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Report on Latvian-Lithuanian ice-jam flood sensitive areas

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Lietuvos hidrometeorologijos tarnyba

Contents

Abbreviations

a.s.l.	above sea level
FRMP	Flood Risk Management Plan
H	Water level
HPP	Hydropower Plant
HS	Hydrological observation station
LEGMC	Latvian Environment, Geology and Meteorology Centre
LEI	Lithuanian Energy Institute
LKS94	Lithuanian Coordinate System
Q	Water discharge
SSP	Shared Socioeconomic Pathways (climate change scenarios)
WGS	Water gaging station
X	Latitude
Y	Longitude

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1. Introduction

This report presents an analysis of ice-jam data, focusing on the occurrence, frequency, and impact of ice jams on river systems. Ice jams are significant hydrological phenomenon that occur when ice masses accumulate, obstructing the natural flow of water. These events can lead to severe flooding, infrastructure damage, and economic losses. By analysing historical ice-jam data, this report aims to identify patterns, assess risk factors, and provide insights into the conditions that contribute to ice-jam formation. The findings are intended to support flood management strategies and inform decision-making processes for mitigating the adverse effects of ice jams. The report also covers data selection criteria. Selection of rivers in Latvia and Lithuania where ice jam risk is higher.

1.1. Ice-jam conditions in the rivers of Northern Hemisphere

River ice plays a vital role in the hydrology of cold regions, notably Canada, northern USA, Russia, northern Europe (especially Nordic countries), Japan, Korea, and China (Madaeni et al., 2020). Like open-water conditions, river ice is an integral component of the cold-climate hydrological cycle (De Rham et al., 2020). In most cold regions, the river-ice season is characterised by two well-defined periods of dynamic hydrological activity: freezing in autumn and breakup typically in spring, and an intermediate period of relative hydrological calm associated with declining flows and increasing ice thickness (Beltaos and Prowse, 2009). The interaction of climatic factors such as temperature and precipitation, hydrological processes such as flow and turbulence, and channel characteristics determines river ice formation processes (Thellman et al., 2021). Observations of variability in river ice types and thicknesses in fluvial environments show the complexity of these interactions (Buffin-Bélanger et al., 2013). In the Northern Hemisphere, ice has been found to seasonally cover almost 60% of the total length of rivers (Prowse, 2005; Bennett and Prowse, 2009).

During the break-up, the ice-covered river turns into an open-water river. In general, river ice break-up, based on its origin, is either thermal or mechanical (Beltaos, 2003). Thermal break-up usually occurs when the ice cover on a river begins to slowly melt and deteriorate because of gradually rising air temperature. It usually does not produce significant jamming and flooding. In contrast, mechanical break-up is a consequence of a rapid increase in river flow (and water level) and is often associated with ice-jam formation.

River-ice jams are distinguished by their ability to cause sudden, intense flooding that challenges the capabilities of public security services. This type of flood is commonly unpredictable and often appears chaotic, as its occurrence depends on multiple interacting weather, hydrological, ice, and morphological parameters (Turcotte et al., 2020). The presence of a jam can easily raise the water level so high as to attain 2.5-3 times the open-water depth required to pass the same flow (Beltaos and Prowse, 2001). Therefore, severe flooding is often the outcome of ice-jamming, even if the discharge is small compared to open-water floods. Ice jams reach thicknesses of several metres and have highly irregular undersides. To pass the river flow, the water level has to rise drastically to accommodate both the large additional resistance created by this new boundary and the keel of the jam, itself being a large part of the thickness (Beltaos and Prowse, 2001). Moreover, resulting high water levels can persist for days, and if the ice jam is the result of a mid-winter breakup event (i.e., usually rain on snow), the flooded area can freeze when cold weather returns, which significantly complicates post-event recovery (Turcotte et al., 2020).

Typically, an ice jam occurs when ice pieces are carried downstream and become stuck, blocking the flow of water and potentially causing flooding upstream. The risk of ice accumulation in certain locations can increase due to natural river characteristics: bends, meanders, and mouths of rivers, where water may slow down; shallow riverbeds, narrow channels or tight bends, where ice may get stuck; areas where anchor ice (river ice freezing to the bottom of the river channel) can form, which can block the flow of ice and redirect water to other areas. The passage of ice can also be blocked by man-made structures such as bridges, culverts, dams, reservoir entrances, fencing, construction materials, and so on (Guide). Beltaos and Prowse (2001) distinguish two major types of factors that govern ice breakup and jamming processes:

(a) physical conditions associated with local and regional geography: (i) channel morphology which is defined by such parameters as width, depth, slope, frequency of islands, planform curvature, etc., and (ii) watershed characteristics related to runoff such as surface retention, infiltration, elevation, slope, aspect, forest cover, and degree of urbanisation.

(b) meteorological conditions throughout the late autumn-winter-early spring period: net radiation (solar and long-wave radiation), sensible and latent heat fluxes (air temperature, humidity, and wind speed), ground heat (for surface snow and streamflow), advective energy (rainfall), and internal energy (coldness of the snow or ice prior to melting).

Groundwater and frozen soil conditions are also runoff-related characteristics of the watershed, but these are primarily influenced by climatic processes.

1.2. Motivation of ICEREG project partners on ice-jam research

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (the so-called Floods Directive) requires the Member States to perform preliminary flood risk assessment in the whole territory of the respective country; to identify areas where potential significant flood risks exist; to prepare flood hazard maps and flood risk maps for these areas, under different floods probability scenarios; and, based on this information, to develop flood risk management plans. These plans (cs) have to be reviewed and updated every six years.

The main objective of FRMPs is to minimise the negative impact of floods on human health, the environment, cultural heritage, and economy.

Ice jams are being recognized as one of the sources of flooding (together with snow melting in spring, rain and storm surges) in Latvia (Latvian River Basin Management Plans and Flood risk management plans, 2022). In Lithuania, Flood risk management plans in the Nemunas, Lielupe, Venta and Daugava basin districts in the 2017-2023, floods caused by ice jams in rivers are classified as high-probability floods (high-probability floods - 10% probability floods, when, based on hydrological calculations, floods of the same characteristics may recur once in ten years).

Nevertheless, unlike other sources of flooding, ice-jam floods are difficult to predict. In-depth analysis and modelling is needed, which in turn will make it possible to update the existing early warning system with the ice-jam flood information and identify the most appropriate flood risk mitigation measures. Recent ice-jam flood event on Daugava River at Jekabpils city in winter 2023 revealed the utmost importance of this research.

2. Climate change impact on ice regime in Latvian and Lithuanian regions

As river ice formation is highly dependent on climatic factors, it is considered a good indicator of climate change (Bennett and Prowse, 2009; Alfredsen et al., 2022).

A study of ice regime dynamics in the largest Lithuanian river, Nemunas, based on the longest data series from the Smalininkai water gauging station covering the period of 1812–2000, revealed that the detected changes followed regional climate change patterns (Stonevicius et al., 2008). Tendencies for the river ice cover period to decrease over the second half of the last century matched other climate change indicators. A recent study by Šarauskienė et al. (2024) aimed to evaluate the changes in ice phenological parameters of the Lithuanian rivers by comparing the data from 1961-1990 and 1991-2020 and to analyse their dependence on air temperature. Considerable changes in the characteristics of river ice cover were detected. In the second period, the rivers froze on average nine days later, and their ice broke up 24 days earlier than in the first period. As a result, the duration of ice cover in the recent period was shortened by 33 days. Significant trends of air temperature increase were also determined during the 60 years. This was especially evident in the last 30-year period, when the air temperature rose by 0.5 °C per decade, compared to only 0.3 °C in the first 30 years. The sum of the negative air temperatures of the cold season (from November 1 to March 31) was found to be a good predictor of the duration of river ice cover, ice break-up, and freeze-up dates.

The global climate change scenarios SSP1-2.6, SSP2-4.5 and SSP3-7.0 show changes of meteorological parameters from “minor” to “significant”. In the period 1961-1990 the annual air temperature in Latvia was +5.6 °C. In the present WMO climate normal period (1991-2020) the annual air temperature is equal to +6.8 °C. Several climatic indicators might be compared with the reference period. Figure 1.2.1. illustrates changes in Latvia the average air temperature in winter season.

Due to increasing of the winter air temperature there are major changes in the number of the frost days in Latvia (Fig 1.2.2).

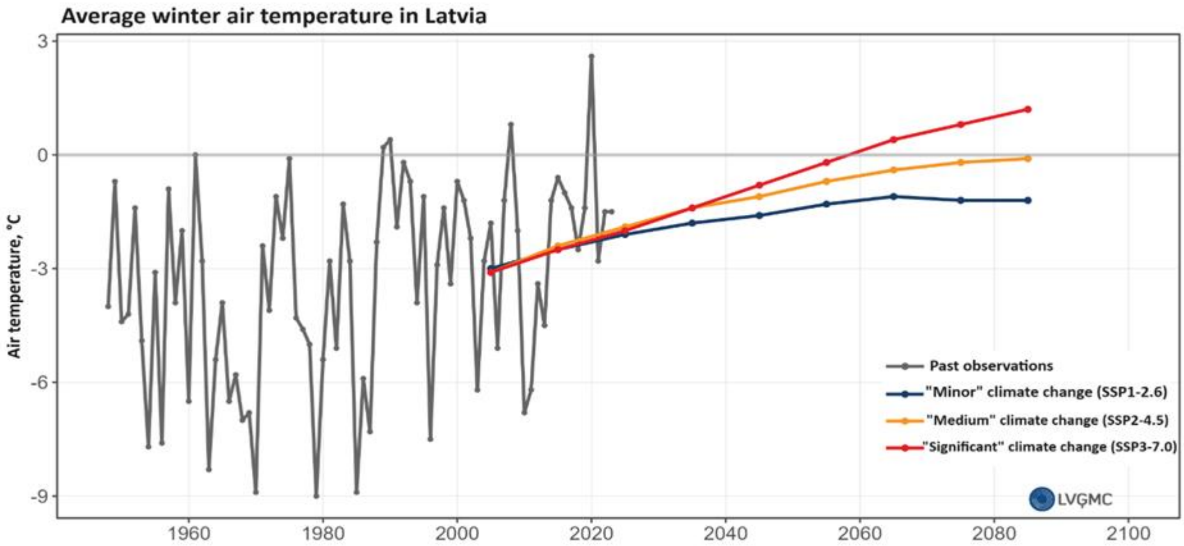

Figure 1.2.1. Yearly average air temperature in winter from 1945 till the end of the 21st century (2071-2100) for three climate change scenarios (SSP1-2.6; SSP2-4.5; SSP3-7.0) in Latvia. ***https://klimats.meteo.lv/klimats_latvija/klimata_riks/***

Monitoring of ice parameters started in 1880 at station Daugavpils dzelzcela tilts on Daugava River. Nowadays ice phenomenon observations are carried out at 65 hydrological monitoring stations within Latvian territory.

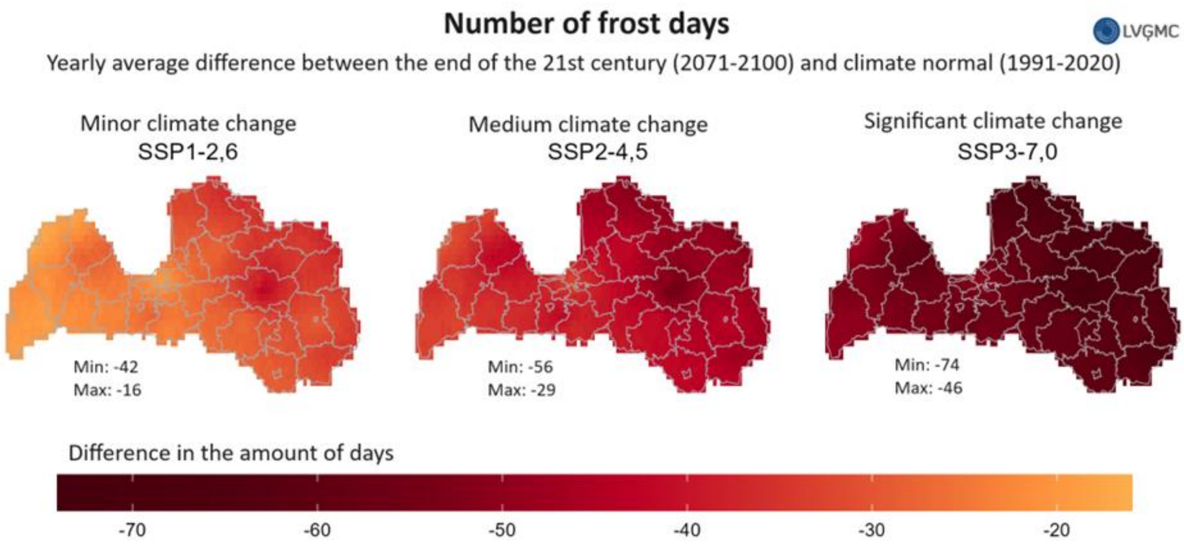

Figure 1.2.2. Yearly average difference between the Number of frost days in Latvia by the end of the 21st century (2071-2100) and climate normal (1991-2020) by three climate change scenarios. ***https://klimats.meteo.lv/klimats_latvija/klimata_riks/***

Warm and unstable winter leads major changes in the ice regime of rivers and lakes. These changes are more visible for the river freeze-up date, the ice cover duration and the date of ice break-up (Table 2.1). Due to unstable winters, there can be multiple freeze-up and break-up events per season. The ice cover duration is presented as actual days' number and as period from the beginning of ice cover to the end of it.

The ice regime duration in Latvia has decreased from 85 days on average to 64, but the difference between actual ice cover period and its duration from start and to end dates increases for 4 days. Periods with ice phenomenon begin 15 days later as well as ice break-up happens 14 days earlier.

Moreover, starting from the 1970s, there are more cases when there was no ice cover. In the Eastern region of Latvia this trend is less significant, i.e., one to three cases per decade, however, the biggest changes are related to the Western region where the ice cover might not form from four to six times during a decade (Latkovska et al., 2016).

Table 2.1. Ice regime changes in Latvian rivers (1961-1990 vs 1991-2020)

River-Station	1961 - 1990				1991 - 2020			
	Ice phenomena start date	Number of days with ice cover		Break-up date	Ice phenomena start date	Number of days with ice cover		Break-up date
		by data difference	actual			by data difference	actual	
Aiviekste-Aiviekstes HPP	20.11.	88	88	25.03.	09.12.	62	58	05.03.
Gauja-Carnikava	24.11.	97	96	23.03.	14.12.	65	63	04.03.
Daugava-Daugavpils	22.11.	99	97	23.03.	07.12.	78	76	12.03.
Daugava-Jersika	23.11.	102	100	26.03.	07.12.	87	82	14.03.
Daugava-Jēkabpils	26.11.	83	83	28.03.	07.12.	63	61	13.03.
Daugava-Kraslava	24.11.	60	60	23.03.	07.12.	54	53	12.03.
Ogre-Lielpeči	05.12.	68	64	23.03.	20.12.	42	37	08.03.
Lielupe-Mežotne	25.11.	86	84	19.03.	13.12.	68	64	05.03.
Lielupe-Staļģene	25.11.	98	89	20.03.	14.12.	76	66	7.03.
Venta-Kuldīga	05.12.	68	64	13.03.	20.12.	43	38	21.02.

Table 2.2 shows the identified changes in the ice regime in the river basins of northern Lithuania belonging to the project area in the periods of 1961-1990 and 1991-2020. The analysis revealed that freeze-up dates changed the least: in the first 30-year period, ice events usually began in late December, and in the second, early January. On average, this date shifted by eight days. Nevertheless, freeze-up dates varied widely among individual rivers, with the earliest ice event observed on 12 December and the latest on 17 January. Meanwhile, a comparison of the dates of the ice breakup of the studied rivers showed that in the second period (1991-2020), this phenomenon began on average three weeks earlier. Ice breakup dates shifted from March to February. As a result, the duration of the ice cover was significantly reduced: on average, by 29 days, and in individual rivers - from 3 to 40 days.

Table 2.2. Changes in the ice regime in the rivers of northern Lithuania (1961-1990 vs 1991-2020)

River-Station	1961 - 1990			1991 - 2020		
	Ice phenomena start date	Number of days with ice cover (by date difference)	Break-up date	Ice phenomena start date	Number of days with ice cover (by data difference)	Break-up date
Svyla-Guntauninkai	12.12	92	14.03	25.12	59	22.02
Nemunėlis-Tabokinė	24.12	87	21.03	27.12	54	19.02
Mūša-Ustukiai	16.12	86	12.03	01.01	58	01.03
Levuo-Bernatonys	26.12	80	16.03	03.01	52	24.02
Tatula-Trečionys	19.12	73	02.03	07.01	36	11.02
Venta-Papilė	29.12	76	15.03	11.01	36	17.02
Venta-Leckava	17.01	47	05.03	12.01	44	25.02
Bartuva-Skuodas	03.01	69	13.03	31.12	37	06.02

Several observational studies emphasize that changes in the ice regime are caused by climate change and anthropogenic pressures, such as the construction of dams and reservoirs.

Variations of frost periods with thaws in winter season lead to frazil ice and slush formation in streams and as a result, occurrence of ice-jams.

A growing body of research testifies to the increasing magnitude of the effects of climate change and its influence on the freshwater ice regime (IPCC, 2019). Therefore, there is no doubt that the phenomenon of ice-jam flooding is sensitive to the changes taking place on our planet. That makes this chaotic phenomenon even more unpredictable. Some argue that “an ice-jammed river is among the most deranged hydraulic phenomenon” (Kennedy, 1975).

3. Sensitive areas for ice-jam formation in Latvia and Lithuania

3.1. Ice-jam formation in Latvian rivers

Ice-jams are the most important of the ice phenomenon related to freeze-up and breakup of rivers. On several stretches of large rivers, on Daugava, Lielupe and Venta rivers, ice-jams lead to significant increase in water levels, causing serious damage to the economy.

The potential of ice-jam formation, as well as their location and volume are to a certain extent dependent on physico-geographical and hydrodynamical conditions (weather conditions, riverbed sinuosity, slope, depth, stream velocity).

First observations of ice-jams in Latvia were conducted in the 1930's. More or less systematic research of ice-jams on Daugava River had been performed in different years prior to construction of the large HPP cascade. On other rivers, data on ice-jams are limited to just records of this ice phenomenon with their corresponding dates. Figure 3.1.1. shows the map of the ice monitoring network in Latvia.

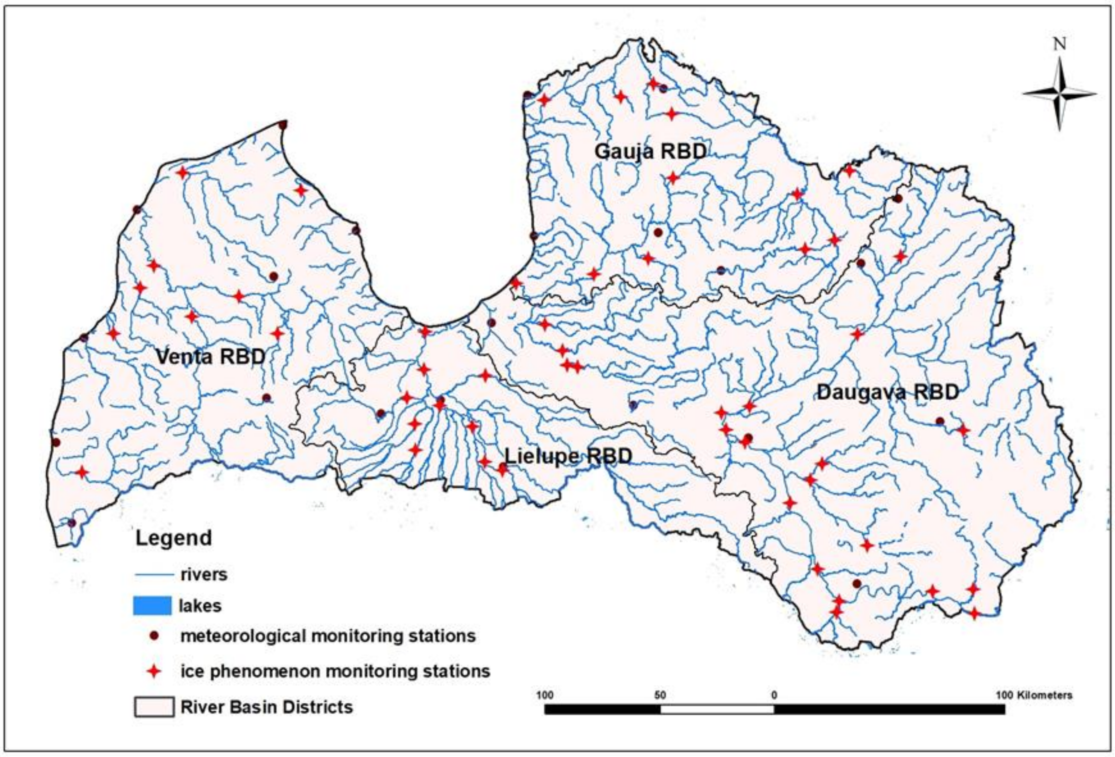

Figure 3.1.1. Ice phenomenon monitoring network in Latvia, 2023

In the period of ice-jam formation, ice thickness is usually about 30 – 50 cm. This is usually firm, crystalline ice; just ¼ or ½ of the overall thickness is slush ice. Ice-jam length varies from 1 – 2 to 10 – 15 km. Ice volume in jams on Daugava River varies from 1 – 2 to 8 – 10 million m^3.

The ice regime of Latvian rivers is characterised by massive and prolonged slush ice running in autumn or winter months, as well as presence of open water reaches that are the source for the slush ice formation. Prolonged slush ice running is common for freeze-up periods when river discharges are high. In winters, when freeze-up period was supplemented with intensive slush ice accumulation, water level can be very high though all winter till ice break-up. In cases when ice break-up occurs with new additional ice-jam formation more likely very high water levels can be observed.

An approximately 50 m long stretch of the Venta River near Kuldiga waterfall freezes only in extremely severe winters.

Ice-jams in Latvia are observed under both high and low water levels, but massive ice-jams usually form during high spring floods, when ice movement downstream towards bottleneck in narrow river stretches is faster.

The formation of ice-jams occurs most often in spring with rapid thawing of snow; nevertheless, in 1954 there were numerous ice-jams observed in a spring with a very gradual water level' increasing.

The most significant ice-jams that caused high water levels were observed in Daugava River at Jekabpils in 1981, 1983, and 2023 (Figure 3.1.2).

Figure 3.1.2. Ice-jam in Daugava River near Jekabpils, 2023 (photo: Kaspars Krafts)

There are several factors having an impact on ice-jam formation: meteorological conditions, ice thickness and ice cover stability; character of water level rising; morphometric characteristics of the riverbed; and, to some extent, direction of water flow. For instance, in Lielupe and Venta rivers that are flowing from south to north, ice-jam formation is related to the fact that snow melting occurs earlier in the upper reaches, while in the lower reaches ice cover is still solid.

On average, ice running in the lower reaches of Lielupe river occurs 13 days later than at the place of confluence of rivers Musa and Memele. Therefore, downstream the river stretches with the ice running, there is always an obstacle – a solid ice cover.

Another factor contributing to the formation of ice-jams in Lielupe River is a rapid change of riverbed slope. It is possible to distinguish 3 stretches where nowadays ice-jams occur quite regularly: 1) confluence of Musa and Memele rivers, where ice-jams can cause increase in water levels up to 2 m high; 2) near Mezotne, where the frequency of ice-jams is about 80% and water level rise is almost 3 m; 3) near Stalgene, where the frequency of ice-jams is 90% and water level rise is up to 4 m. Moreover, Lielupe River near Jelgava city in some ice break-up might be under the ice-jam flood risk (Fig. 3.1.3). In occasional years, water level rise in the stretches under the risk of ice-jams can be substantially higher than the average values given above.

Figure 3.1.3. Ice-jam flood in Lielupe River near Jelgava, 2013 (photo: Ruslans Antropovs)

In severe winters, when the area of open water surface substantially decreases, slush ice formation is relatively low. At the end of winter, the amount of slush ice under the ice cover usually decreases. Sometimes slush ice gets almost completely degraded, but after a moderately severe winter there can be such an amount of slush ice that it has a noticeable impact on ice-jam formation.

Water level rise caused by an ice-jam usually isn't higher than the maximum spring flood level, although it might happen (Daugava near Jekabpils and Zelki). Information on the highest water level rises in the river stretches chosen for the analysis is shown in Table 3.1.1.

On rivers with smaller catchment areas (Tulija, Vaidava, Ogre, Dubna, Imula rivers) ice-jams caused by slush ice occur only rarely, with water level rise usually not exceeding 30 cm, except Dubna River at Sili, where maximum level rise reached 79 cm.

The presence of large areas of open water surface in mild winters is favourable for the formation of frazil and slush ice. Slush ice can fill up to 60 – 80% of the riverbed cross-section. In some places, the river channel can be filled with slush ice to the very bottom.

Ice break-up on Latvian rivers usually takes place in the first decade of March, on Daugava River – in the second decade of March.

Table 3.1.1. Ice-jam characteristics of the rivers chosen for analysis

River, hydrological station	**Years with ice-jams, 1961 – 2024**	**Maximum H rise**	
		H rise*	**Year**
Daugava, Jekabpils	1962-1963, 1966, 1969-1970, 1972-1973, 1975, 1979-1981, 1983, 1985, 1987-1991, 1994, 1996-1998, 2001-2002, 2004-2005, 2007-2014, 2016-2024	434	2023
Daugava, Zelki	1968-1970, 1972-1985, 1987-1991, 1994-1996,1998-2002, 2004-2008, 2010-2019, 2021, 2023-2024	725	1988
Daugava, Daugavpils	1965, 1972, 1975, 1981, 1982, 1987-1989, 1991-1994, 1996, 1998-2000, 2003-2006, 2008-2010, 2012-2014, 2017-2019, 2021-2023	321	1981
Gauja, Carnikava	1962, 1963, 1971, 1979, 1981, 1986, 1990, 1995, 1998, 1999, 2000, 2021	162	1963
Lielupe, Mezotne	1961, 1963, 1971, 1979, 1980, 1983-1985, 1994, 1998, 2007, 2013, 2015, 2018, 2022, 2023	275	1985
Lielupe, Stalgene	1963, 1971, 1980, 1987, 1992, 1994, 1998, 2000-2002, 2017, 2022	397	1994
Ogre, Lielpeci	1962, 1963, 1968, 1969, 1978, 1983, 1987, 1996, 2004, 2007, 2013, 2021	352	2013
Venta, Kuldiga	1963, 1986, 1994, 1998, 2000, 2011, 2018, 2022	525	1994

* The difference between the maximum H during the ice jam, and H at the beginning of the ice jam.

The most considerable flood risk is observed at Jekabpils and Zelki, where ice-jams occur almost each year. The economic consequences of those floods includes as an immediate, as a long-term impacts. Immediate impacts are damage to property, losses in water drainage system, non-functioning of infrastructure facilities. Long-term impacts, such as disruptions to clean water and electricity, transport, communication, education and health care, might be more crucial for economy.

3.2. Ice-jam formation in Lithuanian rivers

In Lithuania, the management plan applies to the territories of Lielupė, Venta and Dauguva river basin districts, where there is a high risk of flooding or there is a possibility that a flood may occur, which may cause significant negative consequences for human health, the environment, cultural heritage and economic activity. There are 8 rivers in the Lielupė River Basin (Mūša, Kruoja, Daugyvė, Lėvuo, Pyvesa, Tatula, Nemunėlis, Apaščia), where flooding may occur, which may cause significant negative consequences.

8 rivers (10 water gauging stations – HS) in Northern Lithuania on the Latvian border were selected for the ICEREG project: Bartuva (Skuodas HS), Venta (Papilė HS, Leckava HS), Mūša (Ustukiai HS, Žilpamūšis HS), Nemunėlis (Tabokinė HS), Lėvuo (Bernatoniai HS), Tatula (Trečionys HS), Daugyvenė (Rimšoniai HS, belonging to the Lielupė River Basin), and Svyla (Guntauninkai HS, belonging to the Daugava River Basin) (Fig. 3.2.1).

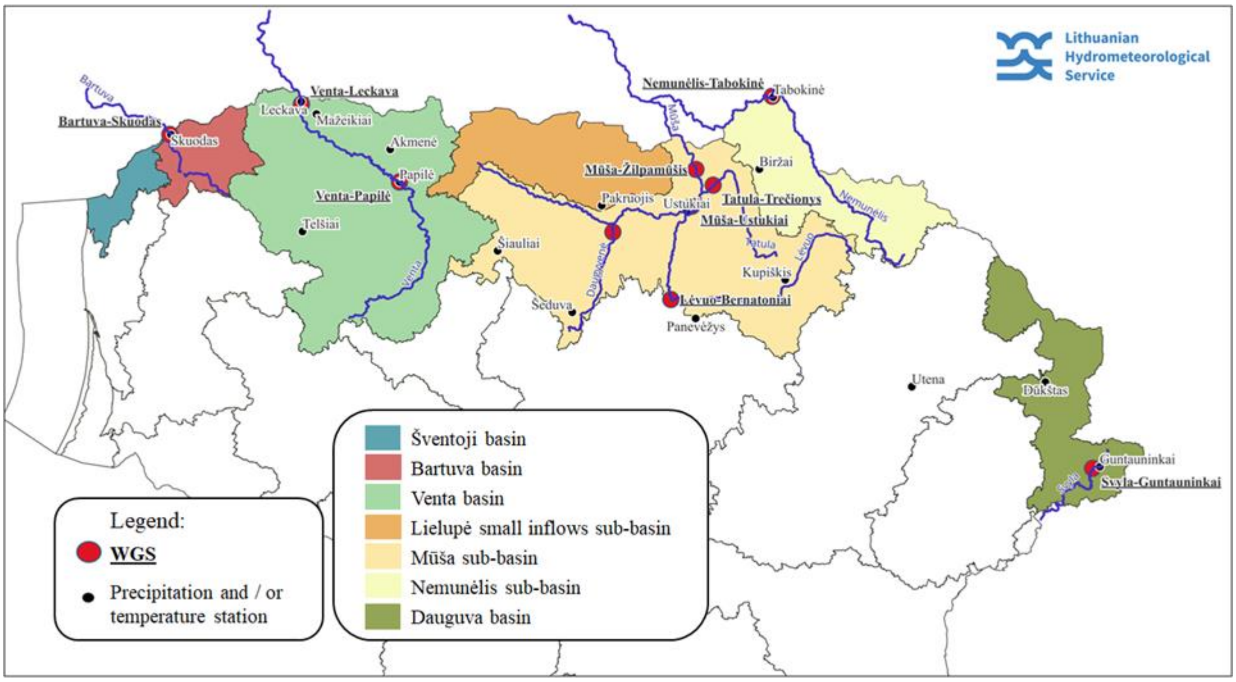

Figure 3.2.1. HS and precipitation and/or temperature station, used to compile data sequences 1961–2023.

Information on the highest water level rises in Lithuanian river stretches chosen for the analysis is shown in Table 3.2.1.

Table 3.2.1. Ice-jam characteristics of the rivers chosen for the analysis.

River, Hydrological station	Years with ice jams, 1961–2023	Maximum H rise	
		H rise*	Year
Bartuva – Skuodas	1978, 1980, 1981, 1982	11	1978
Lėvuo – Bernatoniai	1968, 1970, 1979, 1980–1999, 2001, 2006, 2010, 2018	206	2010
Mūša – Ustukiai	1983, 1986–1994, 1997–1999, 2010, 2013	50	1992
Mūša – Žilpamūšis	2012	22	2012
Nemunėlis – Tabokinė	1967, 1969, 1973, 1992–2004, 2006, 2008, 2010, 2012, 2018, 2019, 2021	129	2010
Svyla – Guntauninkai	1969, 1976, 1978, 2008, 2010, 2013	129	2010
Tatula – Trečionys	1967, 1968, 1969, 1977–1987, 1993–2001, 2003, 2007	67	1987, 1999
Venta – Leckava	1968, 969, 1978, 1981–1989, 1991, 1993–2000, 2002, 2004, 2012, 2014	113	1988
Venta – Papilė	1978, 1979–1996, 1998, 1999, 2001, 2004	80	1979

*The difference between the maximum H during the ice jam, and H at the beginning of the ice jam.

On average, in all HSs, ice jams begin on 10 January, and the average ice-jam duration is 8 days (Table 3.2.2). The start and duration of ice jams depend on the HS. The earliest average ice-jam start is on 31 December (excluding the start date of 10 December for Mūša – Žilpamūšis, which is only a single case) at Tatula – Trečionys and Venta – Papilė. The latest average start date is 30 January at Svyla – Guntauninkai.

Table 3.2.2. Summary of ice-jam cases.

HS	Ice frequency (cases/year)	Ice-jam average duration (No of days)	Average ice-jam start date	Ice-jam maximum duration (No of days)	A river spills out of its banks (H max > H critical)
Bartuva – Skuodas	0.23	3.7	18 January	6 (1978, 1982)	0
Daugyvenė – Rimšoniai	-	-	-	-	-
Lėvuo – Bernatoniai	0.74	8	14 January	29 (1981–1982)	10
Mūša – Ustukiai	0.54	7.1	25 January	16 (1988)	5
Mūša – Žilpamūšis	0.05	2	10 December	2 (2012)	0
Nemunėlis – Tabokinė	0.71	5.5	24 January	20 (1993)	2
Svyla – Guntauninkai	0.14	6.2	30 January	14 (1969)	2
Tatula – Trečionys	0.91	11.3	31 January	84 (1984–1985)	0
Venta – Leckava	0.63	8.7	4 January	38 (1987)	0
Venta – Papilė	0.86	7.8	31 December	41 (1981–1982)	2

Throughout the period from 1961 to 2023, the earliest recorded ice-jam start was on 30 October (HS: Tatula – Trečionys, 1979), and the latest was on 14 April (HS: Mūša – Ustukiai, 2013).

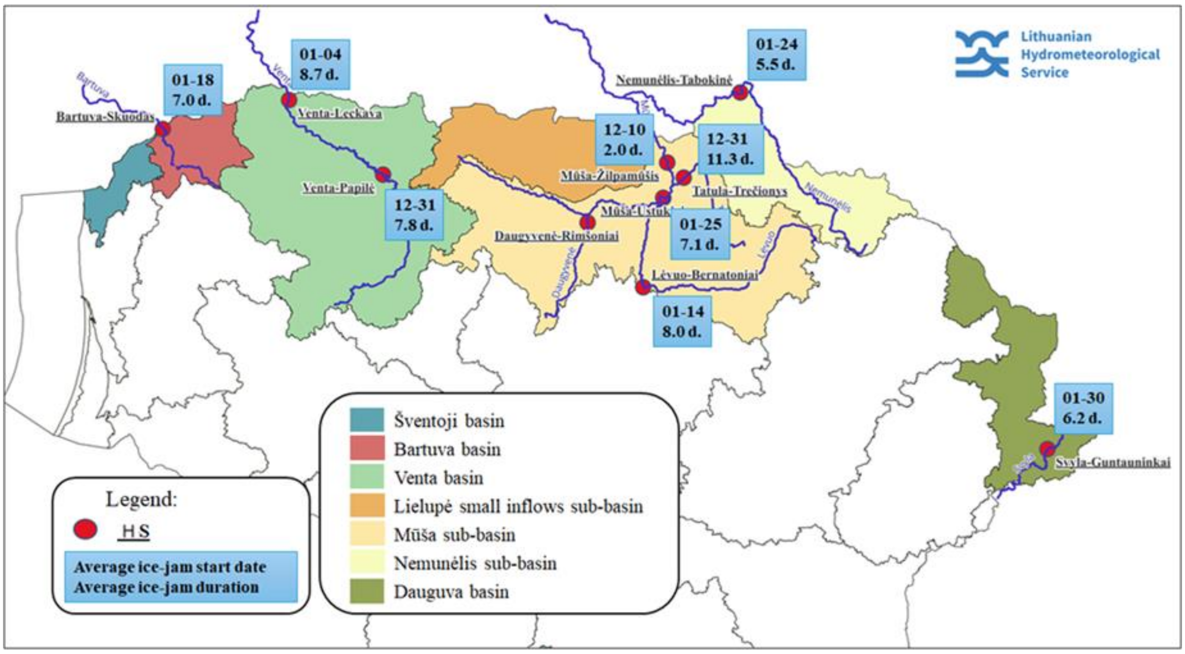

Figure 3.2.2. Average ice-jam start date and duration in Lithuanian HS.

Most ice-jam cases among the nine analysed HS started in December (32.5%) and January (27.4%), totally 59.9% across all stations. Slightly more than a quarter of the cases occurred in February and November (27.9%) (table 3.2.3).

Table 3.2.3. The number of ice-jam cases, which started in the respective month at the HS during 1961-2023.

HS	January	February	March	April	October	November	December
Bartuva – Skuodas	4	2	0	0	0	0	1
Lėvuo – Bernatoniai	8	3	6	2	0	6	12
Mūša – Ustukiai	5	5	4	2	0	3	6
Mūša – Žilpamūšis	0	0	0	0	0	0	1
Nemunėlis – Tabokinė	11	7	6	3	0	4	8
Svyla – Guntauninkai	2	0	1	1	0	0	2
Tatula – Trečionys	12	8	1	0	1	7	21
Venta – Leckava	13	6	1	0	0	4	12
Venta – Papilė	10	5	1	0	0	6	14
Total	65	36	20	8	1	30	77
% part of all cases (237)	27.4	15.2	8.4	3.4	0.4	12.7	32.5

As most floods caused by ice jams have occurred in the rivers Lėvuo and Mūša (table 3.2.4), it would be appropriate to select these rivers as pilot rivers for further project implementation.

Table 3.2.4. River flooding, caused by ice jam.

HS	Year	Ice-jam H max > H critical (difference in cm)
Lėvuo – Bernatoniai	1980	51
	1984	90
	1985	90
	1986	50
	1988	65
	1988	70
	1999	128
	2006	34
	2010	132
	2018	97
Mūša – Ustukiai	1980	34
	1986	62
	1987	108
	2010	94
	2013	125
Nemunėlis – Tabokinė	2002	5
	2010	193
Svyla – Guntauninkai	2010	114
	2013	103

Only a few studies on ice-jam floods in Lithuania are known. Some of the initial studies date back to the 1960s and have focused on the major Lithuanian rivers. There are no studies analysing floods in Northern Lithuanian rivers caused by ice phenomenon.

Table 3.2.5. HS information and selected ice-jam cases for the project.

HS	Observations period	HS coordinates		HS "0" altitude	Cases of H rise	Ice-jam cases
		X (LKS94)	Y (LKS94)			
Bartuva – Skuodas	1960-2023	345716	6241331	11.03	21	7
Daugyvenė – Rimšoniai	2006-2023	497783	6207510	48.6	1	0
Lėvuo – Bernatoniai	1966-2023	517679	6184409	43.81	66	38
Mūša – Ustukiai	1961-2023	523077	6214714	26.81	45	25
Mūša – Žilpamūšis	2001-2023	526280	6228999	20.8	10	1
Nemunėlis – Tabokinė	1960-2023	552774	6253754	36.95	84	39
Svyla – Guntauninkai	1960-2023	664927	6127055	129.47	10	6
Tatula – Trečionys	1961-2023	532192	6223584	29.98	76	50
Venta – Leckava	1961-2023	390821	6252226	39.77	62	36
Venta – Papilė	1960-2023	424535	6224671	67.99	51	36

The cases have been selected according to the dates of maximum H and Q and maximum water level (during the ice jam) exceed the established critical water level. Most cases are excluded for the second reason.

4. Project pilot river stretches

4.1. Daugava River from Nereta to Aiviekste

4.1.1. River stretch morphology

The most sensitive area for ice-jam formation in the Daugava River is a stretch from the Nereta River (tributary in 174.4 km from the river mouth) to the Aiviekste River (tributary in 145.5 km from the river mouth). The length of this river stretch is about 29 km (Figure 4.1.1).

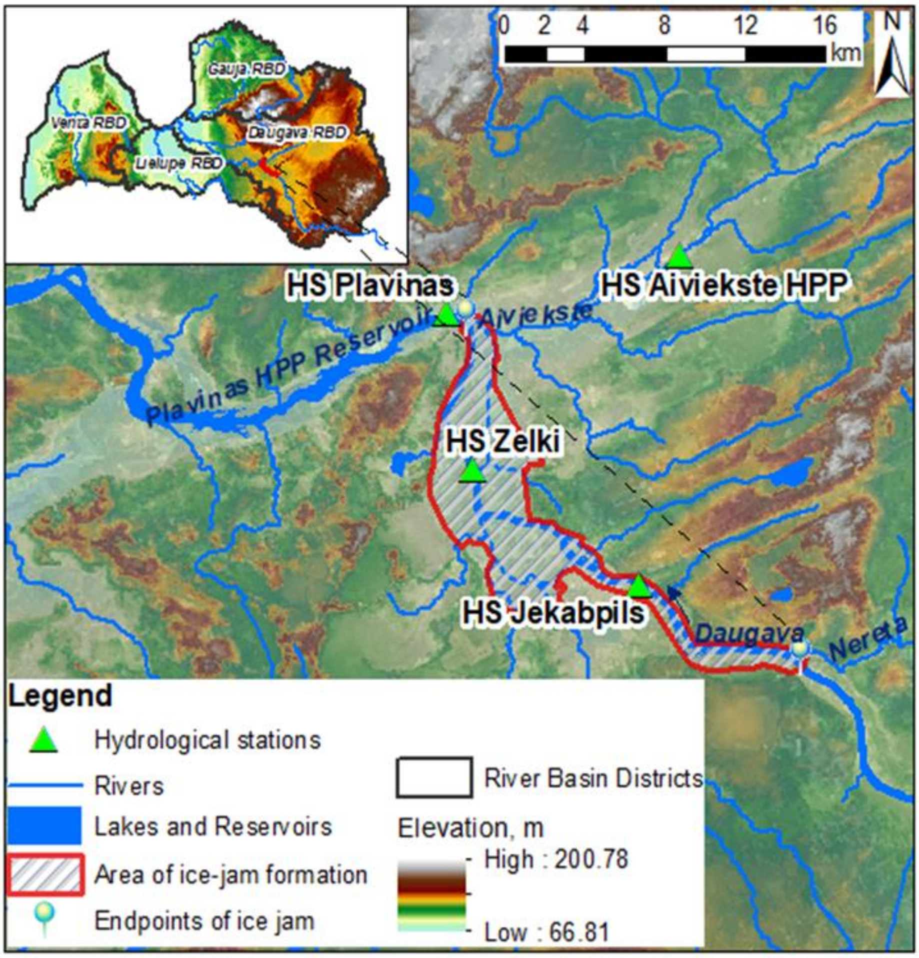

Figure 4.1.1. Area of ice-jam formation in Daugava River

The channel width of the Daugava River is 150-300 m, the average depth is 3-5 m. The average slope of the Daugava River in a section from Nereta to Aiviekste rivers is 0.20 m/km, and flow velocity varies from 0.3 to 0.6 m/s. However, from the Zelki Bridge (about 154 km from the river mouth) downstream, the river turns into a reservoir, where the flow speed is noticeably reduced, therefore ice jams in combination with slush ice can remain here for a long period, depending on meteorological conditions. Due to ice jams, at the confluence with the Aiviekste

River, where the Daugava River forms a sharp meander bend of almost 90 degrees, flowing from south to west, the banks are washed away. It is causing a risk of flooding upstream in adjacent settlement areas of Jekabpils County and considering the potential hazards in the city of Jekabpils. The big railway bridge in Zelki village is an additional cause of ice jams formation. This bridge has four piers that obstacle of the ice movement.

Construction and operation of the Plavinas HPP Reservoir (since 1968), where daily water flow and levels are being regulated, can partially cause the formation of ice jams on the Daugava River in a section from Nereta to Aiviekste. In order to prevent flooding of the town of Plavinas (located downstream of the Aiviekste River) during the spring ice break-up of the Daugava and Aiviekste rivers, accompanied by ice jams, pre-flood drawdown of the Plavinas HPP Reservoir is planned to the level of 67.14 m a.s.l. (at the dam), compared to the normal water level of 72.14 m a.s.l. The minimum permissible level of the Plavinas HPP Reservoir from the end of the ice drift to the third ten-day period of April (i.e. April 21) is 69.14 m a.s.l. with a maximum daily amplitude of level fluctuations of 1.0 m. For example, in 1983, the maximum ice jam level was observed on March 30, reaching a historically high mark of 80.12 m a.s.l. (250 cm above the critical level) at HS Zelki and 82.86 m a.s.l. (90 cm above the critical level) at HS Jekabpils, while in the Plavinas Reservoir (at the dam) the average water level was 67.36 m a.s.l., and the water inflow from the Daugava and Aiviekste rivers was 2270 m^3/s with the maximum inflow of the spring flood being 3890 m^3/s (April 4). At the same time, the formation of a thick ice cover on the river in winter, combined with unfavourable weather conditions (a sudden spring warming with rain), can also result in an ice jam. For example, at HS Zelki, the maximum ice thickness before ice-jam formation was recorded on March 20, 1981, amounting to 110 cm, while the maximum ice jam level reached 79.94 m a.s.l. (232 cm above the critical level) on April 1.

4.1.2. Ice-jam flood events

Daugava River long term annual discharge at HS Jekabpils (about 165 km from the river mouth), is 500 m^3/s and the specific flow rate is 7.1 $l/s.km^2$. In the historical long-term period, the maximum flow rate was observed on May 1, 1931, reaching 7470 m^3/s (106 $l/s.km^2$). In the period (1961-2023), the maximum flow rate was observed in 1966 and 1970 (4060 m^3/s or 57.6 $l/s.km^2$).

After construction of the Plavinas HPP, freeze-up and ice break-up processes in the Daugava River stretch between tributaries Nereta and Aiviekste have been changed significantly. Before, masses of ice and frazil ice quickly passed Jekabpils City, Saka Island and Plavinas City in transit, but further, after the creation of the reservoir, in this section of the river, during the freezing period, an intense accumulation of ice and slush ice is observed.

After the first frost in autumn the reservoir' water temperature is closed to 0 oC and water velocity in the reservoir near Plavinas City is much slower than in Daugava River. Hence, the reservoir starts to cover by very thin ice. Slush ice movement continues in the river and frazil ice masses come from upper river stretches. In years, when the river flow is high and the frost is not enough to cover river by ice, slush ice runs in a very long river stretch, sometimes even from Vitebsk City (620 km from river mouth) or Polock City (474 km from river mouth) till Plavinas Reservoir (about 160 km from river mouth). All ice and slush ice masses after coming into the reservoir significantly losses velocity and accumulates. This process depends on the hydrometeorological situation, so accumulated ice masses can be very different in volume. Sometimes ice measurements aren't carried out due to ice conditions, so the ice volume' calculation isn't possible. However, the calculation results for the period from 1968 to 1986 show the huge variation of an ice volume in different years: from 1.8 km^3 in 1984 to 21.5 km^3 in 1981. It's evident that the ice volume in the freeze-up period effects the ice break-up process.

In autumn 1980, huge frazil ice masses accumulated in Plavinas Reservoir, the ice jam occurred, and water level in Daugava River was very high. In spring 1981, when the ice break-up process started, the next serious ice jams occurred in the river stretch near Jekabpils City. The water level rise here was significant, and it reached the highest observed elevation at HS Jekabpils – 83.66 m a.s.l.

In this river stretch, significant ice jams occur every year in the freeze-up or break-up process, mostly both. In the 21st century, only some years weren't ice jams there. Depending on the hydrometeorological situation, the ice-jam flooding might be appeared in different river stretches like a lower part of Plavinas Reservoir, an upper part of the Reservoir near Zelki or near Saka Island and Jekabpils City.

In Daugava River near Jekabpils City (HS Jekabpils) at the beginning of the 21st century the most significant floods caused by ice jam were observed in 2007, 2018, 2021 and 2023. However, more often ice jams occurred near HS Zelki: 2004, 2006, 2007, 2010, 2012, 2013, 2017, 2018, 2023, 2024 (Figure 4.1.2).

In December 2022, an ice cover formed in some sections of Daugava River, but mostly there was frazil ice movement with varying intensity. Considerable masses of ice and slush were accumulated in the Plavinas Reservoir and in Daugava River. The weather in the first days of January was mild and wet, ice masses moved downstream faster, but still remeined in the Reservoir. After a couple of days came frost, but the river flow was quite high, and ice cover couldn't form. It led to frazil ice' generation in a very long river stretch from Polock to Plavinas Reservoir, ice masses accumulation and ice-jams appearing. Ice jamming was long, it led to water level rising firstly in the Reservoir and then in the upper part of it near HS Zelki. Later the frazil ice masses continued to accumulate and water level rises also near Saka Island and HS Jekabpils. On January 13 Jekabpils City was already in danger, water level rise continued, river flow in upper stretches was high, but due to ice dams, the river was mostly blocked and water flooded wide territories of the city. People were evacuated. On January 14 water level reached 83.61 m a.s.l. at HS Jekabpils.

Figure 4.1.2. Ice drift and flood in Daugava, near Zelki bridge, February 29, 2024 (photo: LEGMC)

In February 2024 break-up floods occurred near HS Zelki. After period of frost came warm period with additional precipitation, Daugava River flow raised, ice moving started in Daugava River and Plavinu Reservoir. As a result of those processes, ice masses were jammed and water level rapidly raised reaching at HS Zelki 78.93 m a.s.l. Territories including houses and roads were flooded from Saka Island to Aiviekste River. It was one of the highest observed water levels near HS Zelki in the whole observation period.

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

4.2.1. River stretch morphology

The most sensitive area for ice-jam formation in the Lielupe River is an upper stretch from the confluence of Musa and Memele rivers near Bauska City downstream to the confluence of Lielupe and Sesava rivers near the settlements of Ane and Tetele. The length of this river stretch is about 40 km (Figure 4.2.1). This is an area where ice jams occur almost each year, considering adverse weather conditions in spring and winter seasons.

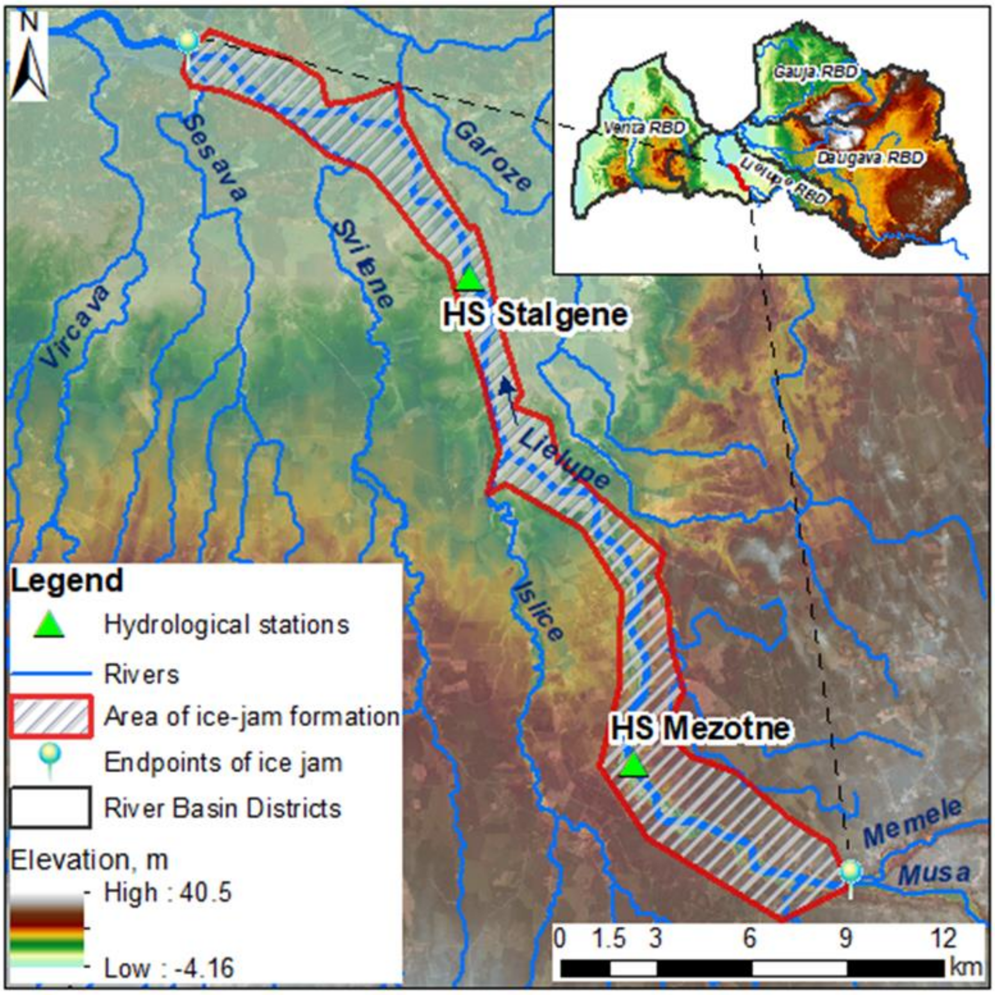

Figure 4.2.1. Area of ice-jam formation in Lielupe River

The Lielupe River in its upper stretch is characterised by a moderately sinuous channel with very smooth meander bends alternating every 3-4 km. There are 10-12 small islands (with a main area of less than 1.0 ha) that are completely or partially flooded in the upper stretch of the Lielupe River. The largest island (about 1.9 ha) is located at the confluence of Musa and Memele rivers, where ice jams are mostly formed. Predominant width of the Lielupe River is 60-100 m, on average. However, the river channel narrows to 20-40 m wide in a section of about 14-20 km from the junction of Musa and Memele rivers (96-102 km from the Lielupe River mouth) where the riverbed is most intensively overgrown with aquatic vegetation in the littoral zone. The Lielupe River widens to 100-160 m in a stretch from the mouth of the Garoze River to the junction of Lielupe and Sesava rivers (75-83 km from the mouth of a river). Ice jams occur not only in spring when the water level of the Lielupe River is rising rapidly but also during winter, interrupted by frequent periods of thaw.

At a river stretch from Mezotne to Stalgene the ice thickness reaches 25-27 cm, on average, but in some severe winters it can be 46-68 cm (for example, in 1963, 1979 and 1985). The sudden warming in combination with rainfall and subsequent ice-jamming in spring causes a rapid rise of water level (by 2.5-5.0 m above the long-term average level), The average depth of the Lielupe River at a stretch from its source to the mouth of the Garoze River is relatively small (0.5-1.5 m) and rarely exceeds 2.5 m; in a section from the Garoze River to the Sesava River, the depth of the Lielupe River increases to 3-3.5 m. Therefore, in some sections, the river channel can be periodically filled with slush ice and ice blocks to the very bottom.

The average river slope is 0.23 m/km, and the flow velocity is 0.3-0.4 m/s. However, the situation with ice-jams formation is aggravated by the presence of the Stalgene Bridge (88.8 km from Lielupe river mouth), 129 m long and 12 m wide, with four piers, and upstream from it the flow rate is reduced due to speed losses. At about 33 km, i.e. from the source of the Lielupe River to the mouth of the Garoze River, the riverbed consists mainly of pebbles and gravel, silty in places and along the rest of the length it becomes sandy.

4.2.2. Ice-jam flood events

Lielupe River long-term (1961-2023) annual discharge at HS Mezotne (107 km from river mouth), is 53.6 m^3/s and the specific flow rate is 5.66 l/s.km^2. The maximum flow rate was observed on April 2, 1979, reaching 1060 m^3/s or 111.9 l/s.km^2. According to analysis of historical flow data, the maximum water discharge of the Lielupe River during ice-jam floods is about 40-50% less than the maximum spring discharge, on average.

At the beginning of the 21st century, significant floods due to ice jams in the upper reaches of the Lielupe River occurred in 2007 and 2013. In the spring of 2007, due to about 3 km long ice jam, the maximum water level in Lielupe near Mezotne reached 8.83 m a.s.l. (67 cm above the critical level). The water level rise during an ice jam was 1.84 m. Ice-jam floods caused damage to a heritage site “Little Mezotne Palace”. On the opposite bank from Mezotne, a road culvert, located in Rundale Parish of Bauska Municipality, was washed away.

In April 2013, ice jams caused extensive flooding of floodplains at a river stretch from Bauska to Stalgene (Figure 4.2.2). At Mezotne, the daily water level rise from ice-jam beginning was 2.26 m and reached 8.80 m a.s.l. (64 cm above the critical level). As a result, the cable-way system at the HS Mezotne was broken. Local roads to seven houses in Stalgene and near two houses in Platone Parish of Jelgava Municipality were flooded. Several residents were evacuated from houses located on the Lielupe River’ banks and on the banks of tributaries.

Figure 4.2.2. Ice drift and flood in upper reach of Lielupe River, downstream from Bauska city, April 17, 2013 (photo: https://weatherfoto.wordpress.com)

4.3. Mūša River from Gustoniai to Ustukiai

4.3.1 River stretch morphology

Mūša is a river in Northern Lithuania, on the territory of municipalities of Joniškis, Pakruojis and Pasvalys districts, and on the territory of Bauska Municipality in Latvia. It is 157 km long (133 km in Lithuania, 6.5 km on the Lithuanian–Latvian border, 17.5 km in Latvia), with a catchment area of 5463 km² (5297 km² in Lithuania). From 133 km of its length in Lithuania, 13 km of river stretch is under periodical ice-jams, which can endanger nearby settlements. The most sensitive area for ice-jam formation in the Mūša River starts 12.5 km upstream from the bridge located in Ustukiai to Gustoniai village (Figure 4.3.1).

The target Mūša River stretch is characterised as a regular-form channel with low sinuous bends and very smooth meander bends. There are several unbranching systems that are formed by small groups of islands. These groups of islands significantly narrow the river profile and can be a natural obstacle to the formation of ice jams. The average width is 30–40 m but can vary between 15 m in the narrowest place up to 70 m in the widest. The depth is mainly between 1–2 m, and in some places, it is up to 4 m. The average river stretch slope is 0.35 m/km. The speed of the current is 0.1–0.4 m/s. The river stretch is highly overgrown with aquatic vegetation in the channel zone during the warm period.

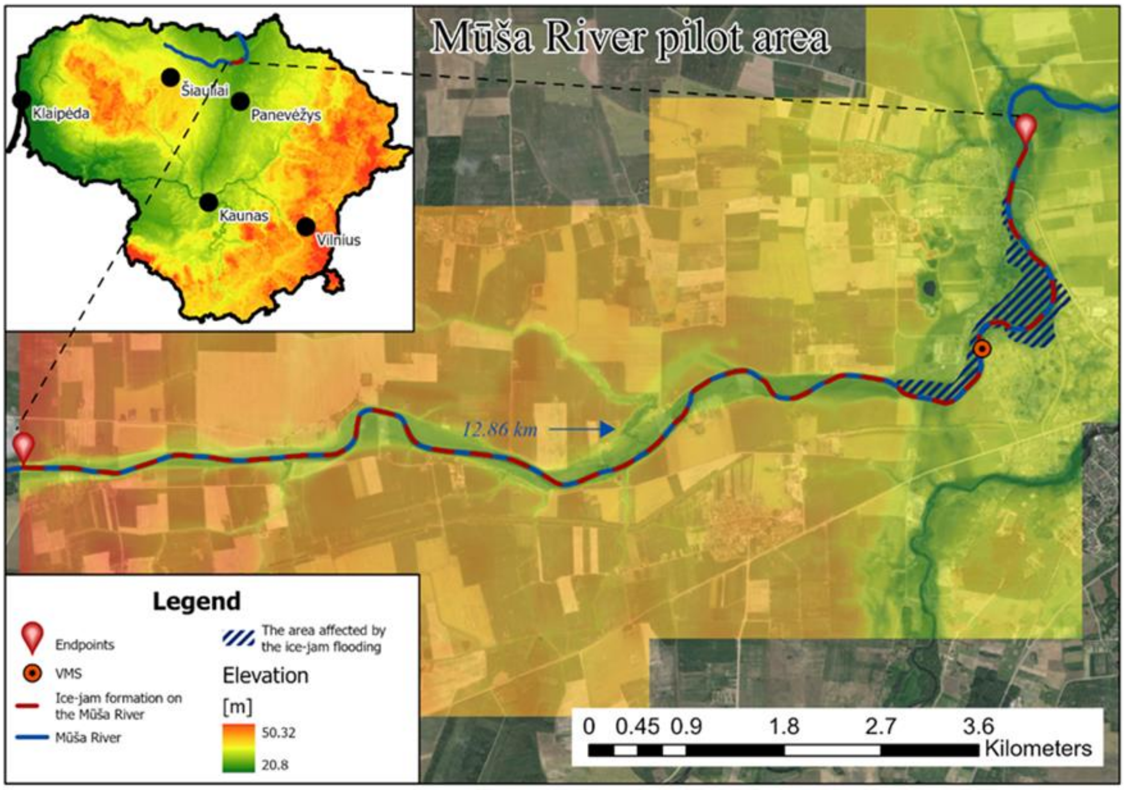

Figure 4.3.1. Mūša River reach selected for ice jam flood modelling

At a river stretch from Gustoniai to Ustukiai the average ice thickness is 29 cm, with a maximum thickness of 50-55 cm (1980, 1987, 2010). The average depth of the river at the Ustukiai HS is 0.92 m and the average width is 44.4 m. The water level of the river rises from 0.63 m to 2.98 m above the perennial mean water level during floods caused by ice drifts. Therefore, in some sections, the river channel can be periodically filled with slush ice and ice blocks.

Ice jams occur here due to some sharp bends of the river and the location of an important logistical bridge over the river at Ustukiai. Ice-jam floods can harm the nearby settlements of Gustoniai and Pasvalys, as well as summer cottages adjacent to the river.

4.3.2. Ice-jam flood events

Mūša River long-term (1961-2023) annual discharge at HS Ustukiai (56 km from river mouth), is 10.2 m^3/s, and the specific flow rate is 4.49 l/s.km^2. The maximum flow rate was observed on April 1, 1979, reaching 364 m^3/s or 159.6 l/s.km^2. According to the analysis of historical flow data, the maximum water discharge of the Mūša River during ice-jam floods is about 67% less than the maximum spring discharge, on average. A large difference was also found between the absolute values, the ice flood discharge is 61% lower than the spring flood in the Mūša River.

There are several settlements near Mūša with a population of 100 inhabitants or more. These settlements are at risk of being affected by flooding caused by ice-jams. The largest settlement is the town of Pasvalys, with a population of almost 6.5 thousand (according to the 2021 census). Smaller settlements such as Saločiai, Ustukiai, Narteikiai, Švobiškis, Pamūšis (Klovainiai eldership), Petrašiūnai, Pamūšis (Pašvitinis eldership) could also be affected. The ice-jam can also damage heritage sites in its path, e.g. Saločiai Park, the grave of the Medema family, the Saudogala village cemetery, fragments of the Žilpamūšis Manor, the Raudonpamūšė Manor, the Pamūšiai Landscape Reserve, etc.

At the beginning of the 21st century, significant floods due to ice jams in the upper reaches of the Musa River occurred in 2010 and 2013. In the spring of 2010, due to ice jams, the maximum water level in Musa near Ustukiai reached 30.25 m a.s.l. (90 cm above critical level). Ice-jam flood in 2010 caused some damage, flooding of floodplains at a river stretch.

Figure 4.3.2. Flooded community garden "Vyturys", April, 2013

In April 2013, ice jams caused extensive flooding in Musa River. At Ustukiai water level reached 30.51 m a.s.l. (125 cm above critical level). Ice-jam flood in 2013 cause a lot of damage in Pasvalys town, where houses, warehouses, summerhouses, greenhouses were flooded. The water layer up to 0.5-1 m deep covered Žemdirbių and Bokšto streets in the community garden "Vyturys" (Figure 4.3.2). However, residents refused to evacuate.

4.4. Lėvuo River from Pamarliškiai to Bridge in Skaistgiriai

4.4.1 River stretch morphology

Lėvuo is a river in Northern Lithuania, on the territory of municipalities of Rokiškis, Kupiškis, Panevėžys and Pasvalys districts; the right tributary of the Mūša. Length 147 km, catchment area 1628.5 km^2. The local climate, the strong winding of the river and the presence of many bridges and canals on the section from Pamarliškiai to Skaistgiriai (22 km) create good conditions for the formation of floods and ice jams. The situation is further complicated by the presence of small settlements and summer residences along almost the entire study area. The most difficult and dangerous place is the connection with the Sanžilės Canal, where, in addition to the bifurcation of the channel, there are two road bridges and an old railway bridge with massive concrete structures around it in a short distance. Therefore, the most sensitive area for ice-jam formation in the Lievuo River from Pamarliškiai to Skaistgiriai (Figure 4.4.1.).

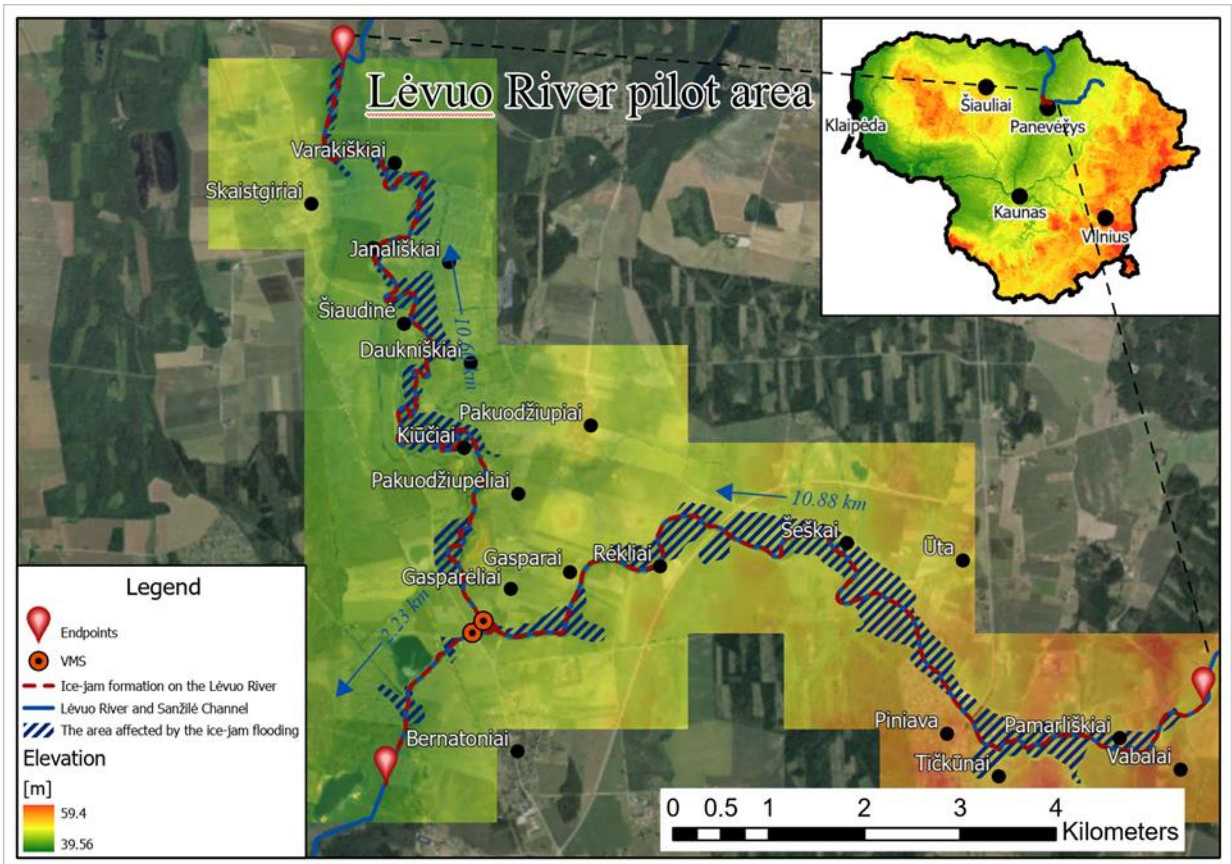

Figure 4.4.1. Levuo river reach selected for ice jam flood modelling

Lėvuo has a flat topography, which means that the rivers have a low gradient, the channels are shallowly incised, and the soils are mainly of heavy mechanical composition. The infiltration properties of such soils are poor, so little groundwater recharges the rivers. The unregulated course of the river is meandering, varying in width from 16 to 35 m and in depth from 0.5 to 3.1 m. The average slope gradient for the selected river stretch is 0.30 m/km, and the flow speed is 0.2–0.3 m/s. The presence of several islands does not play a significant role in ice-jam flood formation compared to the sharp meanders and abundance of artificial structures such as bridges and channels.

At a river stretch from Pamarliškiai to Bridge in Skaistgiriai the average ice thickness is 20 cm, with a maximum of 37-72 cm (1985, 1988, 2010). The average depth of the river at the Bernatoni HS is 0.62 m and the average width is 19.4 m. During floods caused by ice drifts, the water level rises from 0.34 m to 2.45 m above the average perennial water level. Sharp meanders, together with the abundant bridges, cause the ice-jams formation in the selected Lėvuo River stretch. Therefore, in some sections, the river channel can be periodically filled with slush ice and ice blocks.

4.4.2. Ice-jam flood events

Lėvuo River long-term (1968-2023) annual discharge at HS Bernatoniai (48 km from river mouth), is 2.57 m^3/s and the specific flow rate is 3.17 l/s.km^2. The maximum flow rate was observed on March 23, 2010, reaching 107 m^3/s or 93.9 l/s.km^2. According to analysis of historical flow data, the maximum water discharge of the Lėvuo River during ice-jam floods is about 61 % less than the maximum spring discharge, on average. However, if we compare the absolute values, the ice flood discharge in Lėvuo River is only 5% lower than the spring flood.

There are several settlements near Lėvuo with a population of 100 inhabitants or more. These settlements are at risk of being affected by flooding caused by ice-jams. The largest settlement is the town of Pasvalys, with a population of almost 6.5 thousand (according to the 2021 census). Another large settlement is Kupiškis (about 6.2 thousand inhabitants, according to the 2021 census data). Smaller settlements such as Piniava, Tičkūnai, Šeškai, Paliūniškis, Skaistgiriai, Daukniškiai and Naujikai may also be affected by flooding caused by ice-jams. There are several heritage sites close to the River Lėvuo, such as the Balsiai Water Mill and Manor House, the Toliūnai Water Mill and Manor House, the Gaspari Mound Cemetery, etc., which may be threatened by flooding.

At the beginning of the 21st century, significant floods due to ice jams in the upper reaches of the Levuo River occurred in 2010 and 2018. In the spring of 2018, due to ice jam, the maximum water level in Levuo near Bernatoniai reached 46.38 m a.s.l. (97 cm above critical level). Ice-jam flood in 2018 does not cause big damage (Figure 4.4.2).

Figure 4.4.2. Ice drift and flood in Levuo River, March, 2018

In the year 2010 there was a significant flood in Lėvuo. There was a large ice-jam near Piniava village. On 23 March, the water level was rising up 126 cm above critical level and reached 46,67 m a.s.l. (perennial highest water level 46,73 m a.s.l.). Community gardens and roads were flooded. Houses in Tičkūnai and Šeškai villages were also flooded, several families were evacuated, electricity was turned off in 7 community gardens, and the "Kemira GrowHow" seed factory was flooded. The water broke through the embankment at Pakuodžiupiai village, flooded the fields from Bernatoniai village towards the Pušalotas town and started to flood Skaistgiriai villages. The water was slowly receding from the flooded areas of Lėvuo. On 3 April, part of the community gardens of Tičkūnai village were still flooded, even though the water level at Bernatoniai was already only 118 cm.

The Sanžile Canal is located next to Lėvuo. It was dug in 1930 to reduce the floods of Lėvuo. In 2010 the situation was no better in the Sanžile Canal. The thickness of the ice there reached 40–60 cm. The riverbank is covered with bushes and trees, the riverbed is full of spillways, and many bridges of garden communities. All this created the conditions for ice-jams to form. As many as 4 ice jams were formed in the channel, which raised the water level significantly. On the morning of 22 March, the Sanžile Canal reached a dangerous level (216 cm), but the water level continued to rise and by 2 p.m. it had reached 278 cm, which is 4 cm higher than the highest water level of the year. The water in Sanžile flooded the community gardens by the river, part of Berčiūnai settlement and the road by Berčiūnai church. The situation was critical, and it was decided to blast the ice jams on 25 March. It took 5 blasts to dislodge the ice. The water began to recede slowly and within 7 days it had receded 150 cm.

5. Conclusions

Warm and unstable winters lead to major changes in the ice regime of rivers and lakes. Due to unstable winters, there can be multiple freeze-up and break-up events per season. Variations of frost periods with thaws in winter season lead to frazil ice and slush formation in streams and, as a result, the occurrence of ice-jams.

The selected four pilot river stretches are located within the Lat-Lit INTERREG Program area and are the most sensitive to the ice-jam formation due to their specific characteristics.

Within Latvia these areas are located on the banks of two big rivers: Daugava and Lielupe.

The most sensitive area for ice-jam formation in the Daugava River is a stretch between its tributaries Nereta and Aiviekste.

The main factor here is the impact of Plavinas HPP operation. The upper section of the Plavinas Reservoir is located nearby Jekabpils City. After construction of the Plavinas HPP, freeze-up and ice break-up processes in the Daugava River stretch between tributaries Nereta and Aiviekste have been changed significantly. It is related to the reduced flow velocity in the reservoir and the decreased water surface' gradient in the Daugava River stretch Nereta – Aiviekste.

Besides, many small islands in the stream and the big island Saka as well as the four-piers railway bridge in Zelki village impact the ice movement in this pilot river stretch.

Depending on the hydrometeorological situation, the ice-jam flooding might appear in different places, like the upper part of the Reservoir near Zelki or near Saka Island and Jekabpils City.

The second most sensitive area for ice-jam formation in the Lielupe River is an upper stretch from the confluence of the Mūša and Memele rivers near Bauska City downstream to the confluence of the Lielupe and Sesava rivers.

This is an area where ice jams occur almost each year, considering adverse weather conditions in the spring and winter seasons. It is related to the complicated river morphology, characterised by meanders alternating every 3-4 km and 12 small islands in the upper stretch. Besides, the situation of ice-jams formation is aggravated by the presence of the Stalgene with four piers, and upstream from it, the flow rate is reduced due to speed losses.

The Mūša River from Gustoniai to Ustukiai and the Lėvuo River from Pamarliškiai to Bridge in Skaistgiriai are mostly sensitive areas for ice-jam formation in Lithuania.

The **Mūša River stretch from Gustoniai to Ustukiai** is characterised by a smooth flow with a small number of sharp bends. At the same time, long and straight stretches of the river are periodically replaced by sharp turns, which creates a risk of ice jams.

Ice jams were the most common at some sharp bends of the river near Pasvalis and at the location of an important logistical bridge over the river at Ustukiai.

In the **Lėvuo River, the most sensitive area for ice-jam formation is from Pamarliškiai to Skaistgiriai**. Sharp meanders, together with the abundant bridges, cause the ice-jams formation in the selected Lėvuo River stretch. In some cases, the ice jam can run almost the entire length of the river segment and affect fields and biuldings. Situation becomes dangerous due to the large number of settlements along the river.

The most difficult and dangerous place is the connection with the Sanžilės Canal, where, in addition to the bifurcation of the channel, there are two road bridges and an old railway bridge with massive concrete structures around it in a short distance. The situation is complicated by the sharp turn of the river before the bridges, which further contributes to the accumulation of ice in this area.

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