water

MDPI

Commentary

Assessing and Mitigating Ice-Jam Flood Hazards and Risks: A European Perspective

Karl-Erich Lindenschmidt [1,*], Knut Alfredsen [2], Dirk Carstensen [3], Adam Choryński [4], David Gustafsson [5], Michał Halicki [6], Bernd Hentschel [7], Niina Karjalainen [8], Michael Kögel [3], Tomasz Kolerski [9], Marika Kornaś-Dynia [10], Michał Kubicki [11], Zbigniew W. Kundzewicz [4], Cornelia Lauschke [12], Albert Malinger [13], Włodzimierz Marszelewski [14], Fabian Möldner [3], Barbro Näslund-Landenmark [15], Tomasz Niedzielski [6], Antti Parjanne [16], Bogusław Pawłowski [14], Iwona Pińskwar [4], Joanna Remisz [6], Maik Renner [17], Michael Roers [17], Maksymilian Rybacki [13], Ewelina Szałkiewicz [13], Michał Szydłowski [9], Grzegorz Walusiak [6], Matylda Witek [6], Mateusz Zagata [18] and Maciej Zdralewicz [13]

1 Global Institute for Water Security, School of Environment & Sustainability, University of Saskatchewan, Saskatoon, SK S7N 3H5, Canada
2 Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway
3 Institute of Hydraulic Engineering and Water Resources Manage, Nuremberg University of Technology, 90489 Nuremberg, Germany
4 Faculty of Environmental Engineering and Mechanical Engineering, Poznan University of Life Sciences, 60-649 Poznań, Poland
5 Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden
6 Department of Geoinformatics and Cartography, Faculty of Earth Sciences and Environmental Management, University of Wroclaw, 50-137 Wroclaw, Poland
7 Federal Waterways Engineering and Research Institute, 76187 Karlsruhe, Germany
8 Centre for Economic Development, Transport and the Environment for Lapland, Hallituskatu 3 B, 96101 Rovaniemi, Finland
9 Faculty of Civil and Environmental Engineering, Gdansk University of Technology, 80-233 Gdańsk, Poland
10 Institute of Meteorology and Water Management, National Research Institute, 01-673 Warsaw, Poland
11 Jacobs, 30-302 Kraków, Poland
12 Wasserstraßen- und Schifffahrtsamt Oder-Havel, 16225 Eberswalde, Germany
13 Flood and Drought Modelling Centre in Poznań, Institute of Meteorology and Water Management—National Research Institute, 60-594 Poznań, Poland
14 Department of Hydrology and Water Management, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland
15 Swedish Civil Contingencies Agency, SE-651 81 Karlstad, Sweden
16 Ministry of Agriculture and Forestry, 00023 Helsinki, Finland
17 Hochwassermeldezentrale, Landesamt für Umwelt Brandenburg, 15236 Frankfurt (Oder), Germany
18 Department of Inland Waterways, Regional Water Management Board, 70-030 Szczecin, Poland
* Correspondence: karl-erich.lindenschmidt@usask.ca

check for updates

Citation: Lindenschmidt, K.-E.; Alfredsen, K.; Carstensen, D.; Choryński, A.; Gustafsson, D.; Halicki, M.; Hentschel, B.; Karjalainen, N.; Kögel, M.; Kolerski, T.; et al. Assessing and Mitigating Ice-Jam Flood Hazards and Risks: A European Perspective. *Water* **2023**, *15*, 76. https://doi.org/10.3390/w15010076

Academic Editor: Olga Petrucci

Received: 30 November 2022
Revised: 14 December 2022
Accepted: 16 December 2022
Published: 26 December 2022

Abstract: The assessment and mapping of riverine flood hazards and risks is recognized by many countries as an important tool for characterizing floods and developing flood management plans. Often, however, these management plans give attention primarily to open-water floods, with ice-jam floods being mostly an afterthought once these plans have been drafted. In some Nordic regions, ice-jam floods can be more severe than open-water floods, with floodwater levels of ice-jam floods often exceeding levels of open-water floods for the same return periods. Hence, it is imperative that flooding due to river ice processes be considered in flood management plans. This also pertains to European member states who are required to submit renewed flood management plans every six years to the European governance authorities. On 19 and 20 October 2022, a workshop entitled "Assessing and mitigating ice-jam flood hazard and risk" was hosted in Poznań, Poland to explore the necessity of incorporating ice-jam flood hazard and risk assessments in the European Union's Flood Directive. The presentations given at the workshop provided a good overview of flood risk assessments in Europe and how they may change due to the climate in the future. Perspectives from Norway, Sweden, Finland, Germany, and Poland were presented. Mitigation measures, particularly the artificial breakage of river ice covers and ice-jam flood forecasting, were shared. Advances in ice processes were also presented at the workshop, including state-of-the-art developments in tracking ice-floe velocities using particle tracking velocimetry, characterizing hanging dam ice, designing new ice-control structures, detecting, and monitoring river ice covers using composite imagery from both radar and optical satellite sensors, and calculating ice-jam flood hazards using a stochastic modelling approach.

Keywords: European Union's Floods Directive; hydro-electric power; ice-jam flood hazard; ice-jam flood risk; space-borne remote sensing

1. Introduction

On 19 and 20 October 2022, a workshop entitled "Assessing and mitigating ice-jam flood hazard and risk" was held in Poznań, Poland, hosted by the first author with sponsorship from the Global Water Futures research program (https://gwf.usask.ca/ accessed on 14 December 2022). The workshop brought together an international team of engineers, scientists, and officials from universities, research facilities, and government agencies from Europe to review the state-of-the-art developments of and explore advances in ice-jam flood hazard and risk assessments. Government agencies from central, eastern, and northern European countries (e.g., Norway, Sweden, Finland, Germany, and Poland) are in need of new tools to assess ice-jam hazards and risks in order to propose new means of mitigating consequences of ice jamming and ice-jam flooding to communities, infrastructure, and ship navigation. These are issues that will also help research and ice-flood management of rivers in other cold-region countries (e.g., U.S.A., Canada, and Russia) affected by river ice processes and ice flooding.

The Poznań workshop was opened by a welcome from Professor Klaudia Borowiak, the Dean of the Faculty of Environmental and Mechanical Engineering at the Poznań University of Life Sciences. It ran over the course of two half days with numerous presentations, as listed in Table 1. Most of the participants are shown in the group photo in Figure 1. This workshop was a follow-up to the workshop entitled "Developing an ice-jam flood forecasting system for the Oder River" held in Wroclaw, Poland on 26 and 27 November 2018 [1]. The Poznań workshop summarized in this commentary extends the capabilities of the ice-jam flood forecasting discussed in the Wroclaw workshop by to exploring methods and requirements for the assessment and mapping of ice-jam flood hazards and risks from a European perspective. An important question posed at the workshop was: should ice-jam flood hazard and risk assessment and mapping be explicitly mentioned in the EU Floods Directive, at least for members of Nordic countries and countries with continental climates? Comments from Norway, Sweden, Finland, Germany, and Poland are provided in the section "Potential of including ice-jam flood hazard and risk in the EU Floods Directive" below. The section is preceded by "Flood risk and the European Union's Floods Directive" and "Changes to flood risk and ice-jam flood risk due to future climate" to provide background information on the EU Floods Directive and to provide some context on how ice-jam flood risk may change with the climate in the future. Presentations that introduced measures to mitigate ice-jam flood risk and technical advances in ice research to help improve ice-jam flood risk characterization are also summarized in subsequent sections below. Remarks on the workshop outcomes and an outlook for future research themes related to ice-jam floods conclude the commentary.

The paper is structured to capture the topics presented at the workshop. Section 2 provides introductory material in the topic of flood risk and how it is administered in the EU Floods Directive. Section 3 provides a perspective of future flood risk in a changing climate. Perspectives from Norway, Sweden, Finland, Germany, and Poland of including ice-jam flood risk in the EU Floods Directive are provided in Section 4. Section 5 explores different techniques used to mitigate ice-jam risks, such as artificial breakage, flood warning systems, and ice-jam flood forecasting. Current technical advances in river ice research are showcased in Section 6, with topics on particle tracking velocimetry to monitor ice-jam covers, hanging dam characterization, design of ice-control structures, processing composite radar and optical space-borne remote sensing imagery for ice characterization, implementing air-borne remote sensing tools (drones) for ice-cover monitoring, and new modelling approaches in quantifying ice-jam flood hazards. Conclusions and an outlook are found at the end of the paper.

Table 1. Oral talks presented at the workshop.

Presenter	Presentation Title
Day 1	
Klaudia Borowiak	Welcoming remarks from the Dean of Environmental and Mechanical Engineering, Poznan University of Life Sciences
Mateusz Zagata	Polish perspectives on mitigating ice-jam flood risk along the Oder River
Michael Kögel, Fabian Möldner & Dirk Carstensen	A river with ice floods - the Oder river
Iwona Pinskwar & Zbigniew W. Kundzewicz	Changes in flood risk in the Odra and Vistula river basins
Marika Kornaś-Dynia & Włodzimierz Marszelewski	Monitoring of ice phenomena on the Warta River in Poznań over a 60-year period (1961–2020)
Maik Renner & Michael Roers	Challenges for operational flood warning under ice-jam conditions at the Oder River in Brandenburg
T. Niedzielski, M. Halicki, J. Remisz, G. Walusiak & M. Witek	Applying satellite altimetry over the Odra River to issue hydrological predictions at virtual stations
Michał Kubicki	River Ice Detection on High Definition Optical and Radar Satellite Sensors
Karl-Erich Lindenschmidt	Advances in ice-jam flood forecasting, risk assessment and mitigation
Day 2	
Bogusław Pawłowski	Causes of the February 2021 ice jams in the upper Włocławek reservoir
Knut Alfredsen	Ice flood risk reduction in Norway
David Gustafsson	Ice-jam flood risk in Sweden
Tomasz Kolerski	Assessment of the ice jam severity based on the numerical models results
Adam Choryński, Iwona Pinskwar & Zbigniew Kundzewicz	Flood risk reduction in Poland
Maksymilian Rybacki	Modeling flood scenarios from ice jams using MIKE 21 Flow Model FM
Ewelina Szałkiewicz	Determination of the probability of exceedance of maximum ice-jam water states

Figure 1. Most of the participants of the workshop: 1. Cornelia Lauschke, 2. Maciej Zdralewicz, 3. Tomasz Kolerski, 4. Grzegorz Walusiak, 5. Maik Renner, 6. Joanna Remisz, 7. Michal Halicki, 8. Matylda Witek, 9. Dirk Carstensen, 10 Michal Kubicki, 11. Bogusław Pawłowski, 12. Michael Roers, 13. Karl-Erich Lindenschmidt, 14. Tomasz Niedzielski, 15. Michal Szydlowski, 16. Ewelina Szalkiewicz, 17. Wlodzimierz Marszelewski, 18. Iwona Pinskwar, 19. Maksymilian Rybacki, 20. Michael Kögel, 21. Zbigniew W. Kundzewicz, 22. Marika Kornas-Dynia, 23. Mateusz Zagata, and 24. Adam Chorynski (photo taken by Bogusław Pawłowski).

2. Flood Risk and the European Union's Floods Directive

According to the Intergovernmental Panel on Climate Change (IPCC), risk is defined as the potential for consequences where an object of value is at stake and where the outcome is uncertain. The components of such risks are hazards, exposure, and vulnerability. Referring to Figure 2, a hazard is the potential occurrence of a physical event that may cause adverse impacts. The "presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected" [2] is referred to as exposure. Vulnerability can be understood as the "propensity or predisposition to be adversely affected" [2].

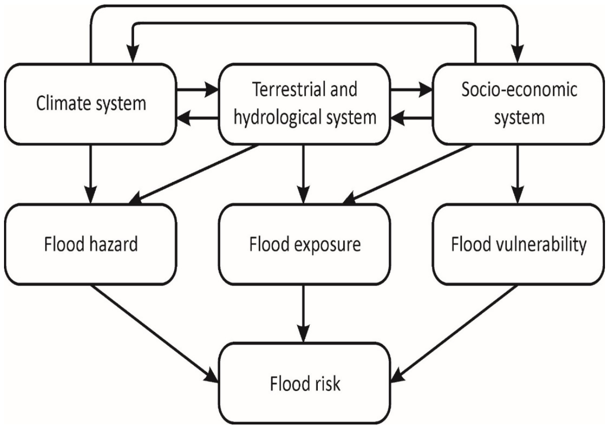

Figure 2. Components of flood risk [3].

> *"The purpose of [the European Union's Floods] Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the [European] Community."* [4]; Chapter 1, Article 1.

Implementation of the Floods Directive is on a six-year cycle with the European Union's member states required to follow three consecutive steps: (i) preliminary flood risk assessments, (ii) hazard maps and flood risk maps, and (iii) flood risk management plans (FRMP). The ultimate goal is to devise a FRMP for each member state to:

1. Reduce flood risk by maintaining and increasing the existing water catchment retention capacity, eliminating, or avoiding an increase in land development in areas of particular flood risk, determining the conditions for the possible development of areas protected by embankments, and avoiding growth and determining development conditions in areas with a low probability of flood occurrence.
2. Reducing the existing flood risk by limiting development in floodplains and reducing the vulnerability of facilities and communities to flood risk.
3. Improving the flood risk management systems which require implementation of forecasting and issuance of warnings about meteorological and hydrological hazards, making the responses of people, companies, and public institutions to floods more effective, increasing resilience to return to preflood states quickly, requiring effective postflood analyses, building legal and financial instruments that discourage or encourage certain behaviors to increase flood safety, and building educational programs to improve awareness and knowledge of the sources of flood hazards and risks.

3. Changes to Flood Risk and Ice-Jam Flood Risk Due to the Future Climate

Observational data show that extreme precipitation is becoming more extreme, nearly on a global scale [5]. Observed connections between heavy precipitation and air temperature broadly agree with the Clausius–Clapeyron law, foreseeing an increase in the vapor-holding capacity of the atmosphere at a rate of approximately 6–7% per 1 °C warming. This sensitivity may be much higher for precipitation on a subdaily scale, i.e., close to 14% per degree of warming for hourly precipitation [6,7].

However, this increase in extreme rainfall does not reflect higher discharges in rivers and decreases are observed at many stations. Globally, the number of stations with significant decreasing trends prevails over the number of stations with significant increasing trends [8].

In the future, along with the warming climate, atmospheric water vapor content is likely to increase, hence the potential for the occurrence of heavy precipitation is on the rise. According to Huo et al. [9], short-duration extreme precipitation may prevail over long-duration extremes. Extreme precipitation events with intensity exceeding the infiltration capacity and the conveyance capacity of the system will very likely result in urban and flash floods of increasing frequency and magnitude. Strong increases in the frequencies of extreme precipitation events (from the 95th to the 99.97th percentile) based on an analysis of observations was presented by Myhre et al. [10]. The total precipitation from these intense events almost doubles per degree of warming, mainly due to changes in frequency. As shown by Hettiarachchi et al. [11] such extremely intense short-duration events will cause flooding in most areas.

The frequency and magnitude of fluvial (river) floods is expected to increase in many regions, but the statement that these kinds of floods are on the rise has not been substantiated. However, projections for the future indicate a greater increase in land areas where river floods become more frequent, compared to the fraction of areas for which fluvial floods will decrease.

At this time there is a lack of consistency between the trends observed in river discharges, which do not indicate an increase, and the model-based projections for the future, which show increasing trends. However, climate change has accelerated, and some changes may yet reveal themselves, so the change expected for the far future could be considerably different from the trend that is now observed [3].

4. Potential of Including Ice-Jam Flood Hazards and Risks in the EU Floods Directive

4.1. Norwegian Perspective

Although ice jams are mentioned in the new guidelines for flood zone maps currently, after hearing from the Norwegian Water Resources and Energy Directorate (NVE), it appears that the guidelines may not be very clear on a specific procedure for mapping ice-induced flooding. For regulated rivers, there are some restrictions on operations to avoid ice-induced floods, particularly the placement and adjustment of intakes to prevent exposing open water to frigid air and avoid huge frazil generation. Operational restrictions are mainly related to freeze-up flooding due to frazil and anchor ice, but also to the risk of breakup in the case of accidental shutdowns and water being released into bypass reaches. In the proposed guidelines, it is stated that ice jams rarely exceed the 200-year open water flood in Norway, and therefore it is not a central component in the flood zone mapping procedure, since the 200-year level is critical in the Norwegian building code. The guidelines acknowledge that it can be an issue and recommend considering ice where problems with ice have been observed in the past. This can particularly be an issue where water is diverted from the river (but not on the 200-year return period level). At best, ice jams that have threatened hydro-power generation or are caused by hydropower shutdowns are archived using maps or local images, an example of an ice-jam event that occurred on the Svorkmo River in Norway is shown in Figure 3.

4.2. Swedish Perspective

The Swedish Meteorological and Hydrological Institute (SMHI) also sees the main issue of ice-jam flood hazards to be frazil ice and ice-jam impacts on hydropower (occasionally there are also problems in nonregulated rivers), but it has no official mandate or task to provide ice information. However, the institute does produce ice-breakup forecasts for the Torne River, including forecasts of breakup dates and a "severity degree" factor indicating the risk for ice-jam complications. The forecasts are provided in collaboration and conjunction with forecasts provided by the Finnish Environment Institute (SYKE), which acquires the necessary ice depth data. Both institutes are involved in research projects to further develop river ice forecasting and monitoring capabilities. An example of a flood hazard map indicating some past flood extents due to ice jams is given in Figure 4.

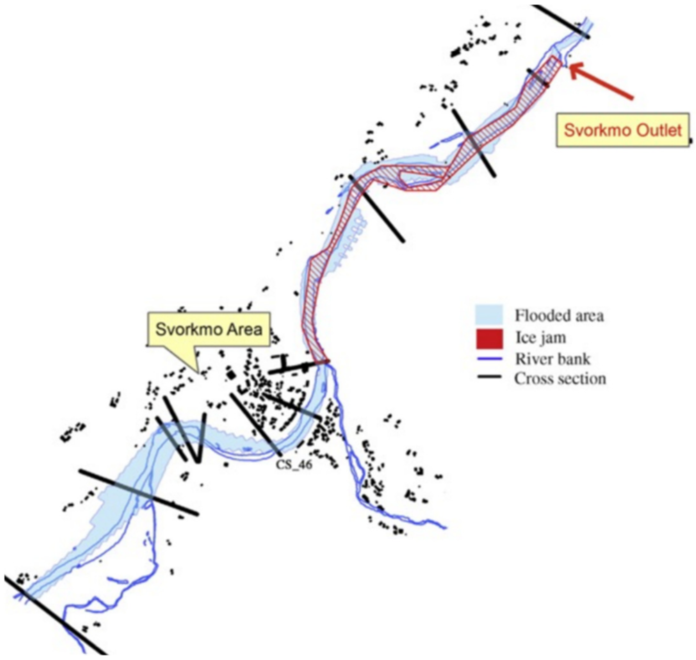

Figure 3. Ice jam on the Svormo River affecting the operation of a downstream hydro-power generation facility (from [12]).

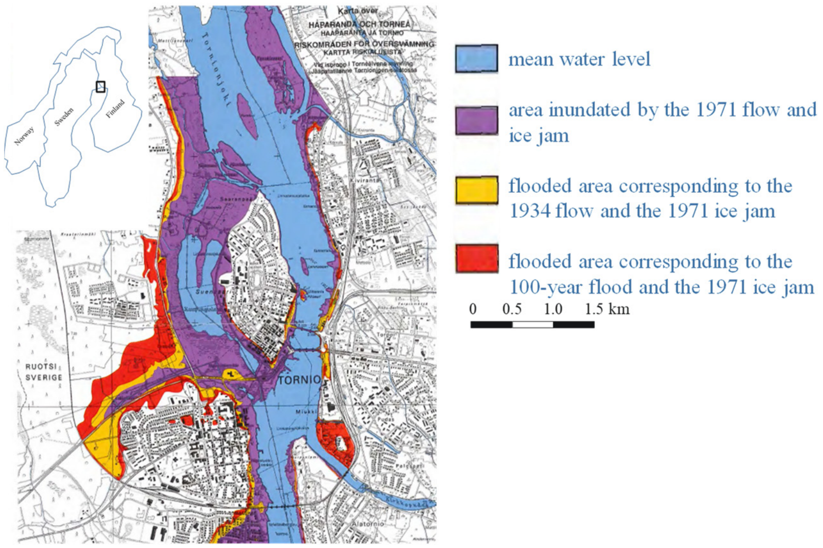

Figure 4. Extent of past ice-jam flood events [13].

4.3. Finnish Perspective

The EU Floods Directive does consider floods caused by frazil ice and ice jams, even though they are not specifically mentioned in the directive itself. However, according to the directive, the preliminary flood risk assessment should be based on information regarding ice-jam or frazil-ice floods that have occurred in the past and provide an outlook for potential future floods. Hence, from a Finnish perspective, the Floods Directive does take ice-jam floods sufficiently into account.

In Finland, there are areas of potentially significant flood risk, where designation is based on ice-jam flood risk (risk for significant adverse consequences by ice jams causing floods). Additionally, goals and measures in the flood risk management plans for those areas are targeted specifically for preventing ice jamming or taking action when there are rapidly rising floodwaters due to ice jams. Finnish government authorities have also prepared flood hazard and risk maps for those areas with past ice-jam flood occurrences (roughly based on similar open water flow velocities), for example for Tornio in Figure 5.

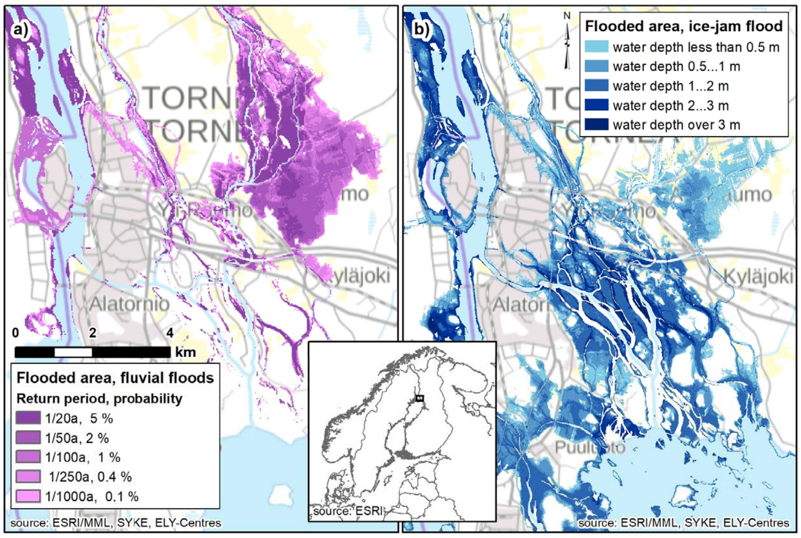

Figure 5. Flood extent for (**a**) different fluvial flood probabilities and (**b**) a severe ice-jam flood (flow = 3100 m^3/s and +2 m sea water level) at the Torne River outlet. (source: SYKE).

4.4. German Perspective

The Oder River is the river that is most often affected by ice jams in Germany. This area, in the most eastern part of the country, experiences continental temperatures in winter. Ice jams generally occur during freeze-up events and are greatly influenced by backwater from the wind setup in the Baltic Sea entering the river's mouth at Szczecin. Ice blockage, in particular, is problematic for flooding at river structures such as bridge piers and weirs. Efforts to release ice jams are carried out by German and Polish ice breakers, but the flow of released ice is hampered by the very mild slope of the lower reaches of the Oder River. Vulnerabilities exist at dikes which have breached in the past due to ice-jam flood events. "The stretch along the Oder Bruch, formally an inland delta drained for agricultural use, is particularly vulnerable due to its containment through dikes and the sediment accretion of the riverbed to elevations higher than the surrounding land. A catastrophic event of extended flooding throughout the adjacent low-lying area of the Oder Bruch occurred in March 1947, in which ice jams caused backwaters to overtop and breach dikes along the Oder Bruch at two locations, with breach widths of over 100 m. Flooding was extensive, leading to the evacuation of 20,000 people" [14]. The fact that ice jamming has become less frequent along the Oder River in recent decades, plus the advances in flood protection and ice defense measures, warning systems, and corresponding disaster control measures, have led to a lack of perception by the people of the dangers and risks of ice-jam floods along the German Oder riverbanks.

4.5. Polish Perspective

At the preliminary flood risk assessment stage and based on the Floods Directive Reporting Guidance 2018 to the European Commission, Poland can identify different types of floods e.g., fluvial and pluvial (from rivers or overland runoff), sea water (flooding of land by water from the sea, estuaries, or coastal lakes) and artificial water-bearing infrastructure (flooding of land by water arising from artificial, water-bearing infrastructure, or failure of such infrastructure). Floods resulting from blockages or restrictions may also be identified, a category which would include ice-jam floods. Other mechanisms that fall into this category include blockages of sewerage systems, restrictive channel structures such as bridges or culverts, and natural occurrences, such as landslides.

It is still uncertain if flood hazard and risk maps for ice jams will be developed for Poland in the future. Much depends on the results of the next preliminary flood risk assessment and the decisions of government authorities. Currently, the Institute of Meteorology and Water Management, a National Research Institute, is working on various aspects of flood protection, including mathematical modeling of ice jams and determining flood hazards from ice phenomena. Figure 6 shows the results of a preliminary study modelling flood hazard areas from ice jams along the test section of the Oder River.

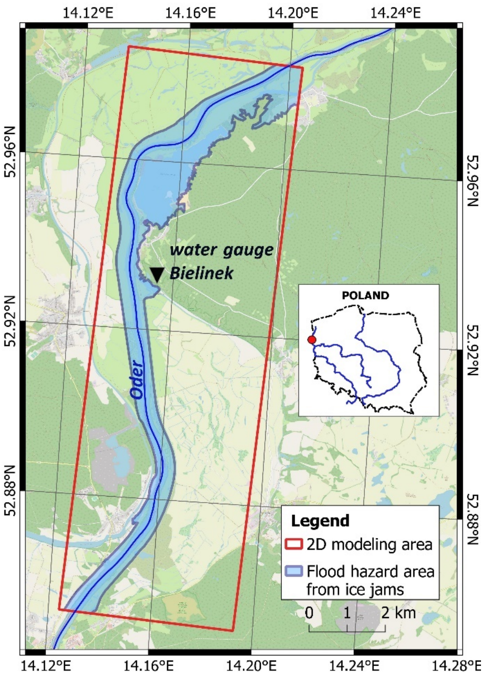

Figure 6. Flooded area along the Oder River at Bielinek, Poland (base map from OpenStreetMap https://www.openstreetmap.org/#map=7/52.012/16.414 accessed on 14 December 2022).

In the upcoming publishing of the river basin management plan for Poland, locations of past ice jams have been identified and mapped for the Vistula River basin, shown in Figure 7. Concentrations of ice-jam locations are indicative of river stretches with a higher propensity for ice-jam flood hazards.

In regard to the changing climate in Poland, in the headwaters of the Vistula River, in the Carpathian Mountains in southern Poland, mean annual air temperatures at the Beskid Zywiecki station have increased by more than 2 °C over the past 40 years. Generally, increases in annual air temperature for stations in the upper Vistula River basin were at the rate of +0.13 °C per 10 years to +0.29 °C per 10 years (based on the period 1951–2015) [15]. Annual total precipitation has also increased, with an increasing trend of approximately 100 mm over the past 50 years. Lupikasza et al. [15] found trends in annual precipitation at ten stations located in the upper Vistula River basin to vary from −7.2 mm per 10 years up to 16.5 mm per 10 years for the period 1951–2015. The intensity of precipitation has also changed, with the number of days of precipitation totaling more than 5 and 10 mm/day increasing over the same time period. Pinskwar et al. [16] also found that, for the area of the upper Vistula River basin, the number of days with precipitation equal to or above 10 mm as well as 20 mm increased in the period 1991–2015 in comparison to 1961–1990. This has repercussions on the flows along the Vistula River and the degree of substances transported from the catchment area into the receiving waters. The more intense rainfalls lead to a greater supply of eroded material to the rivers, exacerbated by the increased weathering of rocks and erosion due to rising air temperatures. The additional sediment transported in rivers can lead to increased accretion of the riverbed, particularly at the inlet of reservoirs, as is the case for the Wloclawek Reservoir showcased below in the Section "Ice characterization of a hanging dam".

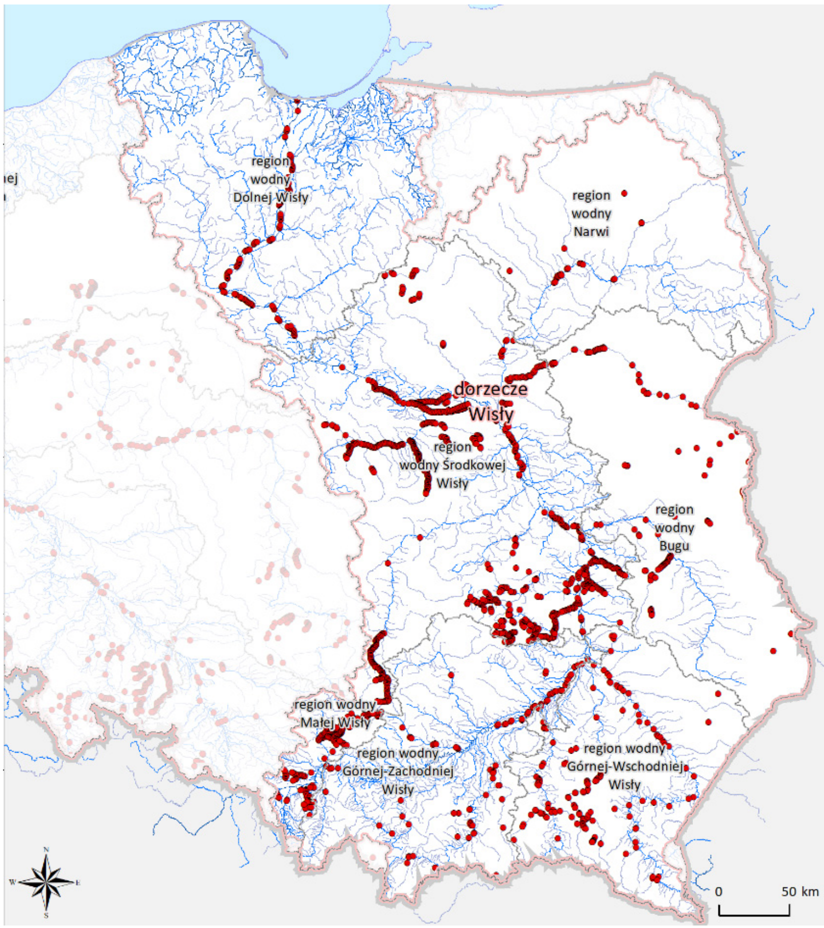

Figure 7. Possible locations of past ice-jam events along the Vistula River and its tributaries (second update of the river basin management plans).

Ice phenomena and phenology have also changed in rivers in Poland. Since 1960, ice phenomena generally appear on the Warta River in December or January of each winter, and the trend is that their occurrences have been delayed by approximately three days per decade at the gauge at Poznań. The ice season generally ends in February or March, with the trend in the end dates occurring approximately four days earlier each decade. This leads to a progressive shortening of the ice season, as shown in Figure 8. The figure also reveals a significant increase in the trend in mean air temperatures measured in Poznań. An interesting correlation between air temperature and the duration of the ice season can be drawn between the two, as indicated in Figure 9. A suggestion was made at the workshop to model water temperature and apply a correction to the ice phenology due to urban heat islands. One of the workshop participants mentioned that most gauges in Poland, with long-term records of ice phenology and thicknesses, are situated in urban centres, which may result in steeper trends toward shorter ice durations and thinner ice nation-wide compared to potential trends due to climatic conditions alone. The additional heat may stem from effluents such as those from wastewater treatment plants or altered air temperatures. In particular air temperature changes should be tested since a large urban area may be required for a significant effect to occur on river ice. A hydrological modelling system with the capability of simulating river temperatures, e.g., the MESH-RBM modelling system [17,18], could help determine biases in ice phenology and thicknesses when comparing "actual" water temperatures (due to climate change and urban heating) to "natural" water temperatures (due to climate change alone). Increased transport of dissolved substances, particularly from the application of fertilizers in the surrounding agricultural region, can also lead to a shortening of the ice season.

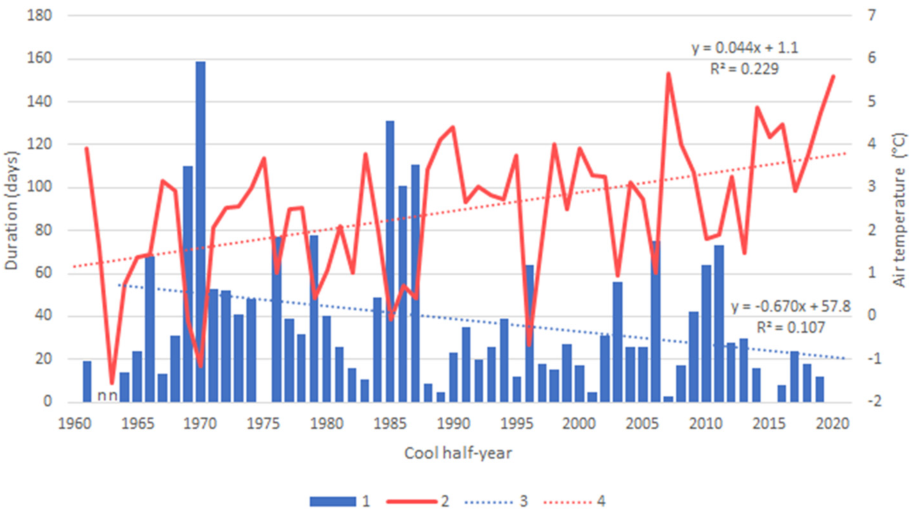

Figure 8. Changes in the duration of ice phenomena on the Warta River in Poznań against the backdrop of the average air temperature in the cool half-year (November to April) in 1961–2020; 1—ice phenomena, 2—average air temperature in the cool half-year, 3—linear trend of ice phenomena in 1964–2020 and 4—linear trend of the average air temperature in the cool half-year in 1961–2020; n—no data (source: data from IMWM-NRI and RWMB in Poznań). (data source: IMWM-NRI and RWMB in Poznań).

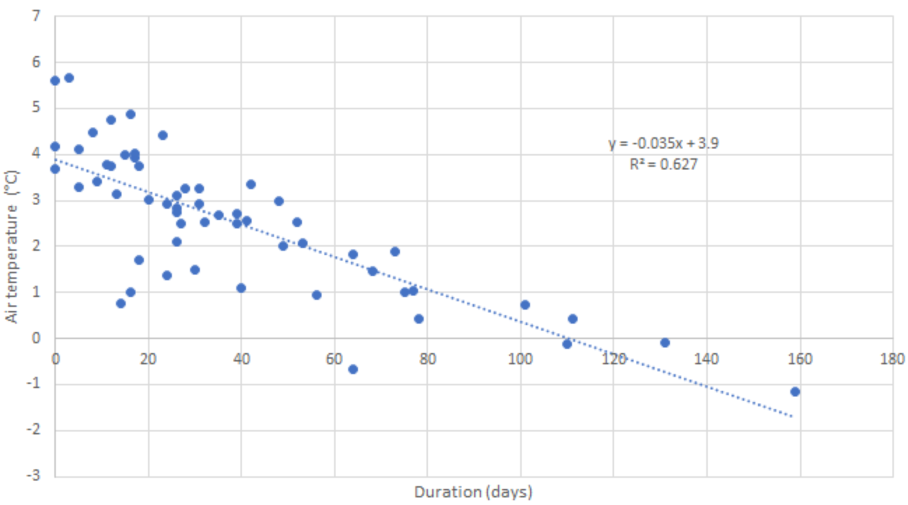

Figure 9. Correlation between average air temperature in the cool half-year (November to April) and duration of the ice phenomena on the Warta River in Poznań for the time period 1964–2020.

On the lower Vistula River, the duration of ice phenomena during the winters in the period 1960–2014 has also decreased [19]. The strongest negative trend was observed in the cross-section of the station situated immediately downstream of the river dam in Wloclawek, approximately −1.5 days/year. Negative trends of −1.64 to −1.97 days/year were also observed at other gauging stations. Negative trends were greater downstream of the Wloclawek Dam than upstream.

5. Ice-Jam Flood Risk Mitigation Measures

5.1. Artificial Ice-Cover Breakage

In order to reduce flood hazards and risks due to ice jamming, ice breakers operate along major waterways to artificially break up ice covers (see Figure 10). The icebreaking operation on the Oder River along the Polish–German border is carried out jointly by the Polish and German waterways administrations. The technical management of the breakage operation of both icebreaker fleets (seven Polish and six German with two reserve icebreakers, one Polish and one German) is exercised by the Polish administration.

Figure 10. Icebreakers releasing an ice jam on the Oder River (source: RZGW, Szczecin).

Generally, a permanent ice cover develops first on Dabie Lake in Szczecin (see map in Figure 11), where frazil ice travelling down the Oder River accumulates and juxtapositions upstream along the Oder River's main stem and its tributaries, the Warta and Lusatian Neisse rivers. Icebreaking begins with crushing the permanent ice cover on Dabie Lake and freeing a gutter through the ice cover to make room for ice floes broken upstream along the river. Frontal icebreakers are directed upriver to break the consolidated ice cover along the river, while linear icebreakers crisscross Dabie Lake to prevent the broken ice from stagnating and refreezing.

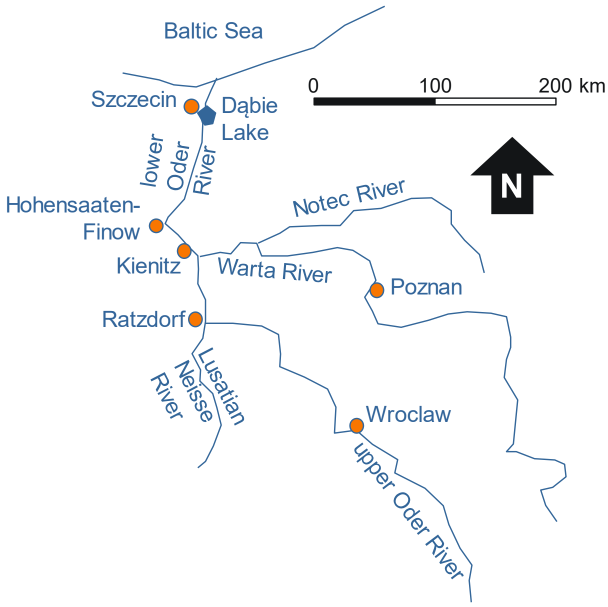

Figure 11. Main stem of the Oder River and its major tributaries (drawn by the first author).

Icebreaking on the Oder River continues upstream towards the mouth of the Warta River, where the resources are split, with the larger part of the icebreaker fleet continuing breakage along the Oder River towards the Lusatian Neisse River mouth and the remaining icebreaker force working its way up the Warta River to the Notec River mouth. Caution must be taken not to begin breakage operations too early so as not to create a large amount of ice floes flowing from the upper sections of the Oder River and its tributaries to the lower reach of the Oder River to create ice jams and, thus, risk inducing a flood artificially.

5.2. Flood Warning under Ice Conditions

Operational flood warning relies on river gauge monitoring. The federal state of Brandenburg, Germany defines four different flood alert levels, which are specified for representative river gauges used in flood reporting services, see Figure 12. An alert level is proclaimed when water levels exceed a certain alert stage and local authorities must take action. The alert levels require increasing operational flood defense actions with increasing water stages [20]: alert level AI—water level reporting service (German: *Meldebeginn*), AII—control service at flood defense infrastructure such as dikes (German: *Kontrolldienst*), AIII—guard duty (German: *Wachdienst*), and AIV—civil protection (German: *Hochwasserabwehr*). These four alert levels allow quick assessment of the potential severity of a flood across different rivers in Brandenburg. The gauges used for the alert level system require high reliability and redundancy of sensors and communication networks.

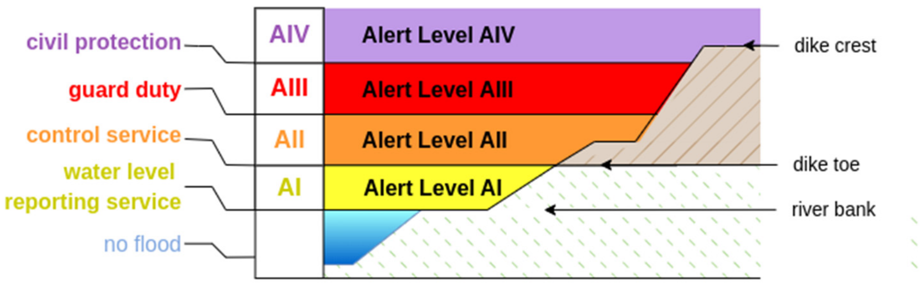

Figure 12. Alert levels for flood warnings (source: Landesamt für Umwelt Brandenburg).

Flood alert gauges are linked to specific sections of a river which are defined according to the local flood risk and hydraulic conditions, as well as the appropriate administrative units. Figure 13 highlights the river sections used for flood alerts at the lower Oder River in Brandenburg, with panel A showing the sections under normal flood conditions. Since ice-jam flood dynamics are completely different at the lower Oder River, with ice-jams moving upstream, two important adjustments have been implemented. First, river sections upstream of the gauges are used for warning (Figure 13B) and lower alert stages are defined, since ice-jams typically lead to damaged dikes and abrupt rises in water levels are expected. With these adjustments the flood warning system is more representative of ice-flood conditions.

5.3. Ice-Jam Flood Forecasting

Ice-jam flood forecasting is a key component in any flood management plan to reduce flood hazards and risks. Advances have been made in the development of ice-jam flood forecasting methodologies and systems, particularly for the Athabasca River at Fort McMurray, Alberta [21], the upper reaches of the Saint John River, New Brunswick [22], and the Sanhuhekou bend of the Yellow River in China [23]. These methodologies and systems have also been implemented successfully in ice-jam flood forecasting systems for operational use by the government of Newfoundland and Labrador for the lower (Atlantic) Churchill River [24,25] and by the government of Manitoba for the lower Red River in Manitoba [26]. Requirements for an operational ice-jam flood forecasting system for the Oder River have been laid out in [1] and the need to include such methodologies for ice conditions can be seen in Figure 14, which shows a rapid rise in the backwater levels at Hohensaaten-Finow (see map in Figure 11 for the location) caused by an ice jam downstream of that gauge in February 2021. Forecasts on the rising limb of the event grossly underestimated the water levels attained by the ice jamming since no river ice processes are integrated in the current hydraulic model used for operational forecasting. The roughness coefficients and the rating curves implemented in the model also require updating to reflect ice-jam backwater effects. An ice-jam hydraulic model has been set up for the Oder River [27] between Ratzdorf and Kienitz (see Figure 11 for locations) and needs to be extended to Dabie Lake to include ice-jam backwater effects at Hohensaaten-Finow.

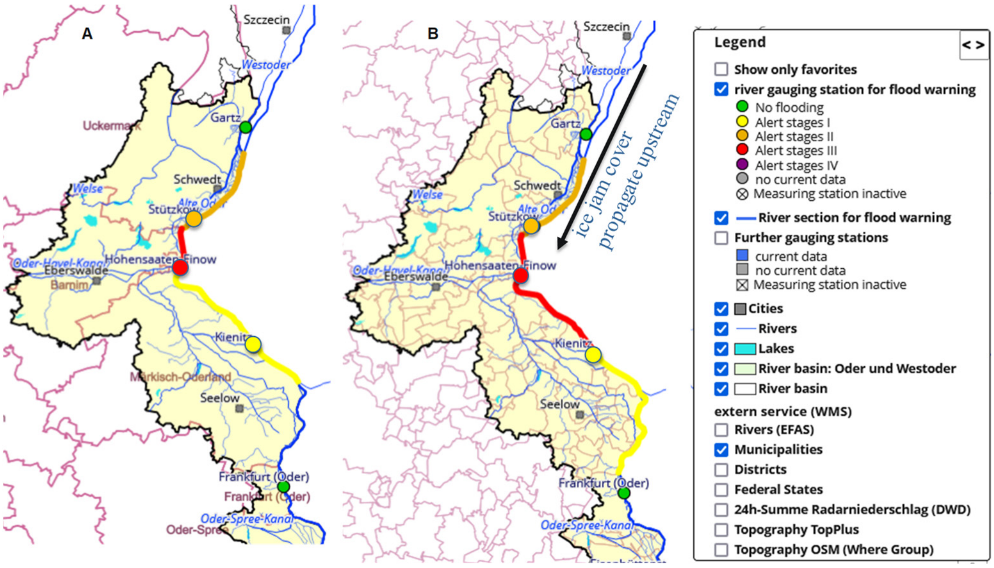

Figure 13. Tracking an ice-jam cover progression using the alert level system, which links gauge readings to upstream river reaches (source: Landesamt für Umwelt Brandenburg) with (**A**) for normal flood conditions and (**B**) for ice-jam conditions.

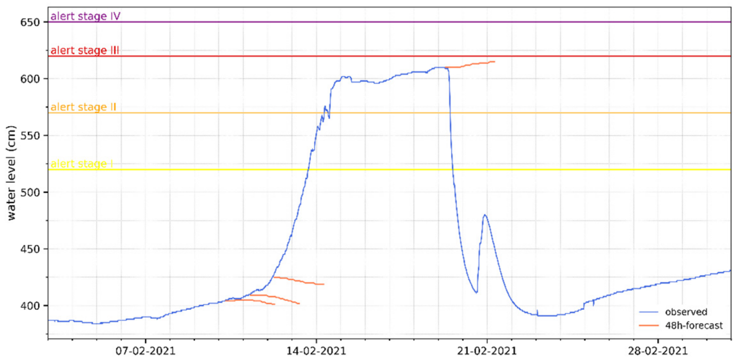

Figure 14. Measurement and forecast of water levels at the gauge at Hohensaaten-Finow, February 2021 (source: Landesamt für Umwelt Brandenburg).

6. Technical Advances in River Ice Research

6.1. Particle Tracking Velocimetry

A novelty presented at the workshop is determining flow velocities of ice using particle tracking velocimetry, which allows the velocities and trajectories of ice floes to be measured remotely. The method tracks the flow velocities of many ice floes using a sequence of images. It includes measuring the camera position and orientation (camera pose), automatic extraction of the water area for feature searching, particle detection and filtering, particle tracking and filtering, and scaling the tracks of (ice floe) velocities [28]. Figure 15 shows such trajectories with velocities of ice floes across the west channel of the lower Oder River during the February 2021 ice-jam event.

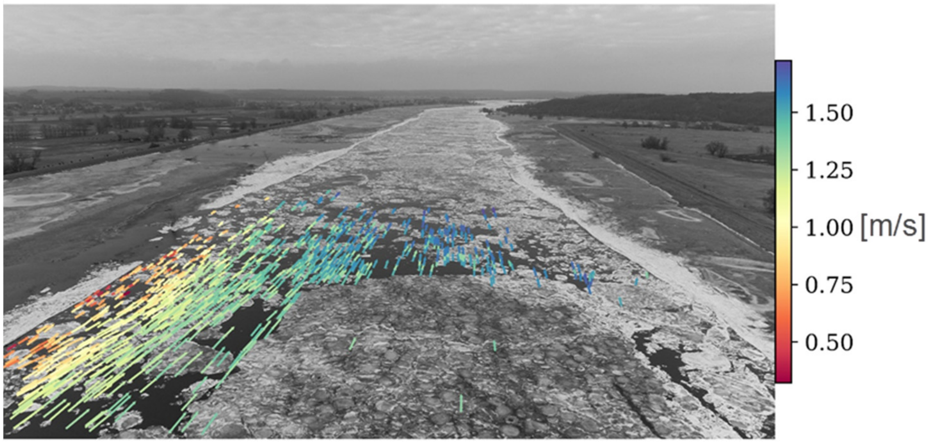

Figure 15. Trajectory and flow velocities of ice floes from the ice-jam event of February 2021 in the west channel of the lower Oder River (source: Technische Hochschule Nürnberg).

6.2. Ice Characterization of a Hanging Dam

In February 2021, a severe ice jam occurred in the upstream end of the Wloclawek Reservoir on the Vistula River near Plock [29]. This area is one of the most ice-jam prone river stretches in Poland. Evidence points to sediment accretion at the reservoir inlet as the reason for the increase in this area's propensity to ice jamming, indicated by a shift in the rating curve over time between the years 2009 and 2020. Efforts to break up the ice jam with ice breakers were hindered by the shallow depth of the reservoir inlet. Dredging works have been cut back in recent years even though the intensity of sedimentation has increased due to greater transport of sediment from the upstream catchment area, with an accretion rate of approximately 5 cm/year downstream of Plock. Despite the shortening of the duration of the ice season, the ice-jam flood risk of this reservoir section remains high.

To determine the volume of ice in the hanging dam that caused the jamming and the thickness of the hanging dam in relation to the water depth, cross-sections of the ice with depth were surveyed at the upstream end of the hanging dam using a sounding device (weight) to penetrate the hanging dam ice. During these frazil slush penetration tests, changes in the compactness of the ice deposits constituting the hanging dam were also recorded to determine the amount of ice grounded on the reservoir bottom during the ice-jam event. Three grades of compactness were classified:

- firm accumulations—sounder must be driven into the ice by force.
- compact accumulations—sounder remains stationary within the slush.
- loose accumulations—sounder penetrates the accumulation driven by its own weight.

The cross-section of the depths of the hanging dam is shown in Figure 16, indicating a decrease in the ice compactness with depth. A water layer was still evident between the bottom of the hanging dam and the reservoir bottom (no grounding); however, the hanging dam did fill a substantial percentage of the cross-sectional flow area. Flow velocity on the right side of the cross-section would have been greater where loose slush ice did not deposit, whereas on the left side, flow velocities would have been less, allowing frazil ice to be deposited on the underside of the hanging dam.

6.3. Design of New Ice-Control Structure

Ice jams are initiated when ice transport conveyance is reduced locally along a river stretch, particularly in meanders or in areas where the river narrows and obstacles are present in the river (e.g., islands, bridge piers, and sand bars) [30]. A continuous high inflow of ice from upstream can also help in the initiation process of ice jams. High volumes of inflowing ice can lead to increases in ice thicknesses constricting the cross-sectional flow area, resulting in the impediment of discharge under the ice jam with an increase in water surface elevations in the section upstream of the jam. One means of reducing the influx of ice in an ice-jam prone area is to arrest the flow of ice upstream of a potential ice-jam location using an ice-control structure (ICS), shown in Figure 17 [31]. The structure mostly impedes the ice transport further downstream but not the flow of the water, which is allowed to bypass the ice accumulation. A transverse set of piers only partially spans across the channel from one bank; the piers then extend longitudinally upstream parallel to the bank to form a side channel between the longitudinal set of piers and the bank. This side channel provides a passage of water to flow around the accumulation of ice which is held back by the piers. With this design, additional space in an adjacent floodplain to bypass water around the ice accumulation is not required.

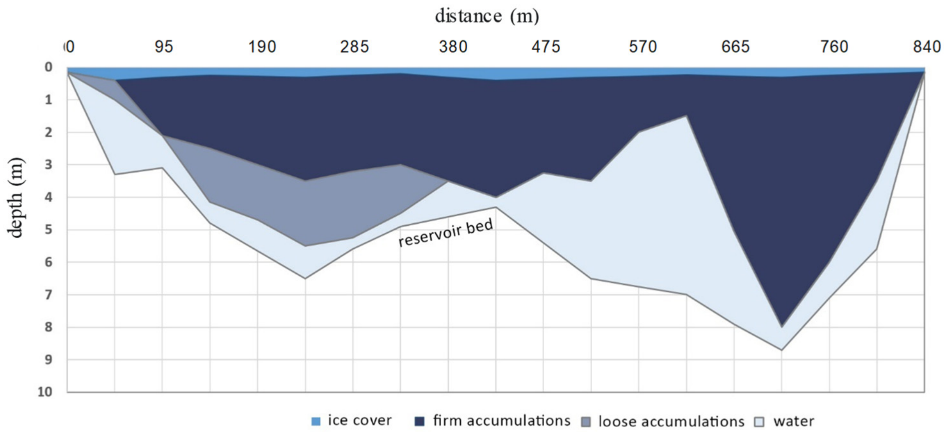

Figure 16. Cross-section of the hanging dam formed at the Wloclawek Reservoir inlet near Plock in February 2021 [29].

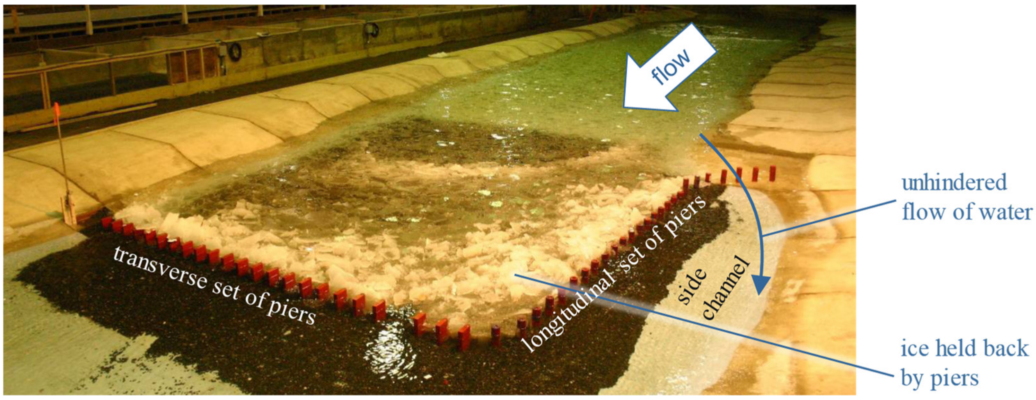

Figure 17. Ice-control structure (photo courtesy of US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire; used with permission).

6.4. River Ice Detection Using Optical and Radar Satellite Imagery in Tandem

The aim of river ice monitoring using satellite data is to (i) provide spatially constant, frequent information about the presence of ice along a river course, (ii) provide imagery support for water management services, and (iii) detect possible threats and natural disasters provoked by ice jams. The two satellite sensors used in this study were:

- Sentinel-1, which is a radar sensor using C-band frequency in two polarization modes (VV/VH). Two satellites (A and B), launched in 2014 and 2015, provided ~2-day revisit times across all of Europe with a spatial resolution of ~10 m and a swath width of ~250 km for the GRD product in IW mode
- Sentinel-2, which is an optical sensor with 13 spectral bands. Two satellites (A and B), launched in 2015 and 2017, provided ~5-day revisit times across Europe to acquire imagery with a spatial resolution of 10, 20, and 60 m with a swath width of ~290 km. Imagery was delivered in UTM grid cuts with overlap.

Figure 18 provides a combined product of the Sentinel-1 and Sentinel-2 images of the west and east channels of the lower Oder River. Sentinel-1 images were calibrated, speckle filtered, terrain corrected, and rescaled to dB, whereas the Sentinel-2 images underwent atmospheric correction, resampling to consistent spatial resolution of 20 m, and spectral indices calculations to strengthen the classification of the desired coverage classes (water, snow or ice, vegetation, and bare soil) before a composite of the two images was created. There are some limitations with both sensors. For example, misclassifications may occur between smooth black ice covers and open water. Misclassifications are also possible when predefined waterbeds are changed due to changing water levels. For Sentinel-2 imagery, misclassifications may also occur when differentiating between smooth black ice and open water. Image areas can also be misclassified as turbid waters or waters having an algal bloom. Clouds will also hamper Sentinel-2 image clarity.

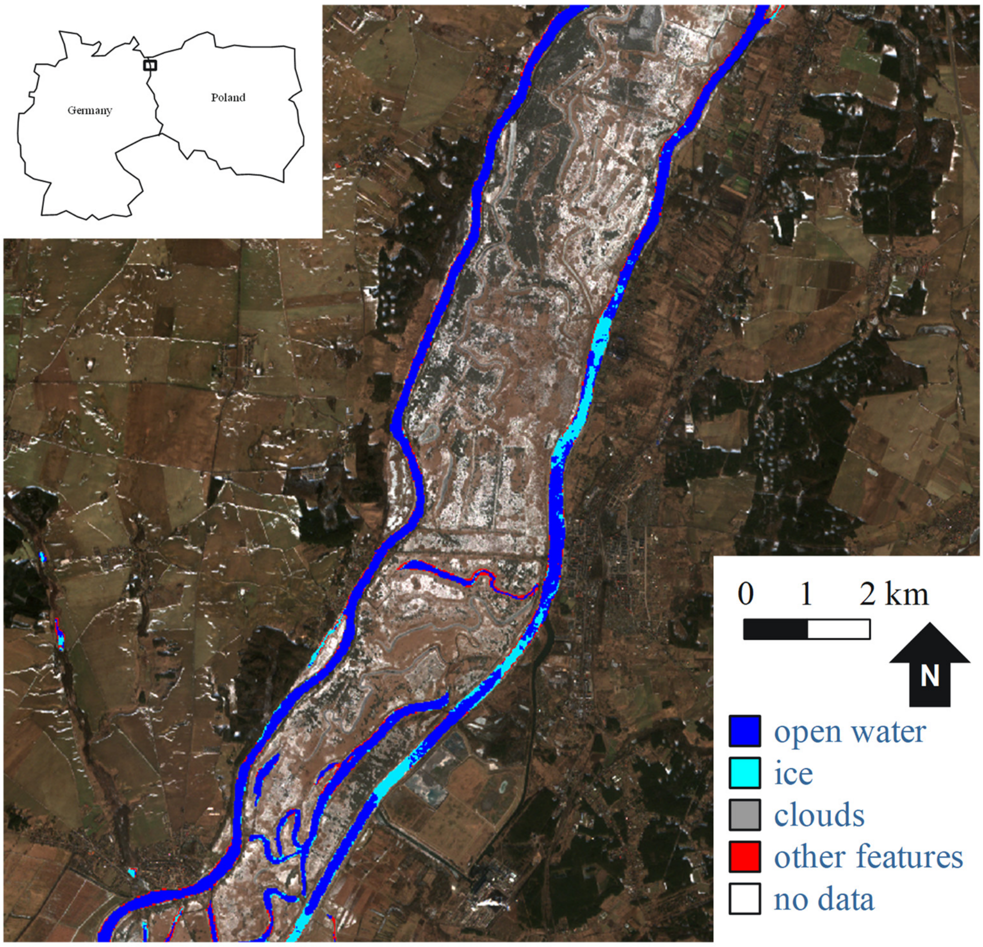

Figure 18. The combined product from Sentinel-1 and Sentinel-2 based classifications. Images credit: https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-snow-and-ice-monitoring; images acquired on 16 February 2017.

The high-resolution sensors from the Sentinel family proved very useful in detecting ice coverage, including ice jams. The Sentinel-2 optical sensor offers better thematic accuracy and should be treated as a primary source for ice classification, whereas the Sentinel-1 radar sensor offers the possibility of providing observations even under cloudy conditions and can be used as a secondary or auxiliary source for ice classification. Ice jams are well presented in the images from both sensors. Success in these composite images have led to the creation of the high-resolution snow and ice monitoring service, developed between 2019 and 2021 under the auspices of the Europe Environmental Agency

6.5. Stochastic Model to Assess Ice-Jam Flood Hazards

The chaotic nature of ice-jam formation and flooding can be captured using a stochastic modelling approach. In this approach, a deterministic river ice hydraulics model runs many times, with each run having a different set of input values for the parameters and boundary conditions. These values are randomly selected from frequency distributions of each parameter and boundary condition. This results in an ensemble of possible ice-jamming outcomes along a river reach of interest. Such an approach has been newly developed to quantify ice-jam flood hazards and risks [32,33]. Figure 19 conceptualizes the approach, which requires frequency distributions of the boundary conditions (shown at the top of Figure 19) and parameter values (not shown) to be input to the deterministic river ice hydraulic model RIVICE (see [34,35]) for model descriptions). The boundary conditions include:

- upstream water flow Q (Figure 19a) represented by an extreme-value distribution of the flows at instantaneous water level maxima during ice-jam events,
- volume of inflowing ice accumulating in the ice jam Vice (Figure 19b), which is a function of Q, with the scatter represented by a confidence band within which random variables are selected,
- downstream water level W (Figure 19c), which is a function of the upstream discharge.
- Location of the ice-jam lodgment x (Figure 19d), which is represented by a stepped uniform distribution to capture the predisposition of ice jamming in some stretches over others.

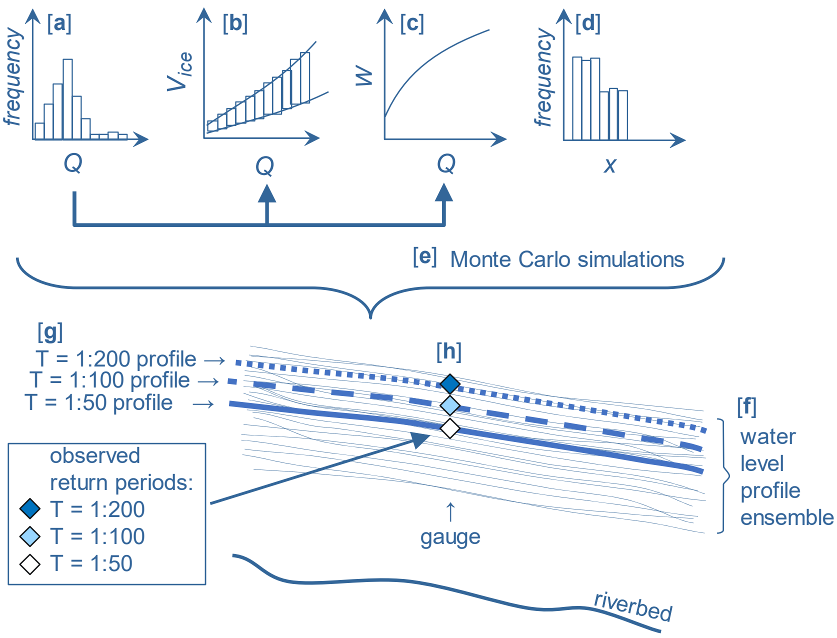

Figure 19. Conceptualization of the stochastic modelling framework for ice-jam flood hazard assessment; explanations for each subfigure are provided in the main text (drawn by the first author).

Parameters are generally uniform distributions between minimum and maximum values determined through calibration.

Using a Monte Carlo approach (Figure 19e), RIVICE runs hundreds of times, with each simulation having a different set of boundary conditions and parameter values chosen randomly from all distributions. One output is an ensemble of backwater profiles (Figure 19f), the results of which can be compiled within a probabilistic context using percentile profiles of exceedance probabilities (Figure 19g). The water level elevations at a gauge can then be compared to the annual exceedance probabilities of the levels recorded at the gauge (Figure 19h). Discrepancies between the simulated and recorded exceedance probabilities can be reduced by adjusting the percentage of the confidence band in the Q vs.

Vice relationship with the processes, including the Monte Carlo simulations, having to be repeated.

Referring to Figure 20, artificially breaking up the ice cover, for example using an ice breaker as described in the section "Artificial ice-cover breakage" above, can be implemented as an option to mitigate ice-jam flood hazards and risks. This scenario can be simulated within the stochastic modelling framework by removing those stretches in the lodgment location distribution (Figure 20D). It is assumed that ice cannot lodge to form an ice jam in areas that have been artificially broken. Rerunning the Monte Carlo analysis should lead to a change in the elevations of the percentile profiles of the backwater level ensemble.

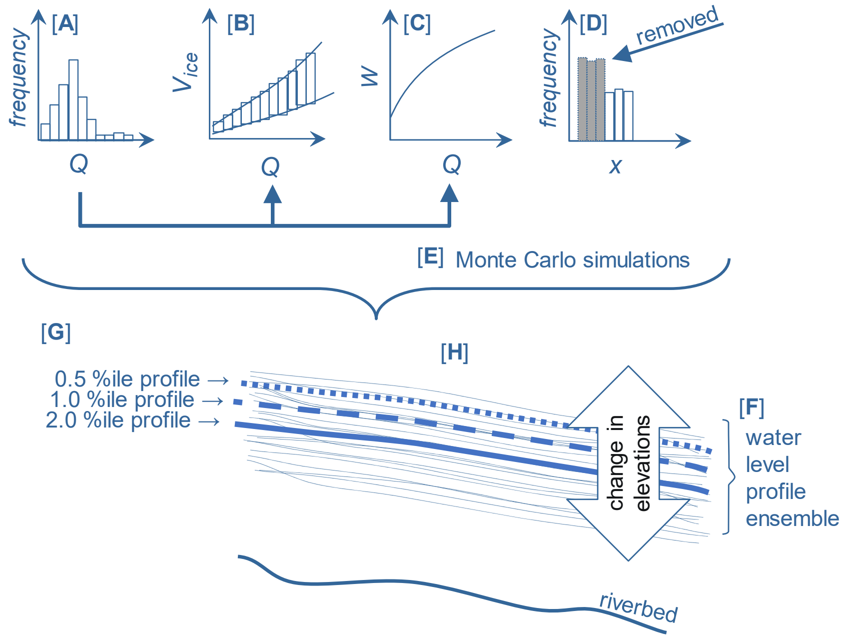

Figure 20. Adjustment in the boundary condition frequency distribution within the stochastic modelling framework when considering mitigation options, such as artificially breaking the ice cover to hinder ice-jam lodgments; explanations for each subfigure are provided in the main text (drawn by the first author).

At the workshop, research was also presented on the testing of different solutions applied to probability analyses of ice jams and ice covers. Time series of the maximum water stages were determined using: (i) extreme-value approaches using annual maximum water staging [36], and (ii) the peak-over-threshold (POT) method. The main idea of the POT method is to prepare a series of maxima on the basis of all events occurring in the analyzed time period that exceed an assumed threshold value, the so-called cut-off level [37]. The application of the POT method makes it possible to include, within the time series, the fact that ice phenomena may occur several times in one year, and, within the empirical probability, the fact that ice phenomena do not occur every year [38]. The final probability of exceedance for the POT time series was determined using the following tested distributions: log-normal, Gumbel, Pearson III, Gamma, log-Gamma, and Pareto.

6.6. Monitoring with UAVs

Growing access to unmanned aerial vehicles (UAVs), also known as drones, opens new possibilities to observe ice on rivers and reservoirs. Even low-cost UAVs are now capable of taking nadir photographs with predefined frontal and side overlap. Such images are standard input data for the structure-from-motion (SfM) algorithm, the products of which are dense point clouds and the resulting digital surface models as well as orthophotomaps. Recently, this popular approach has been adopted to determine the spatial extent of snow [39] or ice [40] as well as to reconstruct snow depth [41] or ice thickness [40].

Figure 21 presents aerial imagery of two frozen reservoirs in the Izerskie Mountains (southwest Poland) as well as two fragments of the unfrozen Oder River (west Poland). It is apparent from the figure that the visual analysis of imagery leads to the differentiation between frozen (top row in Figure 21) and unfrozen water (bottom row in Figure 21), enabling the detection of the presence of ice. Additionally, it is simple to discriminate between spatially uneven ice cover on water reservoirs in Rozdroże Izerskie and Polana Izerska and snow-covered banks or bare land. The knowledge about snow depth and extent and ice thickness and extent, acquired just after collecting UAV data within the concept of rapid mapping [42], may be useful, for instance, to assess the risks of avalanches, snow-melt floods, or ice jams.

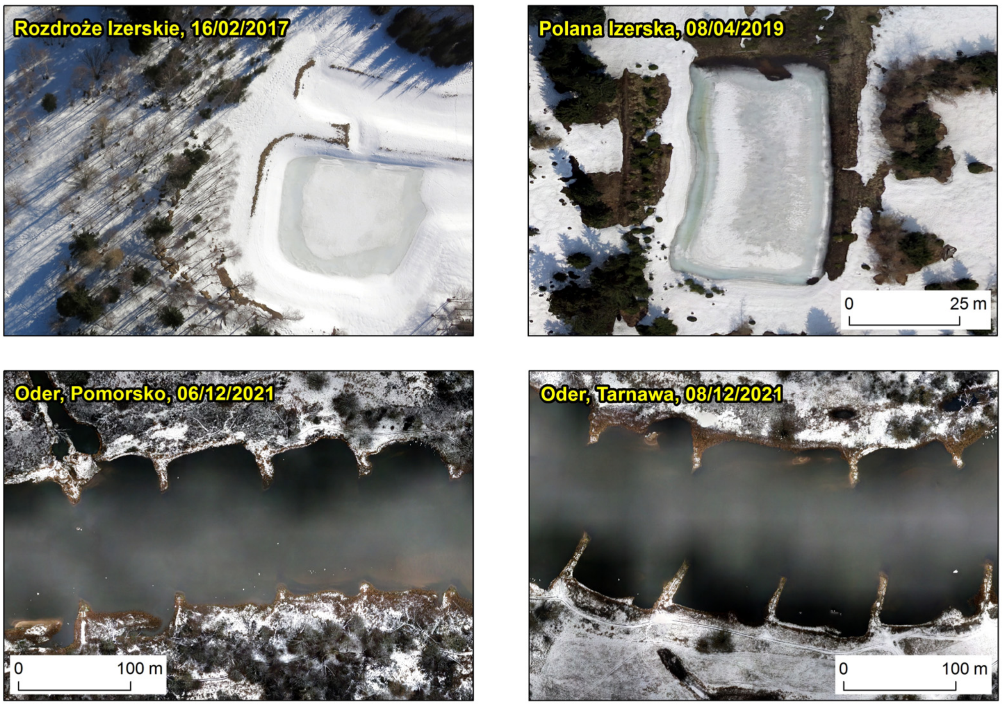

Figure 21. Fragment of single aerial image taken in central projection by a UAV over Rozdroże Izerskie in southwest Poland showing two interconnected frozen reservoirs (**top left**), fragment of the SfM-based orthophotomap of Polana Izerska in southwest Poland centered on a frozen reservoir (**top right**), fragments of the SfM-based orthophotomaps of the Oder River in west Poland in Pomorsko (**bottom left**) and Tarnawa (**bottom right**) showing an unfrozen river channel (source: Department of Geoinformatics and Cartography, University of Wrocław).

7. Conclusions

The workshop brought together many scientists and government officials who were involved in the field of river ice in their work and research. The venue provided an opportunity to present ideas and exchange knowledge in the field of ice-jam flood hazards and risks and how the subject was approached and applied in each of the EU member's countries. One key takeaway message from the workshop was that ice-jam floods are important components in the flood hazard and risk assessment and should be catalogued in the Flood Management Plans of the EU Floods Directive deliverables, but ice-jam floods do not need to be explicitly expressed within the directive itself. This may be partially due to the fact that, in rivers of northern and eastern countries, which are members of the European Union, the floodwater levels for a certain annual exceedance probability (or return periods) from ice jamming is generally lower than for those of open-water floods. A more comprehensive examination of other rivers is required for this statement to be thoroughly conclusive. Depending on the region, ice-jam flood hazards and risks have different foci, for example, hydropower operations in Norway and shipping navigation in Poland and Germany.

At the workshop, many new advances were also presented on monitoring and mitigating ice-jam flood hazards and risks, including application with particle tracking velocimetry, hanging dam characterization, ice-control structure design, remote sensing of ice covers, and modelling ice-jam flood hazards and hazard reductions. As an outlook, areas that need research furtherance include:

- safely measuring flows under covers of loose ice accumulations,
- incorporating near-ground (trail cameras), aerial (drones), and space-borne (satellites) remote sensing imagery into integrated monitoring systems for quick response to ice-jam flood hazard developments, and
- real-time monitoring of ice-cover elevations as a proxy for ice-thickness measurements.

8. Outlook

The workshop focused more on the technical aspects of flood risk assessment. A follow-up workshop could include the social aspects of ice-jam flood risk [43], for example community resilience [44] and socioeconomic vulnerabilities [45]. Research has also been carried out with agent-based modelling (ABM) to incorporate both technical and social aspects in flood risk assessments and management, on the individual [46], household [47] and regional [48] levels, in policy and decision making. An application of ABM specific to ice-jam flood risk assessment and mitigation is currently being explored by Ghoreishi et al. [49,50].

Author Contributions: Conceptualization, K.-E.L., K.A., D.C., A.C., D.G., M.H., B.H., N.K., M.K. (Michael Kögel), T.K., M.K.-D., M.K. (Michał Kubicki), Z.W.K., C.L., A.M., W.M., F.M., B.N.-L., T.N., A.P., B.P., I.P., J.R., M.R. (Maik Renner), M.R. (Michael Roers), M.R. (Maksymilian Rybacki), E.S., M.S., G.W., M.W., M.Z. (Mateusz Zagata) and M.Z. (Maciej Zdralewicz); investigation, K.-E.L., K.A., D.C., A.C., D.G., M.H., B.H., N.K., M.K. (Michael Kögel), T.K., M.K.-D., M.K. (Michał Kubicki), Z.W.K., C.L., A.M., W.M., F.M., B.N.-L., T.N., A.P., B.P., I.P., J.R., M.R. (Maik Renner), M.R. (Michael Roers), M.R. (Maksymilian Rybacki), E.S., M.S., G.W., M.W., M.Z. (Mateusz Zagata) and M.Z. (Maciej Zdralewicz); writing—original draft preparation, K.-E.L.; writing—review and editing, K.-E.L., K.A., D.C., A.C., D.G., M.H., B.H., N.K., M.K. (Michael Kögel), T.K., M.K.-D., M.K. (Michał Kubicki), Z.W.K., C.L., A.M., W.M., F.M., B.N.-L., T.N., A.P., B.P., I.P., J.R., M.R. (Maik Renner), M.R. (Michael Roers), M.R. (Maksymilian Rybacki), E.S., M.S., G.W., M.W., M.Z. (Mateusz Zagata) and M.Z. (Maciej Zdralewicz); visualization, K.-E.L., K.A., D.C., A.C., D.G., M.H., M.K. (Michael Kögel), T.K., M.K.-D., M.K. (Michał Kubicki), Z.W.K., W.M., F.M., T.N., B.P., I.P., J.R., M.R. (Maik Renner), M.R. (Michael Roers), M.R. (Maksymilian Rybacki), E.S., G.W., M.W., and M.Z. (Maciej Zdralewicz); supervision, K.-E.L., D.C. and Z.W.K.; project administration, K.-E.L., D.C. and Z.W.K.; funding acquisition, K.-E.L. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to thank John Pomeroy, director of the Global Water Futures program at the University of Saskatchewan, for his sponsorship to partly fund this workshop. The drone-related fragments of the manuscript are supported by the National Science Centre of Poland through the research project no. 2020/38/E/ST10/00295—carried out by Tomasz Niedzielski, Matylda Witek, Joanna Remisz, Michał Halicki, and Grzegorz Walusiak—within the Sonata BIS programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to extend a special thanks to all the participants for attending and contributing to the workshop.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lindenschmidt, K.-E.; Carstensen, D.; Fröhlich, W.; Hentschel, B.; Iwicki, S.; Kögel, M.; Kubicki, M.; Kundzewicz, Z.W.; Lauschke, C.; Łazarów, A.; et al. Development of an Ice Jam Flood Forecasting System for the Lower Oder River—Requirements for Real-Time Predictions of Water, Ice and Sediment Transport. *Water* **2019**, *11*, 95. [CrossRef]
2. Agard, J.; Schipper, E.L.F. Editorial Board Co-Chairs, 2014. Glossary Annex II 1757. In *IPCC 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
3. Kundzewicz, Z.W.; Pińskwar, I.; Brakenridge, G. Changes in river flood hazard in Europe: A review. *Hydrol. Res.* **2017**, *49*, 294–302. [CrossRef]
4. EU Directive 2007/60/EC of the European Parliament and the Council of 23 October 2007 on the Assessment and Management of Flood Risks, 2007. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007L0060&from=EN (accessed on 20 November 2022).
5. Sun, Q.; Zhang, X.; Zwiers, F.; Westra, S.; Alexander, L.V. A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. *J. Clim.* **2021**, *34*, 243–258. [CrossRef]
6. Lenderink, G.; Van Meijgaard, E. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nat. Geosci.* **2008**, *1*, 511–514. [CrossRef]
7. Berg, P.M.V.D.; Moseley, C.; O Haerter, J. Strong increase in convective precipitation in response to higher temperatures. *Nat. Geosci.* **2013**, *6*, 181–185. [CrossRef]
8. Kundzewicz, Z.W.; Pińskwar, I. Are Pluvial and Fluvial Floods on the Rise? *Water* **2022**, *14*, 2612. [CrossRef]
9. Huo, R.; Li, L.; Chen, H.; Xu, C.-Y.; Chen, J.; Guo, S. Extreme Precipitation Changes in Europe from the Last Millennium to the End of the Twenty-First Century. *J. Clim.* **2021**, *34*, 567–588. [CrossRef]
10. Myhre, G.; Alterskjær, K.; Stjern, C.W.; Hodnebrog, Ø.; Marelle, L.; Samset, B.H.; Sillmann, J.; Schaller, N.; Fischer, E.; Schulz, M.; et al. Frequency of extreme precipitation increases extensively with event rareness under global warming. *Sci. Rep.* **2019**, *9*, 16063. [CrossRef]
11. Hettiarachchi, S.; Wasko, C.; Sharma, A. Increase in flood risk resulting from climate change in a developed urban watershed – the role of storm temporal patterns. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 2041–2056. [CrossRef]
12. Timalsina, N.; Beckers, F.; Alfredsen, K. Modelling winter operational strategies of a hydropower system. *Cold Reg. Sci. Technol.* **2016**, *122*, 1–9. [CrossRef]
13. Zachrisson, G. Torne River—Proposals for Damage Prevention Measures (In Swedish). SMHI in Collaboration With the Finnish Water and Environment Agency, 1989. Available online: https://www.smhi.se/polopoly_fs/1.163738!/Hydrologi_25%20Sv%C3%A5ra%20islossningar%20i%20Torne%C3%A4lven.%20F%C3%B6rslag%20till%20skadef%C3%B6rebyggande%20%C3%A5tg%C3%A4rder.pdf (accessed on 14 December 2022).
14. Lindenschmidt, K.-E.; Huokuna, M.; Burrell, B.C.; Beltaos, S. Lessons learned from past ice-jam floods concerning the challenges of flood mapping. *Int. J. River Basin Manag.* **2017**, *16*, 457–468. [CrossRef]
15. Łupikasza, E.; Niedźwiedź, T.; Pinskwar, I.; Ruiz-Villanueva, V.; Kundzewicz, Z.W. Observed Changes in Air Temperature and Precipitation and Relationship between them, in the Upper Vistula Basin. In *Flood Risk in the Upper Vistula Basin*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 155–187. [CrossRef]
16. Pińskwar, I.; Choryński, A.; Graczyk, D.; Kundzewicz, Z.W. Observed changes in extreme precipitation in Poland: 1991–2015 versus 1961–1990. *Theor. Appl. Clim.* **2018**, *135*, 773–787. [CrossRef]
17. Morales-Marín, L.; Sanyal, P.; Kadowaki, H.; Li, Z.; Rokaya, P.; Lindenschmidt, K. A hydrological and water temperature modelling framework to simulate the timing of river freeze-up and ice-cover breakup in large-scale catchments. *Environ. Model. Softw.* **2019**, *114*, 49–63. [CrossRef]
18. Morales-Marín, L.; Rokaya, P.; Sanyal, P.; Sereda, J.; Lindenschmidt, K. Changes in streamflow and water temperature affect fish habitat in the Athabasca River basin in the context of climate change. *Ecol. Model.* **2019**, *407*, 108718. [CrossRef]
19. Pawlowski, B. *Course of Ice Phenomena on the Lower Vistula River in 1960–2014*; Scientific Publishing House of the Nicolaus Copernicus University in Torun: Torun, Poland, 2017; p. 176. (In Polish)
20. HWMDV Ordinance on the Establishment of a Warning and Alarm Service to Protect Against Water Hazards and for the Transmission of Flood Reports) (German = Verordnung über Die Errichtung Eines Warn—Und Alarmdienstes Zum Schutz Vor Wassergefahren Und Zur Übermittlung Von Hochwassermeldungen—Hochwassermeldedienstverordnung [HWMDV]), 9 September 1997. Available online: https://bravors.brandenburg.de/verordnungen/hwmdv_2016 (accessed on 14 November 2022).
21. Lindenschmidt, K.-E.; Rokaya, P.; Das, A.; Li, Z.; Richard, D. A novel stochastic modelling approach for operational real-time ice-jam flood forecasting. *J. Hydrol.* **2019**, *575*, 381–394. [CrossRef]
22. Das, A.; Budhathoki, S.; Lindenschmidt, K.-E. A stochastic modelling approach to forecast real-time ice jam flood severity along the transborder (New Brunswick/Maine) Saint John River of North America. *Stoch. Environ. Res. Risk Assess.* **2022**, *36*, 1903–1915. [CrossRef]

23. Liu, W.; Lü, H.; Lindenschmidt, K.-E.; Xü, K.; Zhu, Y.; He, C.; Wang, X.; Xie, B. Hazard assessment and prediction of ice-jam flooding for a river regulated by reservoirs using an integrated probabilistic modelling approach for a river regulated by reservoirs using an integrated probabilistic modelling approach. *J. Hydrol.* **2022**, *615*, 128611. [CrossRef]
24. Lindenschmidt, K.-E.; Brown, D.; Khan, A.A.; Khan, H.; Khayer, M.; McArdle, S.; Mostofi, S.; Naumov, A.; Pham, T.; Weiss, A. A novel fully-operational fully-automated real-time ice-jam flood forecasting system. In Proceedings of the 25th IAHR International Symposium on Ice, Trondheim, Norway, 23–25 November 2020. Available online: https://www.iahr.org/library/infor?pid=8570 (accessed on 20 November 2022).
25. Lindenschmidt, K.-E.; Khan, A.A.; Khan, H.; Khayer, M. Parallelisation of a river ice hydraulic model to improve performance of an ice-jam flood forecasting system for the lower Churchill River in Labrador. In Proceedings of the 26th IAHR International Symposium on Ice, Montréal, QU, Canada, 19–23 June 2022.
26. Williams, B.S.; Das, A.; Johnston, P.; Luo, B.; Lindenschmidt, K.-E. Measuring the skill of an operational ice jam flood forecasting system. *Int. J. Disaster Risk Reduct.* **2021**, *52*, 102001. [CrossRef]
27. Kögel, M.; Das, A.; Marszelewski, W.; Carstensen, D.; Lindenschmidt, K.-E. Feasibility study for forecasting ice jams along the Oder River. *Wasserwirtschaft* **2017**, *5*, 20–28. (In German). Available online: https://www.springerprofessional.de/machbarkeitsstudie-zur-vorhersage-von-eisstau-auf-der-oder/12243598 (accessed on 15 November 2022). [CrossRef]
28. Eltner, A.; Sardemann, H.; Grundmann, J. Technical Note: Flow velocity and discharge measurement in rivers using terrestrial and unmanned-aerial-vehicle imagery. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 1429–1445. [CrossRef]
29. Pawlowski, B.; Kolerski, T. Zator na Wisle w rejonie Plocka w lutym 2021 r. *Gospod. Wodna* **2022**, 6–10. Available online: https://mostwiedzy.pl/pl/publication/zator-na-wisle-w-rejonie-plocka-w-lutym-2021-r,157992-1 (accessed on 15 October 2022). [CrossRef] [PubMed]
30. Shen, H.T.; Gao, L.; Kolerski, T.; Liu, L. Dynamics of ice jam formation and release. *J. Coast. Res.* **2008**, *10052*, 25–32. [CrossRef]
31. Tuthill, A.; Ashton, G.; Hendershot, P.; Quadrini, J. Grasse River Ice Control Structure, Physical Model Study. Presented at the 19th IAHR International Symposium on Ice, Vancouver, BC, Canada, 6–11 July 2008. Available online: https://inis.iaea.org/search/search.aspx?orig_q=RN:40000053 (accessed on 17 September 2022).
32. Lindenschmidt, K.-E. *River Ice Processes and Ice Flood Forecasting—A Guide for Practitioners and Students*, 2nd ed. Springer Nature Switzerland AG: Berlin/Heidelberg, Germany, 2024; *in preparation*.
33. Lindenschmidt, K.-E. Extension and refinement of a stochastic modelling approach to assess ice-jam flood hazard. *Hydrol. Res. accepted*.
34. Lindenschmidt, K.-E. RIVICE—A non-proprietary, open-source, one-dimensional river-ice and water-quality model. *Water* **2017**, *9*, 314. [CrossRef]
35. Lindenschmidt, K.-E. *River Ice Processes and Ice Flood Forecasting—A Guide for Practitioners and Students*; Springer Nature Switzerland AG: Berlin/Heidelberg, Germany, 2020; p. 267. [CrossRef]
36. Stanley, S.J.; Gerard, R. Probability analysis of historical ice jam flood data for complex reach: A case study. *Can. J. Civ. Egineering* **1992**, *19*, 875–885. [CrossRef]
37. Bacová-Mitková, V.; Onderka, M. Analysis of extreme hydrological events on the Danube using the peak over threshold method. *J. Hydrol. Hydromech.* **2010**, *58*, 88–101. [CrossRef]
38. Byczkowski, A.; Banasik, K.; Hejduk, L. Obliczanie przeplywów powodziowych o okreslonym prawdopo-dobienstwie przekroczenia. *Infrastrukt. I Ekol. Teren. Wiej.* **2008**, *5*, 199–208.
39. Niedzielski, T.; Spallek, W.; Witek-Kasprzak, M. Automated Snow Extent Mapping Based on Orthophoto Images from Unmanned Aerial Vehicles. *Pure Appl. Geophys.* **2018**, *175*, 3285–3302. Available online: https://link.springer.com/article/10.1007/s00024-018-1843-8 (accessed on 17 October 2022). [CrossRef]
40. Alfredsen, K.; Haas, C.; Tuhtan, J.A.; Zinke, P. Brief Communication: Mapping River ice using drones and structure from motion. *Cryosphere* **2018**, *12*, 627–633. [CrossRef]
41. Mizinski, B.; Niedzielski, T. Fully-automated estimation of snow depth in near real time with the use of unmanned aerial vehicles without utilizing ground control points. *Cold Reg. Sci. Technol.* **2017**, *138*, 63–72. [CrossRef]
42. Tampubolon, W.; Reinhardt, W. UAV data processing for rapid mapping activities. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *40*, 371–377. Available online: https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-3-W3/371/2015/ (accessed on 10 October 2022). [CrossRef]
43. Aznar-Crespo, P.; Aledo, A.; Melgarejo-Moreno, J.; Vallejos-Romero, A. Adapting Social Impact Assessment to Flood Risk Management. *Sustainability* **2021**, *13*, 3410. [CrossRef]
44. Nofal, O.M.; van de Lindt, J.W. Understanding flood risk in the context of community resilience modeling for the built environment: Research needs and trends. *Sustain. Resilient Infrastruct.* **2022**, *7*, 171–187. [CrossRef]
45. Chakraborty, L.; Thistlethwaite, J.; Minano, A.; Henstra, D.; Scott, D. Leveraging Hazard, Exposure, and Social Vulnerability Data to Assess Flood Risk to Indigenous Communities in Canada. *Int. J. Disaster. Risk Sci.* **2021**, *12*, 821–838. [CrossRef]
46. Erdlenbruch, K.; Bonté, B. Simulating the dynamics of individual adaptation to floods. *Environ. Sci. Policy* **2018**, *84*, 134–148. [CrossRef]
47. Haer, T.; Botzen, W.J.W.; de Moel, H.; Aerts, J.C.J.H. Integrating Household Risk Mitigation Behavior in Flood. Risk Analysis: An Agent-Based Model Approach. *Risk Anal.* **2017**, *37*, 1977–1992. [CrossRef]

48. de Ruig, L.T.; Haer, T.; de Moel, H.; Brody, S.D.; Botzen, W.J.W.; Czajkowski, J.; Aerts, J.C.J.H. How the USA can benefit from risk-based premiums combined with flood protection. *Nat. Clim. Chang.* **2022**, *12*, 995–998. [CrossRef]
49. Ghoreishi, M.; Das, A.; Lindenschmidt, K.-E. Advancing ice-jam flood risk management: Integrating dynamic adaptive behavior using an agent-based modelling approach.
50. Ghoreishi, M.; Das, A.; Lindenschmidt, K.-E. Advancing Ice-jam Flood Risk Assessment Using Agent-based Modeling: A Conceptual Framework on Human Adaptation. AGU Fall Meeting Abstracts, 2022. Available online: https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1164013 (accessed on 10 October 2022).