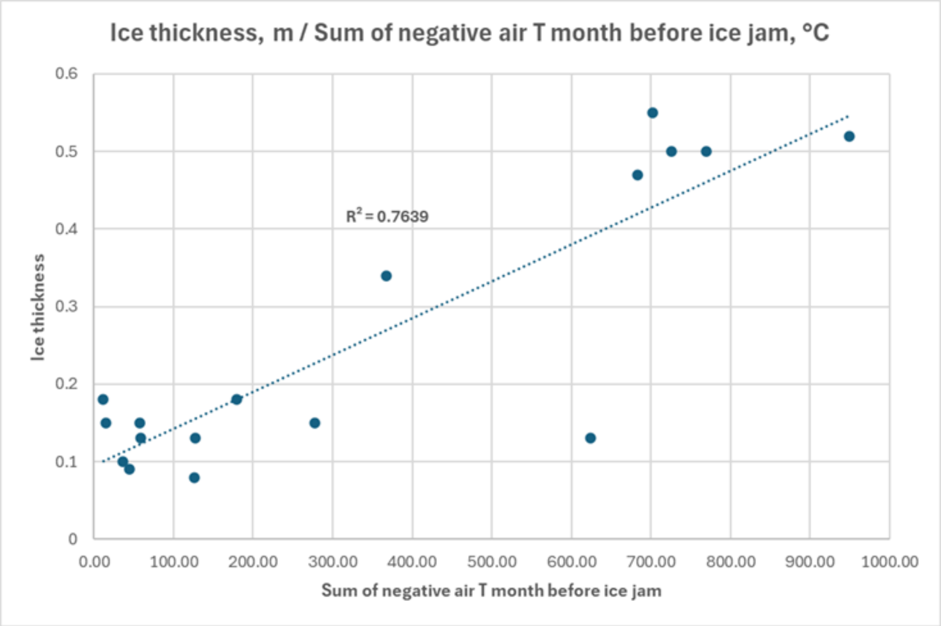


Figure 3.3.4. Scatter plot of relationship between sum of negative air temperature month before ice jam (°C) and ice thickness (m) in Muša - Ustukiai HS

Onset of thawing and increased river discharge

As temperatures rise, the number of positive air temperature days and accumulated positive temperatures increase in the days preceding the ice jam. These parameters show moderate to strong correlations with river discharge (Q max of ice jam), indicating that warming trends contribute to increased melting and runoff, elevating streamflow. Positive temperatures of the last 5 – 2 days are of particular importance, as their correlation coefficients vary from 0,70 (correlation with positive air T days during last 5 days) to 0,89 (correlation with sums of positive air T during the last 2 days).

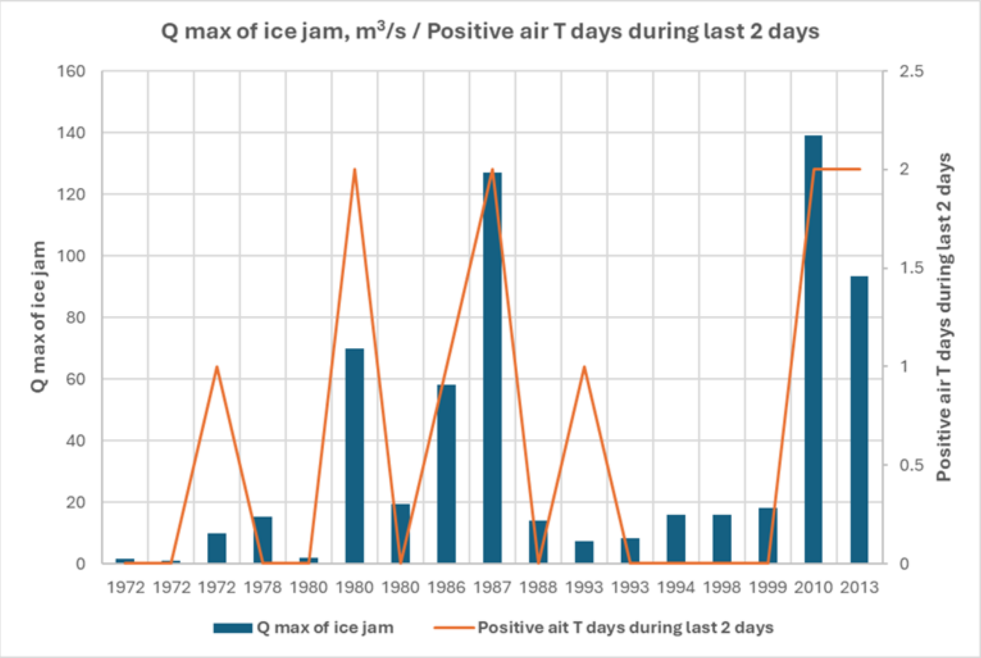


Figure 3.3.5. Relation between Q max of ice jam (m^3/s) and Sum of positive air temperature days during the last 2 days before ice jam in Muša - Ustukiai HS

In 2010 and 2013, higher sums of positive air temperatures (10°C and 11,1°C, respectively) coincided with very high Q max values (139 m^3/s and 93,3 m^3/s). This suggests that short-term warming events may contribute to increased ice jam intensity (Fig. 3.3.5).

The scatter points indicate that as positive air temperature increases, Q max of ice jam also increases. Several ice jams occur even when positive air temperatures are 0°C, with Q max values still reaching 15-20 m^3/s. This means that other factors (e.g., ice accumulation, river flow) also influence ice jam formation (Fig. 3.3.6).

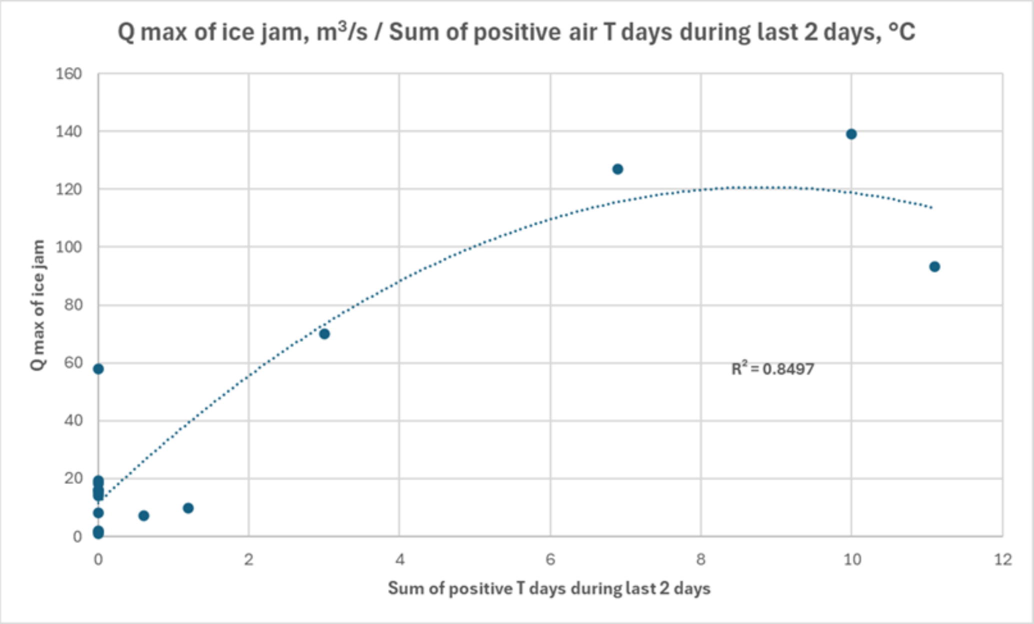


Figure 3.3.6. Scatter plot of relationship between sum of positive air temperature 2 days before ice jam and Q max in Muša - Ustukiai HS

The analysis shows that **H at the beginning of the ice-jam depends on stream velocity** (correlation coefficients 0,90), sums of positive air T during the last 2 days (0,85). Faster-moving water can break up ice more effectively, causing it to pile up and form thicker jams. Conversely, slower-moving water may allow ice to form more gradually and evenly. Higher stream velocities can transport more ice downstream, leading to the accumulation of ice at certain points, which increases the height of the ice-jam.

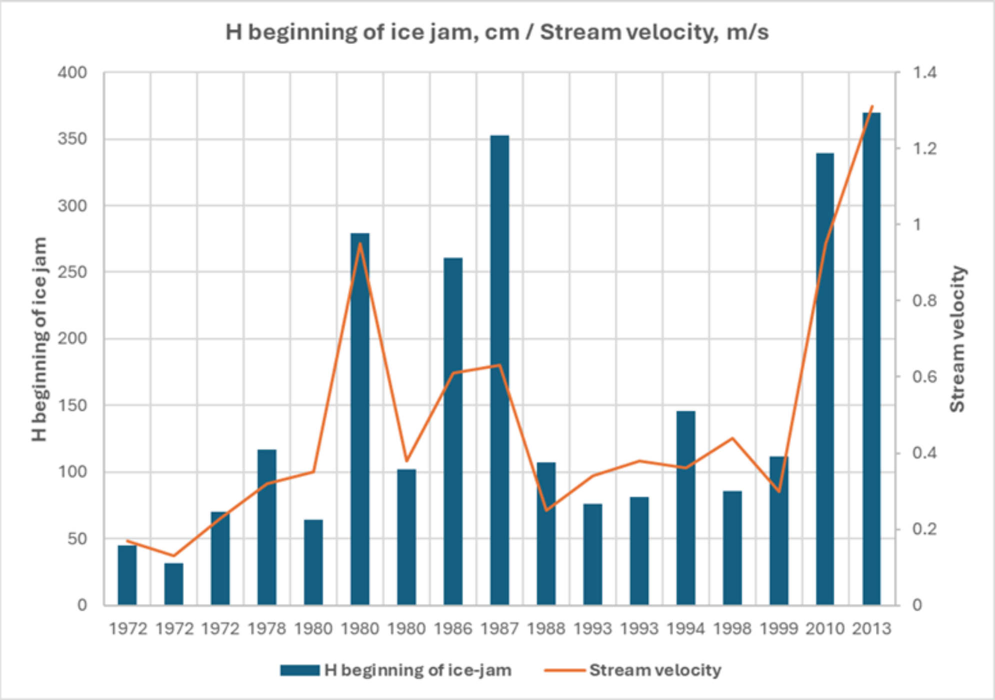


Figure 3.3.7. Relation between H beginning of ice jam (cm) and stream velocity (m/s)

Before 2000, stream velocity remained below 0,5 m/s but spiked in 2010 (0,95 m/s) and 2013 (1,31 m/s). This increase suggests that faster streamflow might be influencing higher water levels during ice jams (Fig. 3.3.7).

The data points are not evenly distributed, indicating non-uniform behavior in how ice-jam heights respond to different stream velocities. At lower stream velocities (below 0,5 m/s), the points are scattered widely, showing high variability in ice-jam heights, meaning that other environmental factors may also contribute to ice-jam height formation. At higher stream velocities (above 0,9 m/s), the points are closer together, suggesting that higher velocities consistently lead to larger ice-jam heights. These extreme values pull the trend line upward, confirming a strong positive relationship between stream velocity and ice-jam height (Fig. 3.3.8).

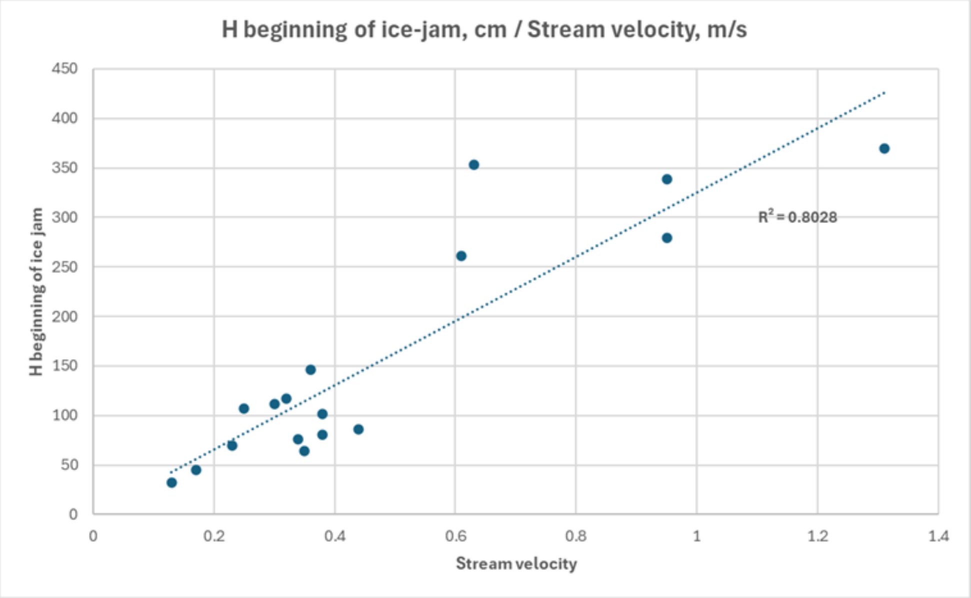


Figure 3.3.8. Scatter plot of relation between H beginning of ice jam (cm) and stream velocity (m/s)

Ice breakup and flow acceleration

The onset of ice breakup is marked by increasing stream velocity, which correlates strongly with maximum river discharge (0,81). As stream velocity increases, ice fragments are mobilized downstream, where they accumulate and form an obstruction.

Between 1972 and 1999, Q max of ice jam remained mostly below 20 m^3/s, except for a few spikes. During this period, stream velocity also remained relatively low (below 0,5 m/s). In 2010 and 2013, both Q max and stream velocity peaked, indicating severe ice jam events occurring with high river flow speeds. This suggests that faster river flow might contribute to more extreme ice jam discharges (Fig. 3.3.9).

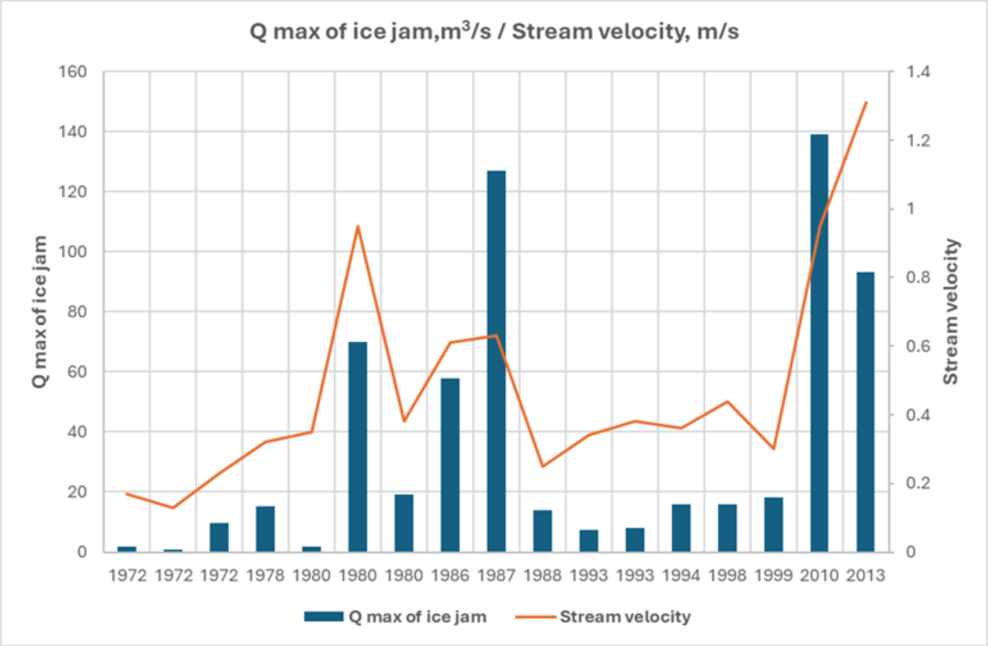


Figure 3.3.9. Relation between Q max of ice jam (m^3/s) and stream velocity (m/s)

The majority of points are clustered between 0,2 and 0,5 m/s with Q max values below 20 m^3/s. High stream velocity values (above 0,9 m/s) correspond to extreme Q max values (above 90 m^3/s). Between 0,5 m/s and 1,0 m/s, Q max values show greater spread (ranging from 20 m^3/s to 139 m^3/s). This suggests that while higher stream velocity is a factor, other environmental conditions (e.g., ice thickness, air temperature) may also play a role in extreme ice jam events. The trendline follows the data closely, showing a general upward pattern (Fig. 3.3.10).

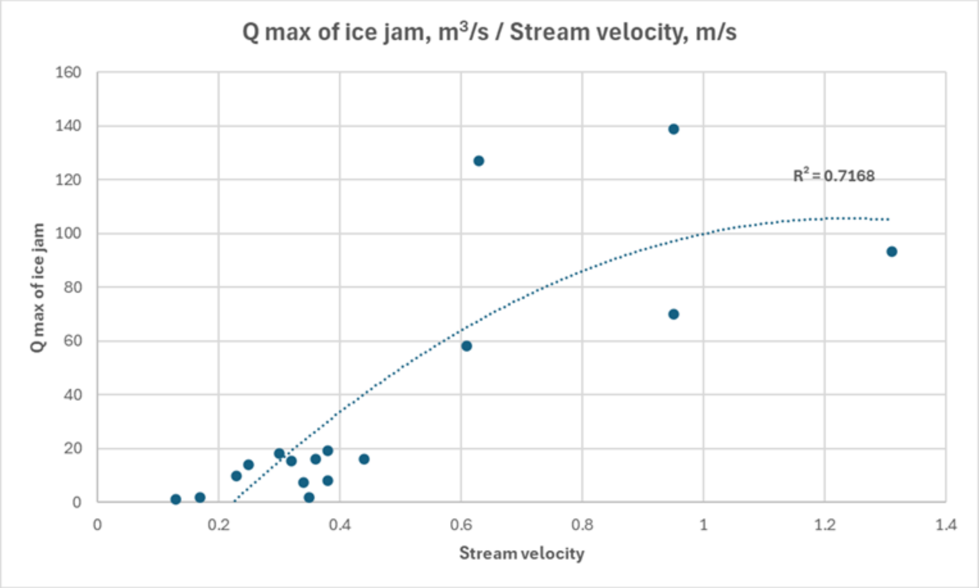


Figure 3.3.10. Scatter plot of relation between Q max of ice jam (m^3/s) and stream velocity (m/s)

Ice jam formation and water level rise

Water level at the beginning of ice jam (H beginning of ice-jam) is strongly correlated with maximum water level during the ice jam (H max of ice jam) at 0,99, suggesting that initial water levels play a crucial role in determining peak water level during the ice jam.

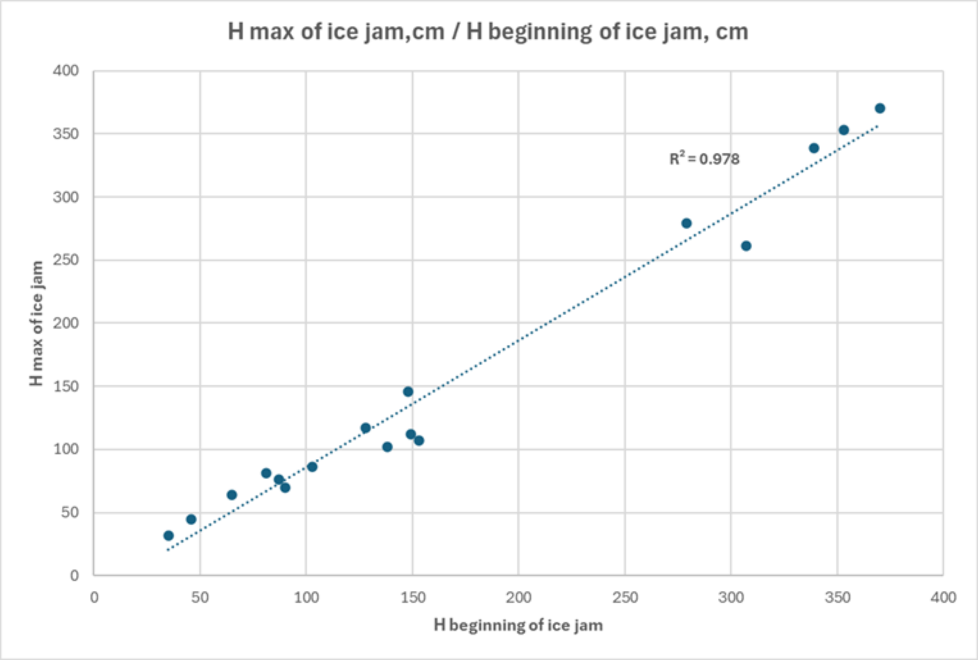


Figure 3.3.11. Scatter plot of relation between H max of ice jam (cm) and H beginning of ice jam

There is a strong positive correlation between initial and maximum ice-jam water levels. The data points follow a linear pattern, meaning that higher initial ice-jam heights tend to result in higher maximum ice-jam heights. The trend line closely follows the data points, confirming a strong relationship between the two variables. Predicting the maximum ice-jam water level based on initial observations could be useful for flood forecasting (Fig. 3.3.11).

As fragmented ice accumulates at a constriction point, an ice jam forms, causing a rise in water levels. The maximum ice jam water level (H max of the ice jam) is highly correlated with discharge (Q max of ice jam) at 0,93 and stream velocity (0,86), reflecting the direct impact of increased flow on ice jamming. The difference in water level between the onset and peak of the ice jam shows a weaker correlation, indicating that local conditions may influence the extent of backwater rise.

1980, 2010, and 2013 stand out as years where both H Max and Q Max are high, indicating extreme ice-jam events. While Q max shows peaks, its trend is less consistent, suggesting it is influenced by additional environmental conditions (Fig. 3.3.12).

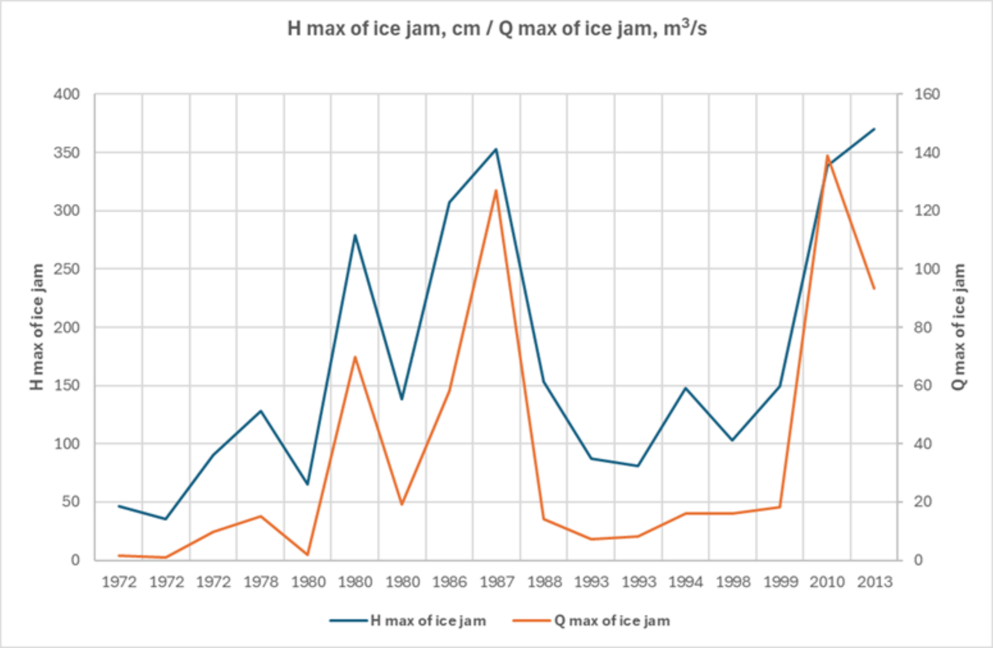


Figure 3.3.12. Relation between H max of ice jam (m^3/s) and Q max of ice jam (m^3/s)

1980, 2010, and 2013 exhibit both high ice-jam water levels and high stream velocities, suggesting a strong relationship between flow speed and ice-jam growth. In 2013, stream velocity peaked at 1,31 m/s, while H max of the ice-jam reached 370 m^3/s, the highest recorded in the dataset. This indicates that faster river flows may contribute to larger ice jams, likely by increasing ice accumulation and ice transport downstream (Fig. 3.3.13).

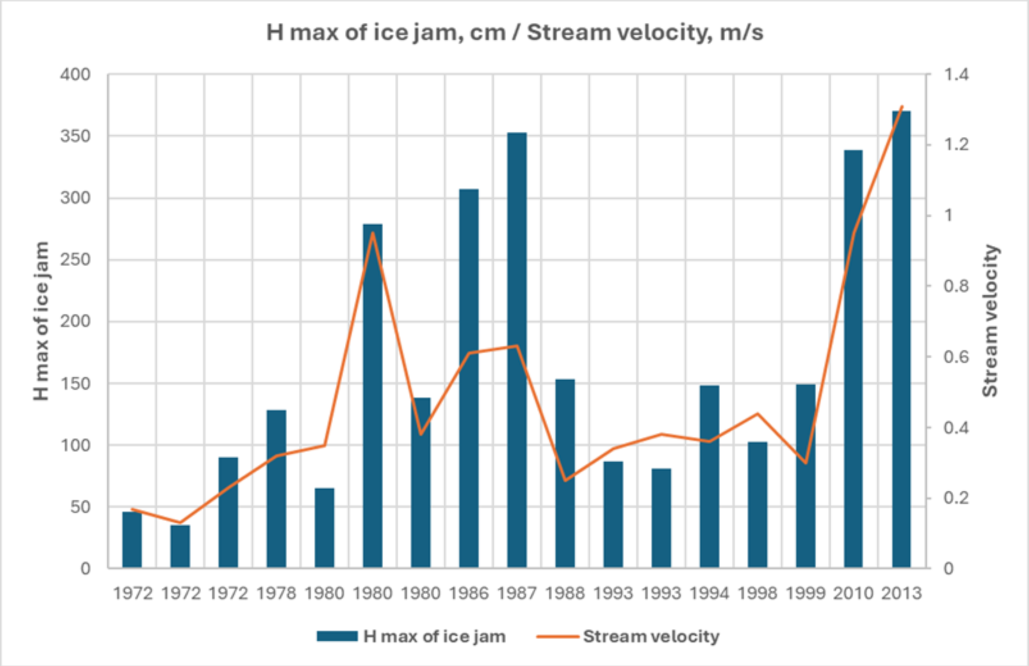


Figure 3.3.13. Relation between H max of ice jam (m^3/s) and stream velocity (m/s)

Strong positive correlation is observed between stream velocity and ice-jam height: the scatter points follow an upward trend, indicating that higher stream velocities are generally associated with higher ice-jam water levels. However, some points deviate significantly, suggesting that additional influencing factors exist beyond stream velocity alone (Fig. 3.3.14).

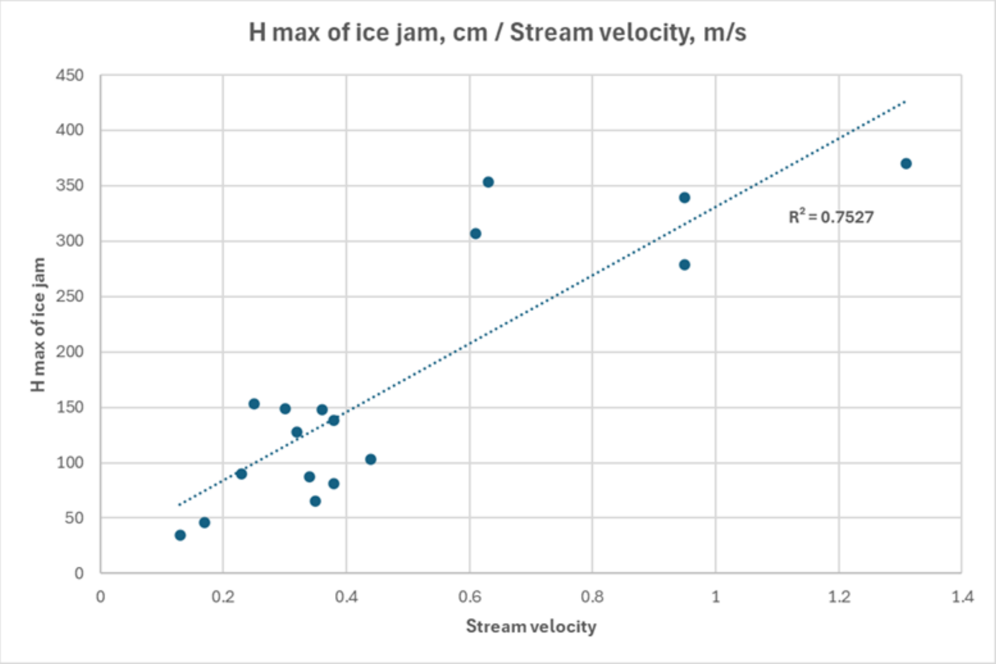


Figure 3.3.14. Scatter plot of relation between H max of ice jam (cm) and stream velocity (m/s)

At the peak of the ice jam, water levels reach their maximum, leading to potential flooding if the ice jam persists. The **ice jam volume**, while correlated with **maximum discharge (Q max of ice jam)** (0,73), exhibits variability due to dynamic river conditions. The final stage involves either the gradual melting of the jam or its sudden mechanical breakup, which results in downstream ice movement and a subsequent drop in water levels.

The 2010 peak in Q max (139 m^3/s) corresponds to the highest ice jam volume (~2.48 mil. m^3), showing a strong link between flow discharge and total ice accumulation. Similar correlations are visible in 1980 and 1986, reinforcing the idea that years with severe ice jams often experience both high discharge and large ice accumulations (Fig. 3.3.15).

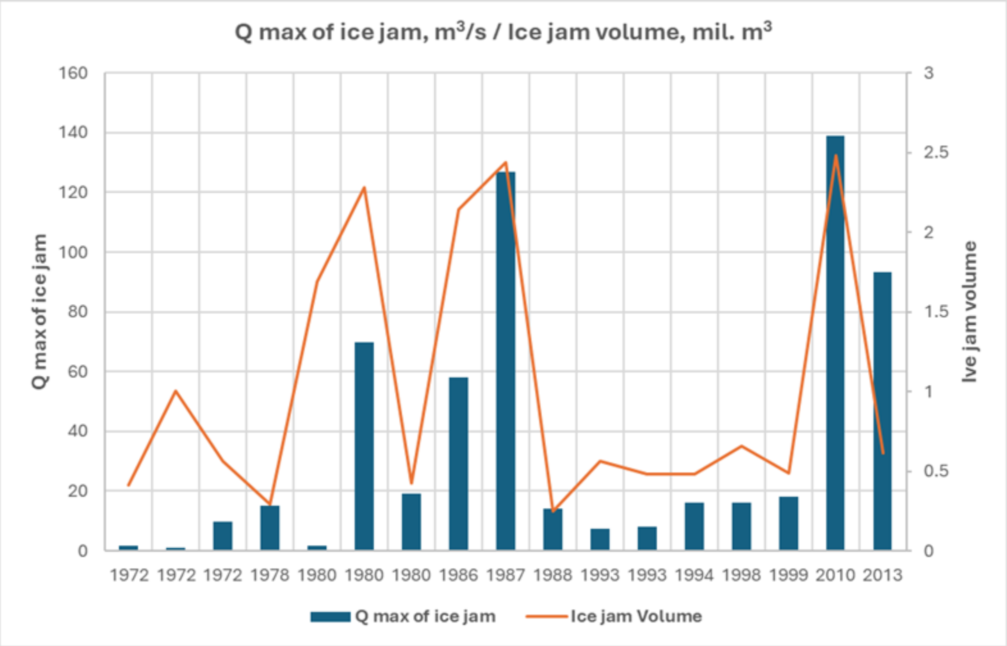


Figure 3.3.15. Relation between Q max of ice jam (m^3/s) and ice jam volume (mil. m^3)

When the ice jam volume is below 1,0 mil. m^3, Q max values vary widely (from 0,96 m^3/s to over 15,0 m^3/s). This suggests that small ice jams do not always cause severe flow discharges, likely due to other factors like stream velocity and temperature. The largest ice-jam events (~2,0 mil. m^3 to 2,5 mil. m^3) consistently correspond to higher Q max values (above 50 m^3/s, with extreme cases reaching 139 m^3/s). This supports the idea that severe ice-jam conditions often result in extreme river blockages and flooding potential (Fig. 3.3.16).

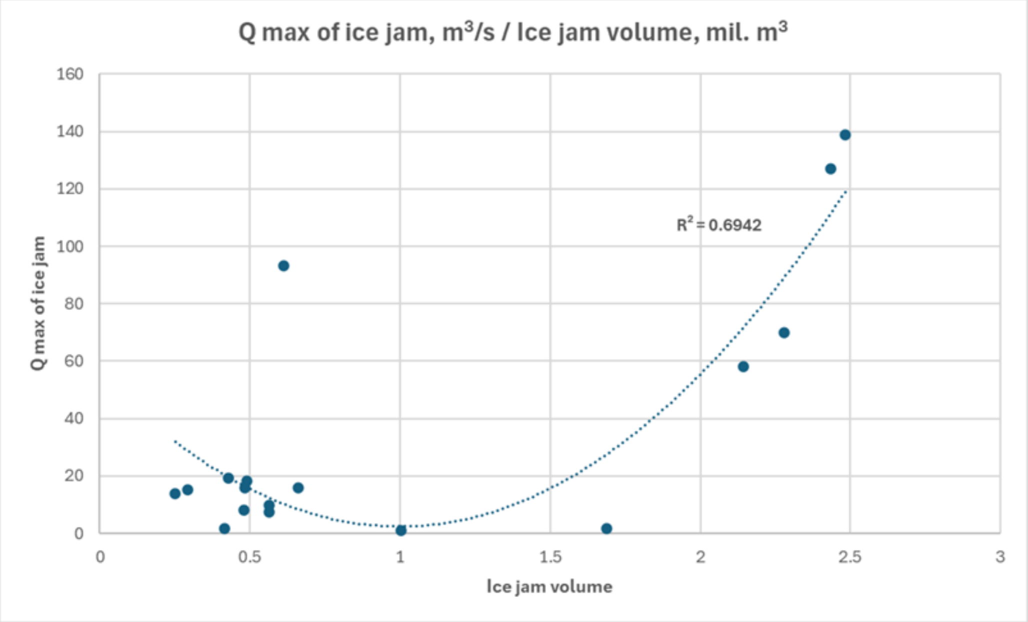


Figure 3.3.16. Scatter plot of relation between Q max of ice jam (m^3/s) and ice jam volume (mil. m^3)

Main factors for the ice-jam formation in the Muša River:

- Colder temperatures before ice-jams lead to thicker ice, larger ice-jam volumes, and stronger river blockages;
- Short-term positive air temperatures (last 5-2 days before the ice-jam) strongly influence ice-jam discharge (Q max), possibly due to rapid melting and ice instability;
- Stream velocity plays a key role in Q max, as faster-moving water contributes to higher ice-jam discharges;
- Monthly precipitation does not show a significant impact on ice-jam formation, suggesting that temperature and river dynamics are the primary drivers.

3.4. Lėvuo River from Pamarliškiai to Bridge in Skaistgiriai

Morphological conditions

The combination of the local climate, the river's pronounced meandering (sinuosity coefficient 2,0), and the presence of multiple bridges and canals along the stretch between Pamarliškiai and Skaistgiriai creates favorable conditions for floods and ice jams. This issue is further complicated by the presence of small settlements and seasonal residences throughout much of the area. The most challenging and hazardous location is where the river connects with the Sanžilė canal. Here, in addition to the division of the channel, multiple road bridges and an old railway bridge with large concrete structures in close proximity contribute to the risk. As a result, this river stretch is particularly vulnerable to ice-jam formation.

The Lėvuo River flows through a flat landscape, meaning it has a low gradient, shallow channels, and predominantly dense soils with limited permeability. Due to these soil characteristics, minimal groundwater replenishes the river. The river follows an unregulated, winding path, with variations in width and depth. The flow is relatively slow, and while several islands exist along this stretch, they have a minor impact on ice-jam floods compared to the sharp bends and numerous artificial structures such as bridges and canals. The combination of sharp meanders and numerous bridges contributes to the formation of ice jams, leading to sections where slush ice and ice blocks periodically accumulate.

Meteorological and hydrological conditions

For Lėvuo - Bernatoniai HS, correlation matrix data analysis was performed based on 19 ice jam events: 1970, 1980, 1984, 1985, 1987, 1988 (3 events), 1989, 1991, 1993 (3 events), 1994 – 1996, 1999, 2006, 2010.

Table 3.4.1. The hydrological and meteorological parameters of Lėvuo river (Bernatoniai WGS). Correlation coefficients (equal or above 0,70 and equal or less than -0,70) were determined as significant

Hydrological / morphological parameters	***H beginning of ice-jam***	***H max of ice jam***	***Q max of ice jam***	***Stream velocity***	***Δ H (beginning - max)***	***Ice thickness***	***Ice jam volume***
H beginning of ice-jam	-						
H max of ice jam	0,86	-					
Q max of ice jam	0,33	0,76	-				
Stream velocity	0,91	0,79	0,39	-			
Δ H (beginning - max)	-0,05	0,47	0,90	-0,02	-		
Ice thickness	0,29	0,62	0,78	0,21	0,70	-	
Ice jam volume	0,50	0,73	0,72	0,40	0,56	0,96	-
Sums of negative air temperature month before ice-jam	0,79	0,89	0,66	0,75	0,37	0,67	0,79
Sums of positive air T during last 5 days	0,72	0,51	0,06	0,68	-0,25	0,00	0,15
Sums of positive air T during last 2 days	0,72	0,57	0,14	0,66	-0,13	0,11	0,23

Initial conditions: ice jam volume and sums of negative air temperatures month before the ice jam (r = 0,79). Formation of ice jams begins with the accumulation of ice during the preceding winter months. A strong correlation (r = 0,79) between the ice jam volume and sums of negative air temperatures in the month before ice jam formation indicates that prolonged cold conditions contribute to extensive ice buildup. These low temperatures lead to thicker ice formation, increasing the likelihood of an obstruction when temperatures begin to rise. Monitoring negative air temperatures provides an early indication of the potential severity of ice jams.

1985, 1999, 2006, and 2010 show higher negative air temperature sums along with larger ice-jam volumes. This confirms that colder winters lead to greater ice-jam accumulation. In 1985, negative air temperature sum exceeded 900 °C, leading to an extreme ice-jam event with a high ice jam volume. Similar trends occurred in 1999 and 2010, where prolonged cold conditions resulted in larger ice-jam formations. Years with lower negative air temperature sums (e.g., 1987, 1996) have smaller ice-jam volumes (Fig. 3.4.1).

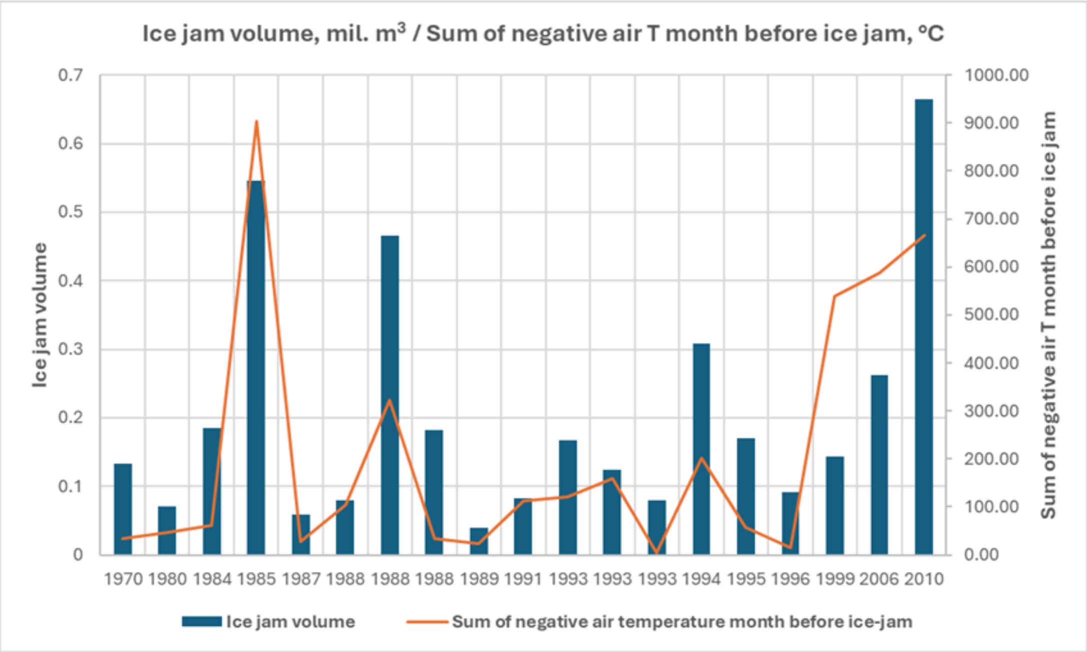


Figure 3.4.1. Relation between ice jam volume (mil. m^3) and sum of negative air temperature from the month before ice jam (°C)

H at the beginning of ice-jam and H max of the ice jam (r = 0,86). As temperatures remain below freezing point, river ice thickens, gradually restricting water flow. The initial stage of ice jam formation is marked by rising water levels as ice accumulates and begins to obstruct the river. A strong correlation (r = 0,86) between the level of water at the beginning of the ice jam and the maximum ice jam height suggests that early water level increases are key indicators of impending ice blockages. Monitoring initial water levels can help predict the severity of an ice jam event.

The majority of the data points follow a near-linear pattern, indicating a strong positive correlation between the initial water level of ice-jams and the maximum water level of ice jams. This suggests that if an ice jam starts at high initial water level, it is very likely to reach high maximum water level before dissipating (Fig. 3.4.2).

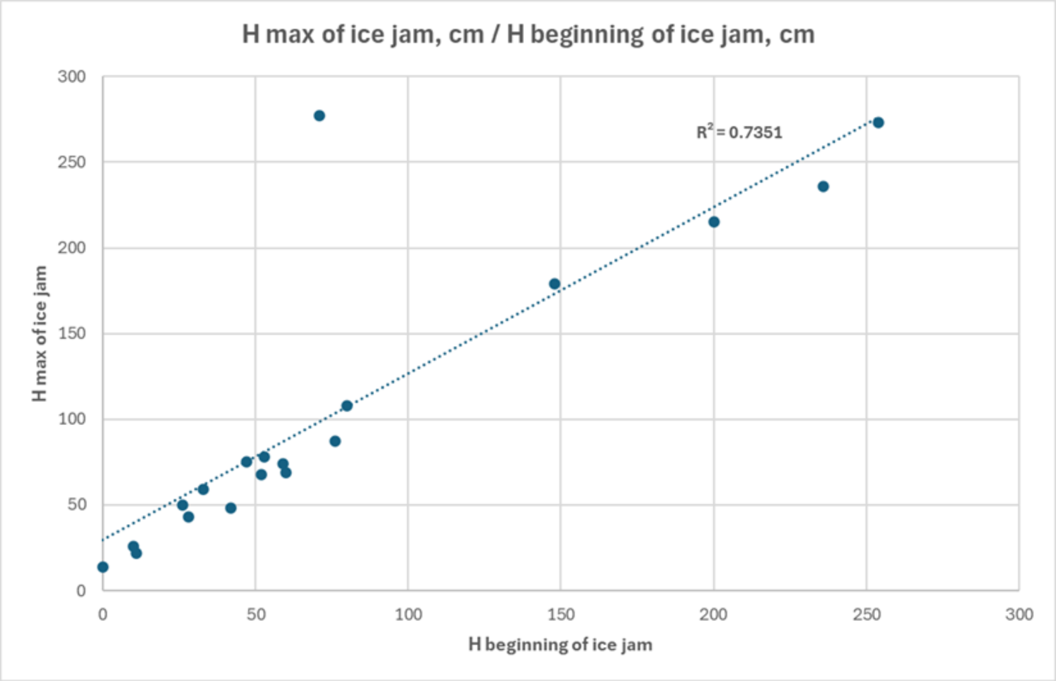


Figure 3.4.2. Scatter plot of relation between H max of ice jam (cm) and H at the beginning of ice jam (cm)

Positive temperature influence. The correlation between sums of positive air temperatures (last 5 – 2 days before the ice jam) and ice jam breakup (r = 0,72) highlights the role of warming in destabilizing ice cover.

Stream velocity and H beginning of ice-jam (r = 0,91). As ice builds up, the river's stream velocity plays a crucial role in transporting ice chunks downstream. The correlation between stream velocity and water levels at the beginning of the ice jam (r = 0,91) suggests that higher stream velocities contribute to increased ice accumulation.

The trend shows that moderate stream velocities contribute to increasing ice-jam water levels, but beyond a certain velocity, the rate of increase slows down. When stream velocity is below 0,3 m/s, ice-jam beginning water levels are generally low (< 50 cm). This suggests that low flow speeds may not provide enough force to transport ice chunks downstream, limiting accumulation. In the range of 0,3 – 0,6 m/s, ice-jam heights increase significantly, showing that moderate water movement enhances ice accumulation. This is likely because sufficient flow velocity allows ice to move and jam in constricted areas of the river. The highest ice-jam beginning water levels (~250 cm) occur when stream velocity is around 1,0 m/s. This supports the idea that higher velocities contribute to ice transport and accumulation in key locations. The trendline flattens and slightly curves downward at very high stream velocities. This suggests that excessive flow velocity (>1,2 m/s) may disrupt ice-jam formation by preventing stable ice accumulation (Fig. 3.4.3).

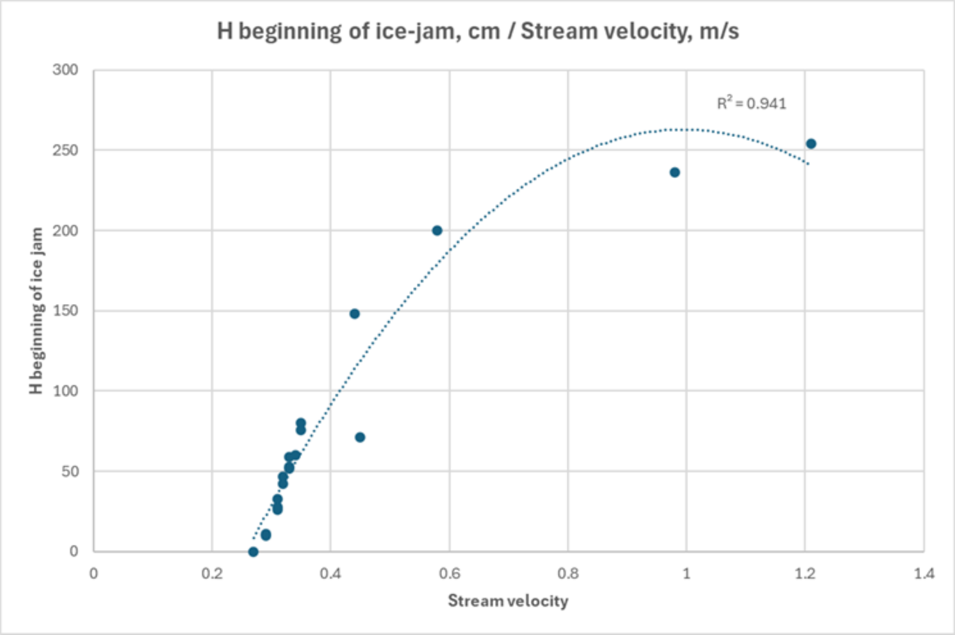


Figure 3.4.3. Scatter plot of relation between H beginning of ice jam (cm) and stream velocity (m/s)

ΔH (beginning – max) and Q max of ice jam (r = 0,90). As the ice jam nears its peak, water levels experience a significant rise. The change in water level from the beginning to the maximum stage correlates strongly (r = 0,90) with the maximum discharge during the ice jam. This indicates that as ice accumulates, the potential for extreme discharge events and flooding increases significantly. The rapid rise in water levels necessitates continuous monitoring to anticipate possible flooding events.

The polynomial trendline suggests a curvilinear relationship, meaning that height changes (ΔH) increase exponentially at higher Q max values. The graph shows that higher Q max values result in a greater increase in ice-jam water levels compared to lower values. Most of the data points are concentrated in the lower Q max range (0-15 m^3/s). These events have moderate ΔH values (5-30 cm), suggesting that small to medium ice-jam flows do not significantly increase the height of ice accumulations. When Q max exceeds ~15-20 m^3/s, ΔH increases more sharply. The highest Q max event (Q max = 102 m^3/s) shows an extreme ΔH of 206 cm, reinforcing this pattern (Fig. 3.4.4).

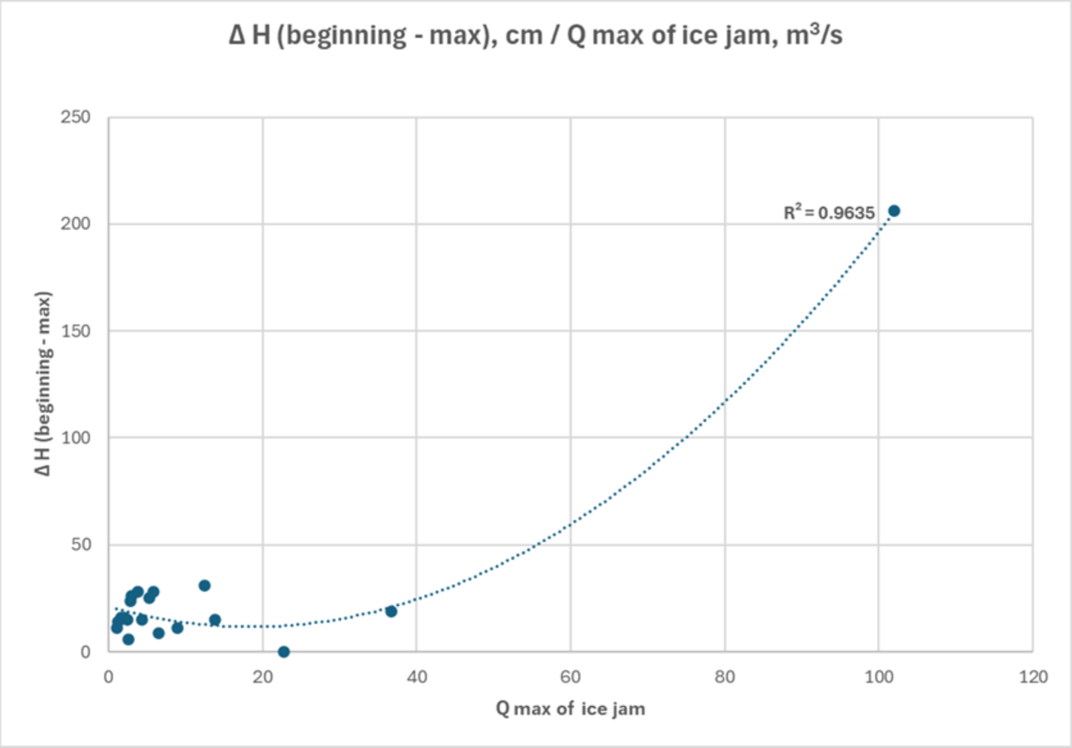


Figure 3.4.4. Scatter plot of relation between change in water H levels (cm) and Q max of ice jam (m³/s)

Main factors for the ice-jam formation in the Lėvuo River:

- Colder temperatures in the month before an ice-jam strongly contribute to ice thickness, increasing ice-jam severity;
- Sudden short-term warming (last 5-2 days before the ice jam) may destabilize ice and increase ice-jam intensity;
- Higher stream velocities contribute to both higher ice-jam discharge (Q max) and higher water levels of ice jams;
- Strong river flows (high Q max) are a major factor in determining ice-jam height growth (ΔH);
- Like in Muša river, there is no strong evidence that precipitation before an ice-jam significantly impacts ice-jam events. This could mean that formation of ice-jams is more dependent on air temperatures and river hydrological conditions;
- Monitoring a combination of ice thickness, stream velocity, and temperature fluctuations provides the best early warning signals.

4. Climate change impact on the main factors for the ice-jam formation process

Thermal and hydrological conditions belong to the main factors of ice-jam development (see Chapter 2). It is therefore inevitable that climate change processes will, in the nearest decades, change the patterns of ice jam formation and ice-jam flooding.

In the frame of the ICEREG project, detailed future climate change modelling for the project areas has been performed. Historical climate information, as well as CMIP6 models based on scenarios SSP2-4.5 and SSP3-7.0 (scenarios representing moderate and significant climate changes, respectively) were used for this task. Full description of modelling results, including analysis of mean air temperatures, negative degree days and positive degree days, as well as precipitation amount, can be found in the project deliverable D1.2.2 “Report on the climate change modelling in Latvia and Lithuania”.

The historical and projected climate changes along the Muša River (between Gustoniai and Ustukiai) and the Lėvuo River (from Pamarliškiai to the bridge in Skaistgiriai) in Lithuania and Daugava River (between tributaries Nereta and Aiviekste) and Lielupe River (from Mūsa and Mēmele confluence to Sesava River) in Latvia follow similar trends. Air temperature and analyzed indices show only marginal differences, suggesting that climate change will affect the primary factors influencing ice-jam formation in similar ways for both areas.

The historical warming trend is evident when comparing the reference period (1961–1990) to the climate normal (1991–2020). During this time, mean seasonal (November–April) air temperature increased by 1.5–1.7 °C across the four river basins, whereas monthly air temperatures increased by 0.7–2.5 °C. November air temperature has increased the least, the difference between the reference and climate normal being 0.7 °C for all rivers, but January has experienced the highest increase of 2.3–2.5 °C. Future projections show continued warming across all rivers and scenarios. Seasonal air temperature is expected to rise by 2.1–4.5 °C relative to 1991–2020, with Lithuania experiencing a larger increase. At the end of the century, even the coldest 10% and 25% of winters are expected to be 0.1–2.4 °C warmer than the typical winters now (Fig. 4.1).

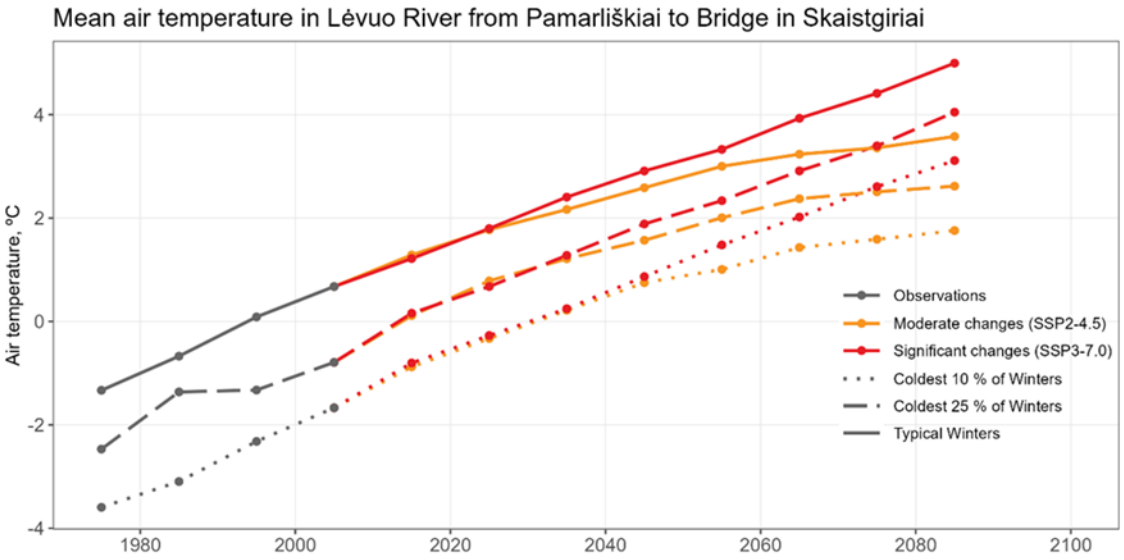


Figure 4.1. The average November–April air temperature of typical, coldest 25 % and coldest 10 % of winters in Lėvuo River: from Pamarliškiai to Bridge in Skaistgiriai from 1951 (observational data) to 2100 (climate model scenarios SSP2-4.5 and SSP3-7.0 data)

This significant warming indicates that while ice-jams may still form, their probability will likely decrease, especially towards the end of the 21st century. Mitigation policies will play a critical role in determining the extent of these changes, as SSP3-7.0 projects significantly greater warming from mid-century onward compared to the more moderate SSP2-4.5 scenario.

Negative degree days (NDDs), which are indicative of ice formation and thickening, are projected to decline substantially. Larger NDD values historically contributed to the accumulation of thicker ice covers, increasing the likelihood of ice-jams when the ice cover broke. Thicker ice transported by rivers typically leads to the formation of more resistant ice jams and more severe flooding. NDDs have already decreased seasonally by 159.7–188.1 °C from 1961–1990 to 1991–2020, mostly due to reductions in January and February. Substantial reductions in NDDs are projected in the future for the November–April period, with seasonal NDDs at the end of the century reaching values below 200 °C and even close to 100 °C, almost the same as the current normal for January (~120 °C), see Figure 4.2 for example. This reduction in NDDs suggests a lower probability of breakup jams and thinner ice cover in rivers.

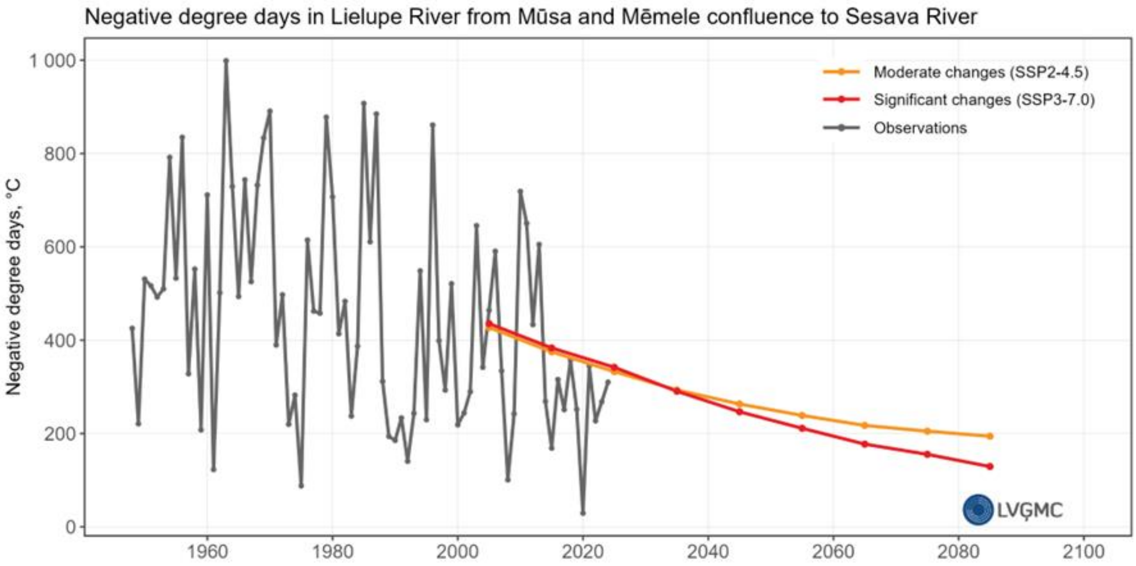


Figure 4.2. The November–April negative degree days (NDD) in Lielupe River from the confluence of Musa and Memele rivers to the junction with Sesava River from 1948 (observational data) to 2100 (climate model scenarios SSP2-4.5 and SSP3-7.0 data)

The **number of days with mean air temperatures below 0 °C**, crucial for frazil ice formation and freeze-up jams, will also decline significantly. Historically, such events occurred primarily at the start of the cold season, but with rising temperatures, frazil ice formation has become more sporadic, even during the current climate norm period (1991–2020). Projections show a consistent reduction in the number of days with mean temperatures below 0 °C across all scenarios, though Lithuanian rivers are projected to experience a larger decrease of days with negative air temperature. While in Latvian river regions the number of days with negative air temperature by the end of the century will decrease by 22 or 37 days, which is a reduction of less than half from the normal period, Lithuanian river regions are expected to see a larger reduction – more than half compared to the normal period. These reductions in freezing days, especially consecutive ones, imply a significant decline in the likelihood of frazil ice formation and associated ice-jams.

Positive degree days (PDDs), which are linked to thawing events that could trigger thermal or physical ice cover breaks, are projected to increase. Very high PDD values may indicate conditions too warm for ice cover to form or significant limitations on ice accumulation. PDDs could be associated with ice-jam formation only after substantial NDD accumulation and a preceding period of below-freezing days. This combination would result in thicker ice and greater snow melt flow, leading to a higher potential for ice-jams. However, with much warmer cold seasons even by the mid-21st century the PDDs would reach ~720–770 °C, which is a significant increase in comparison to climate norm period (Fig. 4.3). PDDs are expected to reflect ice-jam formation conditions only during the coldest months and winters and by the late 21st century, PDDs are unlikely to be a decisive factor, especially under SSP3-7.0.

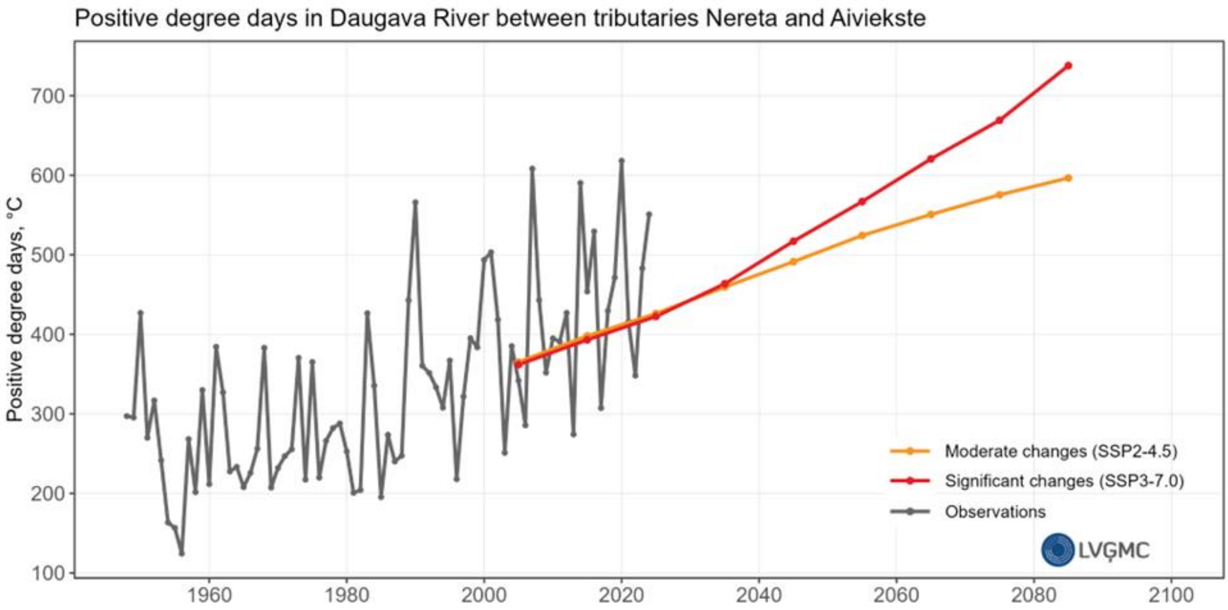
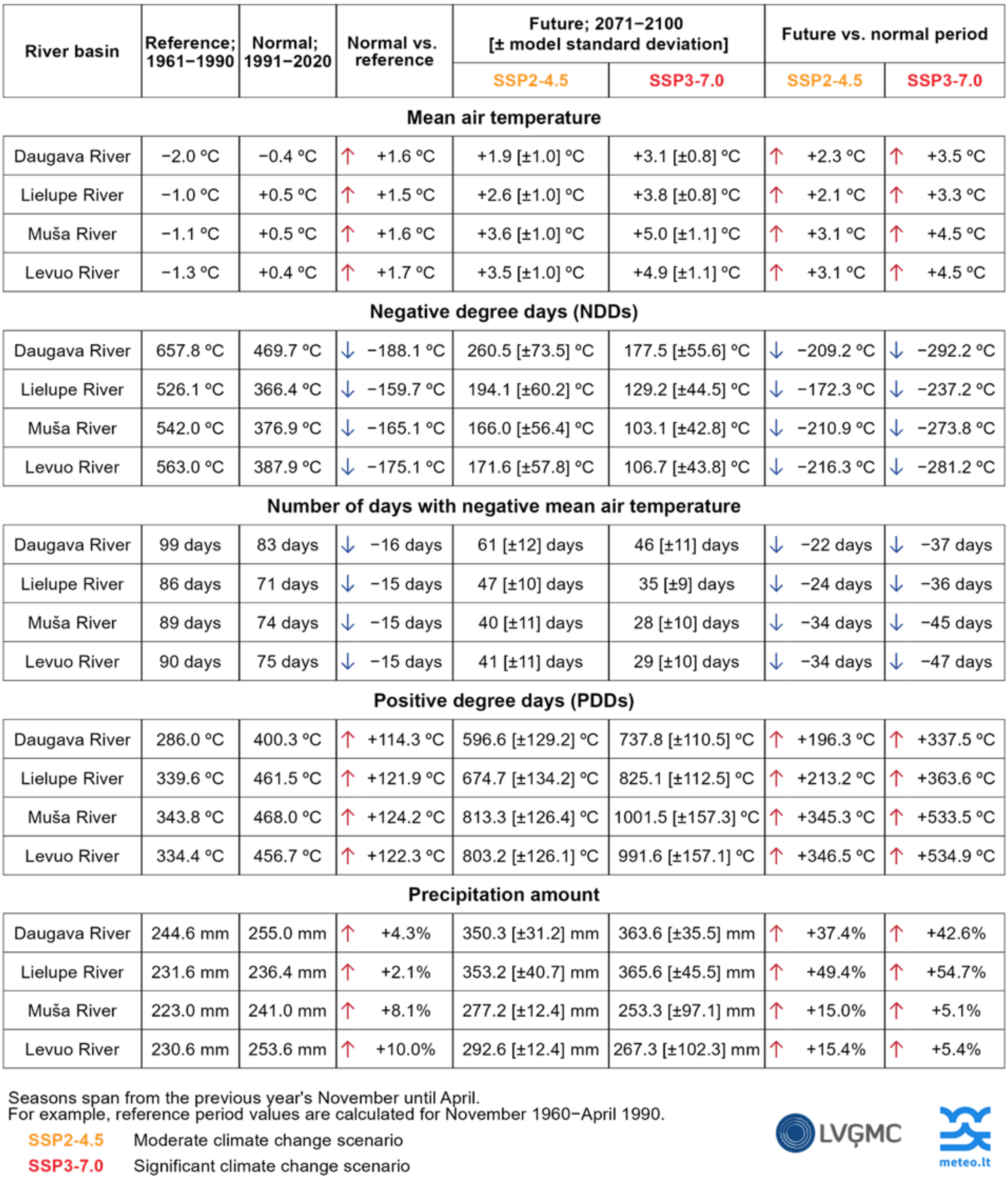


Figure 4.3. The November–April positive degree days (PDD) in Daugava River tributaries Nereta and Aiviekste from 1948 (observational data) to 2100 (climate model scenarios SSP2-4.5 and SSP3-7.0 data)

Precipitation indirectly affects ice-jams through runoff formation and can directly weaken ice cover during extended rain spells. Seasonal precipitation has increased by 2–10% since the reference period (1961–1990), though there are notable monthly variations. Future projections indicate increased precipitation for all river regions, though a smaller increase in Lithuanian regions (up to 15%) compared to Latvia (up to 43%). Comparatively large projected increases of precipitation amount in December could create more favorable conditions for ice-jam formation, substantial warming during the cold season will likely offset this effect.

In summary, climate change can significantly reduce the frequency and severity of ice-jams due to warmer temperatures, fewer freezing days, shorter accumulation periods for NDDs, and declining frazil ice formation. The moderate climate change scenario (SSP2-4.5) projects more stable conditions, while the significant climate change scenario (SSP3-7.0) suggests greater variability throughout the century and a more extreme reduction of ice-jam risk in the late 21st century.

Table 4.1. Observed historical and projected future seasonal values of analysed indices for each river basin



River basin	Reference; 1961–1990	Normal; 1991–2020	Normal vs. reference	Future; 2071–2100 [± model standard deviation]		Future vs. normal period	
				SSP2-4.5	SSP3-7.0	SSP2-4.5	SSP3-7.0
Mean air temperature							
Daugava River	−2.0 °C	−0.4 °C	↑ +1.6 °C	+1.9 [±1.0] °C	+3.1 [±0.8] °C	↑ +2.3 °C	↑ +3.5 °C
Lielupe River	−1.0 °C	+0.5 °C	↑ +1.5 °C	+2.6 [±1.0] °C	+3.8 [±0.8] °C	↑ +2.1 °C	↑ +3.3 °C
Muša River	−1.1 °C	+0.5 °C	↑ +1.6 °C	+3.6 [±1.0] °C	+5.0 [±1.1] °C	↑ +3.1 °C	↑ +4.5 °C
Levuo River	−1.3 °C	+0.4 °C	↑ +1.7 °C	+3.5 [±1.0] °C	+4.9 [±1.1] °C	↑ +3.1 °C	↑ +4.5 °C
Negative degree days (NDDs)							
Daugava River	657.8 °C	469.7 °C	↓ −188.1 °C	260.5 [±73.5] °C	177.5 [±55.6] °C	↓ −209.2 °C	↓ −292.2 °C
Lielupe River	526.1 °C	366.4 °C	↓ −159.7 °C	194.1 [±60.2] °C	129.2 [±44.5] °C	↓ −172.3 °C	↓ −237.2 °C
Muša River	542.0 °C	376.9 °C	↓ −165.1 °C	166.0 [±56.4] °C	103.1 [±42.8] °C	↓ −210.9 °C	↓ −273.8 °C
Levuo River	563.0 °C	387.9 °C	↓ −175.1 °C	171.6 [±57.8] °C	106.7 [±43.8] °C	↓ −216.3 °C	↓ −281.2 °C
Number of days with negative mean air temperature							
Daugava River	99 days	83 days	↓ −16 days	61 [±12] days	46 [±11] days	↓ −22 days	↓ −37 days
Lielupe River	86 days	71 days	↓ −15 days	47 [±10] days	35 [±9] days	↓ −24 days	↓ −36 days
Muša River	89 days	74 days	↓ −15 days	40 [±11] days	28 [±10] days	↓ −34 days	↓ −45 days
Levuo River	90 days	75 days	↓ −15 days	41 [±11] days	29 [±10] days	↓ −34 days	↓ −47 days
Positive degree days (PDDs)							
Daugava River	286.0 °C	400.3 °C	↑ +114.3 °C	596.6 [±129.2] °C	737.8 [±110.5] °C	↑ +196.3 °C	↑ +337.5 °C
Lielupe River	339.6 °C	461.5 °C	↑ +121.9 °C	674.7 [±134.2] °C	825.1 [±112.5] °C	↑ +213.2 °C	↑ +363.6 °C
Muša River	343.8 °C	468.0 °C	↑ +124.2 °C	813.3 [±126.4] °C	1001.5 [±157.3] °C	↑ +345.3 °C	↑ +533.5 °C
Levuo River	334.4 °C	456.7 °C	↑ +122.3 °C	803.2 [±126.1] °C	991.6 [±157.1] °C	↑ +346.5 °C	↑ +534.9 °C
Precipitation amount							
Daugava River	244.6 mm	255.0 mm	↑ +4.3%	350.3 [±31.2] mm	363.6 [±35.5] mm	↑ +37.4%	↑ +42.6%
Lielupe River	231.6 mm	236.4 mm	↑ +2.1%	353.2 [±40.7] mm	365.6 [±45.5] mm	↑ +49.4%	↑ +54.7%
Muša River	223.0 mm	241.0 mm	↑ +8.1%	277.2 [±12.4] mm	253.3 [±97.1] mm	↑ +15.0%	↑ +5.1%
Levuo River	230.6 mm	253.6 mm	↑ +10.0%	292.6 [±12.4] mm	267.3 [±102.3] mm	↑ +15.4%	↑ +5.4%

Seasons span from the previous year's November until April.
For example, reference period values are calculated for November 1960–April 1990.

SSP2-4.5	Moderate climate change scenario
SSP3-7.0	Significant climate change scenario

5. Conceptual Model of ice-jam formation

Formation of ice jams in the Project pilot river stretches, much like other rivers, is influenced by a variety of morphological, hydrological, and meteorological factors. Ice-jams occur when ice blocks the flow of water, causing local flooding and changes in the river dynamics.

Analysis of historical data shows that one of the main factors in this process is air temperature. At the beginning of the cold season, prolonged cold weather causes water to freeze, forming ice on the river surface. Ice jams are more likely to form when temperatures fluctuate around the freezing point. As for spring, or other sudden warming periods, high temperatures cause ice to melt, and when the meltwater combines with rising river flow, the ice can break into fragments that accumulate and cause the ice jam. Also, negative air temperatures cause ice thickening, which is one of the factors that lead to the ice jam formation, as thicker ice is more likely to accumulate and cause a jam.

The second main factor is water flow value. When the water flow is high, it pushes ice downstream where it can accumulate against artificial structures, bends, or other obstructions. This is often observed during spring thaw or heavy rain events and also the so-called rain on snow events. In the periods of low flow, the river stream velocity is insufficient to carry the ice downstream, allowing it to accumulate in place and, potentially, cause blockages.

However, river characteristics (e.g. depth, width, obstacles) belong to the factors on which ice jam formation depends, but some of these conditions can change over time.

The ice-jam formation conceptual model in the form of a diagram on Figure 5.1 includes the most significant factors described above in Chapter 3.

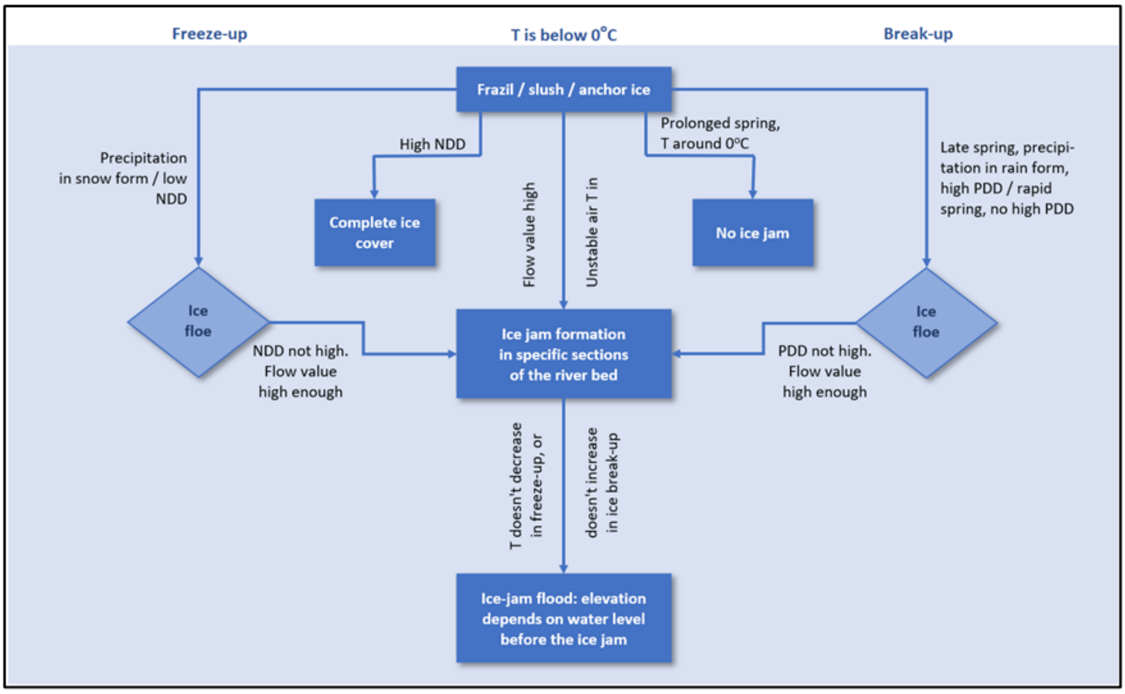


Figure 5.1. Conceptual model of ice-jam formation in pilot river stretches

The most advanced ice-jam models nowadays include the possible climate change impact on the magnitude of ice-jam floods (Fig. 5.2).

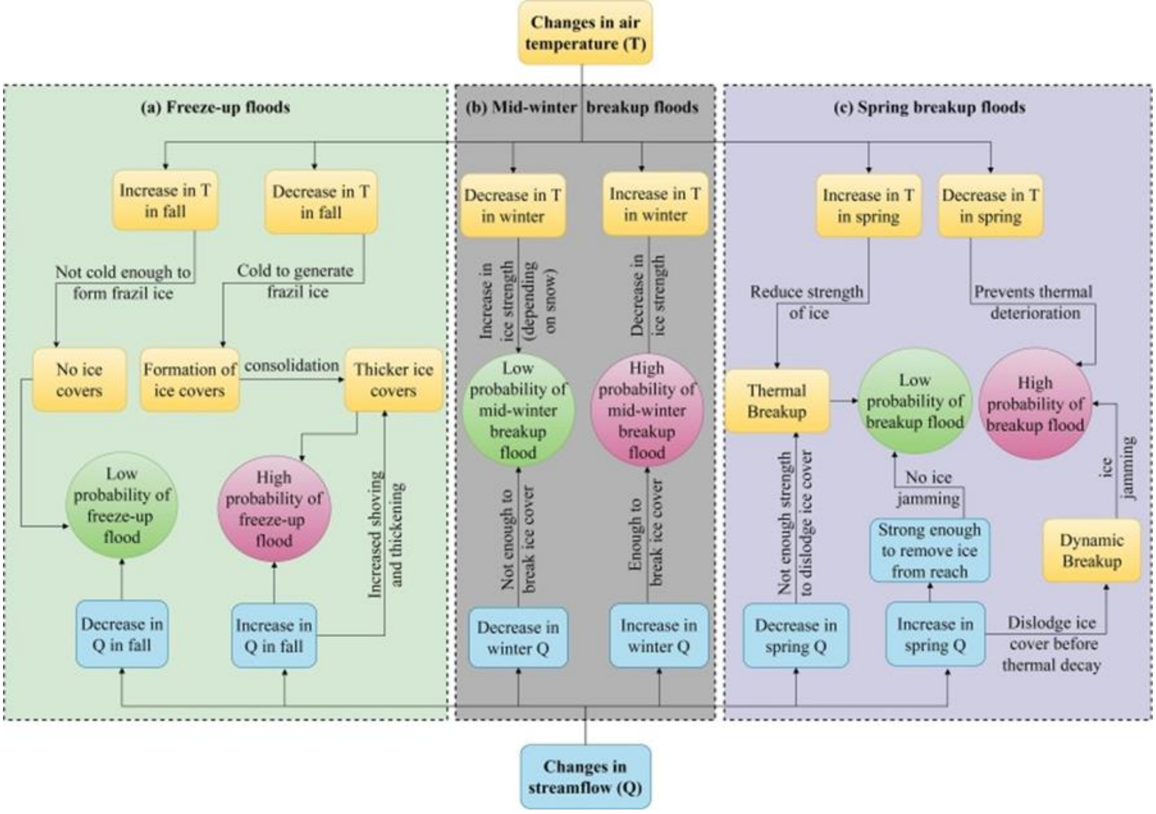


Figure 5.2. Decision tree for probability of seasonal ice-jam flood (IJF) occurrence given future changes in air temperature and streamflow (Rokaya et al., 2022)

Figure 5.2 presents a simplistic representation of how ice-jam flood risks may change under different climatic conditions based on air temperature and discharge. Therefore, it does not include implications of several other hydro-meteorological factors such as snow and radiation that also play an important role (Rokaya et al., 2022).

One of the next tasks of the ICEREG project is modelling and mapping of the ice-jam flood with different probabilities. Hence, the decision tree on Figure 5.2. might be approved or rejected.

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