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Review

Review of River Ice Observation and Data Analysis Technologies

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Abstract: This paper provides a comprehensive review of the available literature on the observation and characterization of river ice using remote sensing technologies. Through an analysis of 200 publications spanning from 1919 to June 2024, we reviewed different observation technologies deployed on in situ, aerial and satellite platforms for their utility in monitoring and characterizing river ice covers. River ice information, captured by 51 terms extracted from the literature, holds significant value in enhancing infrastructure resilience in the face of climate change. Satellite technologies, in particular the multispectral optical and multi-polarimetric synthetic aperture radar (SAR), provide a number of advantages, such as ice features discrimination, better ice characterization, and reliable delineation of open water and ice, with both current and upcoming sensors. The review includes data analysis methods employed for the monitoring and characterization of river ice, including ice information retrieval methods and corresponding accuracies. The need for further research on artificial intelligence and, in particular, deep learning (DL) techniques has been recognized as valuable for enhancing the accuracy of automated systems. The growing availability of freely available and commercial satellites, UAVs, and in situ data with improved characteristics suggests significant operational potential for river ice observation in the near future. Our study also identifies gaps in the current capabilities for river ice observation and provides suggestions for improved data analysis and interpretation.

Keywords: river ice; Earth observation (EO); remote sensing; ice classification; data analytics

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1. Introduction

1.1. Background Information

River ice forms due to the freezing of water in rivers during cold weather conditions and is typically observed in countries of the Northern Hemisphere where the air temperature drops below 0 °C (Figure 1). As part of a study to quantify the surface extent and volume of freshwater ice in the Northern Hemisphere, an analysis was performed on 256 rivers, yielding a total surface area of 1.2×10^5 km^2 and a total volume of 140 km^3 [1]. The majority of countries where river ice is present, including Canada, the USA, China, Russia, and most European countries, routinely monitor river ice conditions for various applications.

According to Environment and Climate Change Canada nomenclature [2], river ice is "ice formed on a river, regardless of observed location". River ice characteristics depend on its stages of development, forms, and processes. River ice processes involve complex interactions between hydrodynamic, mechanical, and thermal processes e.g., [3,4]. Phenomena associated with river ice include formation, evolution, transport, accumulation, dissipation, and deterioration of various forms of surface and underwater ice. These processes depend on meteorological and hydrological conditions and vary significantly depending on channel types (geometry, hydraulics, roughness) [5]. For environmental studies and engineering applications, processes of ice freeze-up, ice cover formation, and consolidation, dynamics/motion, jam formation, break-up (thermal or mechanical), and the resulting fluctuations in water levels need to be observed and monitored, e.g., [6,7].

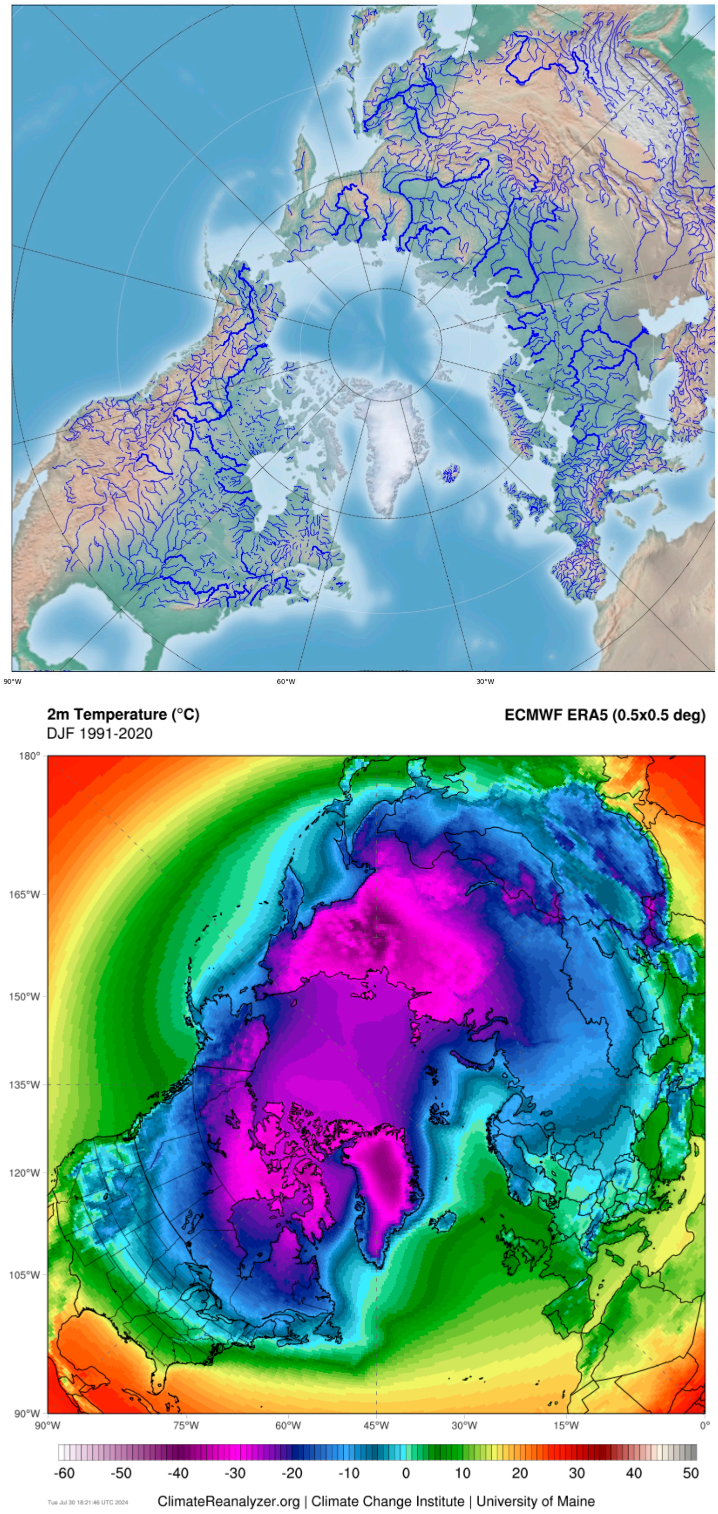

Figure 1. Regions with river ice: (**top**) Map showing rivers where ice may potentially be observed, including 62 rivers mentioned in the paper (highlighted with thicker lines). (**bottom**) Monthly reanalysis map (https://climatereanalyzer.org/research_tools/monthly_maps/ (accessed on 1 August 2024)) (mean of the surface temperature at 2 m for December–January–February (DJF) for the period of 1991–2020) from the European Centre for Medium-Range Weather Forecasts (EMCWF).

River ice processes (Figure 2), as described by Shen [3,4], may be divided into two branches: calm water results in skim ice, and turbulent water produces frazil ice [8]. This scheme was utilized for river ice type identification in SAR satellite data [9]. Remote sensing technologies are widely employed to retrieve river ice information by detecting energy that is emitted or reflected [10].

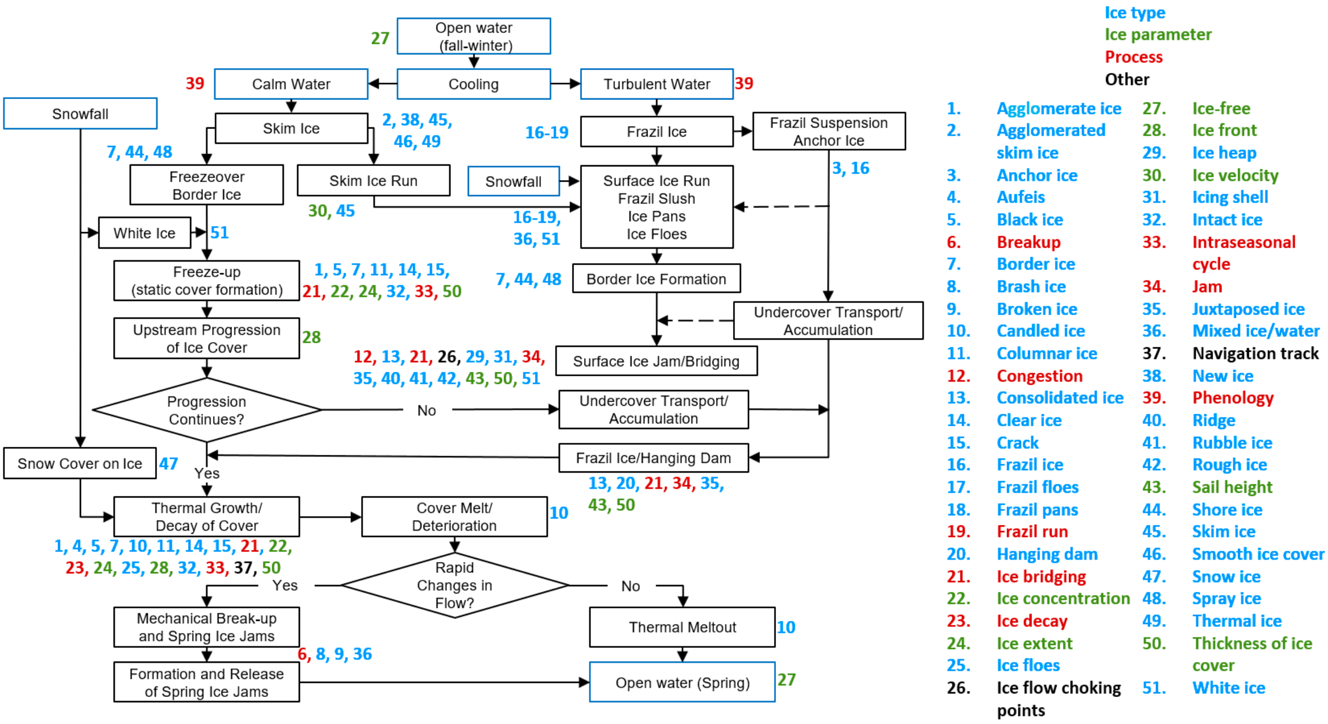

Figure 2. Flowchart illustrating river ice processes adapted from [3,4] along with river ice terms Appendix A that were identified from the literature and which are relevant to the present study.

1.2. Importance of River Ice Information

River ice plays a significant role in hydrology and ecology, and it impacts infrastructure and human activities. It influences water flow patterns, water quality, aquatic habitat availability, and navigation, and poses ice-related hazards like flooding and infrastructure damage. River ice can potentially compromise the operation and security of infrastructures [11,12], including water intakes and power plant operations.

Ice-related considerations with a focus on stream crossings, while also identifying potential concerns regarding the interaction of river ice with various types of infrastructure, were overviewed in [12,13]. Ice formation and movement can damage bridges, dams, and other infrastructure along rivers. Ice jams have the potential to cause localized flooding and other hydrological impacts. By monitoring river ice conditions, hydrologists can recommend appropriate maintenance and design measures to mitigate the risk of damage. With climatic change, engineering solutions have to incorporate design methodologies for infrastructure that consider the changed future environment. This could involve selecting the most probable or worst-case projections regarding future hydroclimatic conditions [14].

Climate change is expected to result in rising air temperatures, increased precipitation, and a shorter duration of cold weather seasons. In a review of historical trends in lake and river ice cover in the Northern Hemisphere over a span of 150 years (from 1846 to 1995) [15], it was shown that the first date of full ice cover shifted later by an average of 5.8 days per century, while break-up dates have advanced by an average of 6.5 days per century [15] with increased interannual variability in both dates since 1950. A review of the hydrologic aspects of river ice shows strong climatic links and illustrates the sensitivity of the entire ice regime (freeze-up timing, ice thickness, and break-up severity) to changes in climatic conditions including both drought and increased snowfall [16]. Climate change is projected to cause more dramatic alterations to break-up timing and magnitude [17].

The extent of river ice observed using over 400,000 clear-sky Landsat scenes shows a mean decline of 2.5% globally in the past three decades (1984–2018) [18]. The mean seasonal river ice duration decreases by 6.10 ± 0.08 days per 1 °C increase in global mean surface air temperature. Air temperature variability has an impact on ice jam frequency and intensity. The probability of future ice-jam flooding may decrease; however, the occurrence of extreme ice-jam flooding events remains possible [19], with adverse effects on hydropower operations [20]. High flows and evolving break-up conditions [21] lead to increased sediment transport, potential contaminant mobilization, and heightened flooding risks, impacting human health and security, as well as transportation and infrastructure integrity. Analysis of Landsat imagery from 1973 to 2021 indicates a significant (53%) reduction in the duration of river ice travel seasons (resulting from delayed or incomplete freeze-up and early break-up) due to rising air temperatures [22]. The weekly probability of an adequate ice cover for river crossings declined by an average of 53%. The timing of break-up affects severity, with early rises in discharge potentially resulting in damaging ice jams, while delayed snowmelt can trigger sudden runoff and large-scale ice mobilization, also leading to flood risks.

A thorough understanding of river ice formation, dynamics, and characteristics is critically important for effective water resource management and the mitigation of cold weather-related impacts on rivers and their surrounding environments. The findings of Beltaos and Prowse [23] indicated that certain parts of Canada are experiencing increased occurrences of mid-winter break-up events and higher freshet flows. These changes could potentially amplify the frequency and severity of ice jams. Ice jams (freeze-up and break-up) are identified as a major cause of floods in mid- to high-latitude regions [24], and ice-jam flood hazards and risks vary depending on the region [25]. The types of ice jams, their causes and prediction as well as mitigation measures were discussed in [11]. Information needs and requirements for estimating and forecasting ice jam floods include (i) thermal conditions governing ice formation and deterioration, snowmelt, and runoff; (ii) hydrological factors affecting flow magnitude and distribution, and (iii) mechanical conditions associated with ice cover break-up, conveyance, and accumulation. Important factors include jam thickness, roughness, extent, and strength characteristics [24].

The findings in [26] indicate that, with climate change, ice-jam floods will likely cause greater damage in the future. Forecasting ice-jam floods is challenging because it requires not only flow forecasting but also an understanding and the modeling of complex and non-linear processes of river ice formation, break-up, and ice jamming, and their influences on water levels [27]. In Canada, operational flood mapping, forecasting, and flood hazard mitigation are the responsibility of provincial and territorial governments (https://geo.ca/flood-mapping/province-territory/ (accessed on 5 April 2024)). They are conducted by multiple entities distributed across the country [28,29]. The federal government provides funding for activities to advance flood mapping throughout Canada (https://natural-resources.canada.ca/science-and-data/science-and-research/natural-hazards/flood-mapping/flood-mapping-roles-and-resources/24229 (accessed on 5 April 2024)).

Remote sensing applications in the context of ice-related flood events and infrastructure resilience involve various stakeholders and play important roles in mitigating flood hazards impacted by climate change. These applications encompass a range of technologies and methods, including satellite imagery, aerial surveys, and ground-based sensors, which are utilized by government agencies, research institutions and businesses, emergency responders, and local communities. River ice information extracted from remote sensing instruments is used for multiple applications [30], such as transportation routes (winter roads and wildlife corridors), hydroelectric power station operation, shipping, jams and floods mitigation and response, infrastructure integrity, and climate modeling. In combination with daily observation and flight surveys of ice conditions, ice break-up monitoring using real-time satellite imagery enables the production of high-quality maps, aiding in identifying and forecasting ice jam hazards [21]. The methods and future needs for ice-related flood hazard area delineation and mapping were investigated in [31], highlighting the need for river ice classification, flow velocity, and ice-jam information collection, analysis and modeling. The literature describes a variety of ice terms representing the observed river ice information, including ice types/classes, features, characteristics, and processes. The UNESCO-WMO International Glossary of Hydrology [32] establishes recognized international equivalents of hydrological terms, including river ice terminology (see Appendix A). The majority of river ice terminology definitions can be found in [33]. However, if a specific term is absent from IAHR's river ice terminology, its definition is provided from the referenced source. The list of observed river ice information, including a reference in which it was used, is provided in the Appendix A.

1.3. Objective

This review paper analyses the observation of river ice using satellite, airborne, and in situ sensors. Its objective is to identify and aggregate documented technologies for river ice observation. It is acknowledged that in instances where multiple publications cover the same technology, only selected ones will be included in this review. The paper reviews research conducted in Canada, Europe, the USA, China, and Russia. However, it is important to note that publications in Chinese and Russian were not included, despite the significant number of research articles available in these languages.

The practical significance of river ice observation lies in its ability to inform infrastructure resilience strategies, mitigate flood hazards, and enhance safety measures, particularly in regions susceptible to ice-related flooding and changing climatic conditions. Hence, the purpose of reviewing river ice observation technologies is to comprehensively assess the available methods and solutions for monitoring river ice conditions, identify their strengths and limitations, and evaluate their effectiveness in providing accurate and timely information for various stakeholders. Data analysis methods are vital for river ice observation as they allow the extraction of information from remote sensing data, leading to a better understanding of ice dynamics, processes, and hazards.

1.4. Paper Structure

Section 2 summarizes the methodology and presents river ice observation technologies, discussing sensor types (optical, SAR, etc.) and platforms (satellite, airborne, and in situ). Section 3 provides details on methods for processing and analysing observation data, considering the application of machine learning technologies. It also discusses reporting methods and the integration of river ice observations into hydraulic models and existing operational river ice services. Section 4 identifies gaps, challenges, and future directions in river ice observation. Key findings and implications of this article are summarized in Section 5.

2. Literature Review Methodology and Inventory of Observations

Literature sources were identified using the Google search engine and from sources such as IEEE Xplore, ScienceDirect, ResearchGate, and the Memorial University libraries (searching over all resources, including books and journal and conference articles). The search employed predefined keywords such as "river ice", "frazil", "river ice map", "river ice observation", and "river ice recognition" in publication titles, keywords, and abstracts. This search was finalized in June 2024, spanning a period of about 100 years from the earliest publication on river ice detection in 1919 to June 2024. Only publications written in English were considered.

River ice observation involves interdisciplinary fields including remote sensing, river ice processes, and hydrology through modeling, data processing, computer vision, machine learning, and other technologies and studies. It is important to mention that in the last 50 years, multiple publications analysed river ice observation technologies available at that time. Many of these technologies remain relevant and applicable to the current state-of-the-art practices. Reviews of early radar technologies were conducted in [34–40]. The investigation in [41] identified and ranked the instrumentation used for field measurements of river ice and formulated recommendations based on their findings. The Ice Engineering Manual [42] reviewed technologies for in situ, aerial, and satellite-based river ice observation. The monitoring of river ice characteristics and processes was demonstrated using synthetic aperture radar (SAR) ERS-1, ERS2, JERS-1, RADARSAT-l images supplemented by aerial photographs, passive microwave, and Landsat images [43]. Remote sensing technologies for river ice were also analysed in [44,45]. Certain SAR-based river ice observation methods were reviewed in [46]. The study in [47] reviews certain literature on river ice mapping and describes results showing that Sentinel-1 SAR backscatter can be used to detect ice with high confidence. A review of UAS/UAV remote sensing was performed in [48].

In addition to journal publications and books, two frontier conferences consistently offered valuable updates on river ice observation technologies:

- Committee on River Ice Processes and the Environment (CRIPE) (Workshop on the Hydraulics of Ice Covered Rivers) and
- The Symposium on Ice, under the umbrella of the Ice Research and Engineering Committee of International Association for Hydro-Environment Engineering and Research (IAHR).

Our review covered a total of 200 selected references, including journal articles, conference papers, reports, books, and PhD and master's theses. It can be mentioned that our review did not cover every publication on river ice observation. However, our selection process aimed to encompass representative sources relevant to the scope of our study. There were no specific exclusion criteria for the publications. The scope of our study focused primarily on publications related to river ice, omitting any of the literature related to lake ice or sea ice, ensuring that all analysed publications were directly relevant to the specific topic of interest.

River ice observation technologies are classified based on three distinct platforms: satellite, aerial, and in situ (Table 1). Tables 2–4 present a chronological summary of selected publications focusing on satellite-based observations, organized by publication year. Each table is structured with 11 columns, representing the following:

- Publication year.
- Satellite name.
- Sensor name (important for distinguishing between satellites with multiple sensors).
- Band: electromagnetic wave characteristic (band or combination of bands, polarization).
- Sensor resolution in meters (some publications may use pixel spacing (PS)).
- Ice information (refer to Section 1.2).
- Retrieval method: describes the approach(es) utilized to retrieve river ice characteristics.
- Validation sources: field data or other remote sensing observations and techniques used for validation (ground truth).
- Quantitative or qualitative assessment: indicates the analysis of results.
- Main purpose: describes the primary objective of the publication (e.g., technology demonstration, introduction of new ice information, practical application).
- AOI (area of interest): specifies the river name and country where ice observation occurred (Figure 1).
- Reference: identifies the publication.

Figure 1 shows AOI with rivers where ice may potentially be observed, including 62 rivers mentioned in the paper (highlighted by the thicker lines). Also, the monthly reanalysis map (mean of the surface temperature at 2 m for DJF) for the period of 1991–2020 from the European Centre for Medium-Range Weather Forecasts (EMCWF) indicates areas (temperature is less than 0 °C) of the Northern Hemisphere where river ice can be observed.

To enhance clarity and illustrate key aspects of our review, we have included several visual and tabular elements:

- Table 1 provides a synopsis of various sensor and platform combinations for river ice observation. Different colors are used to indicate whether each combination has been documented or if it holds potential for future use in river ice observation.
- Tables 2–4 include a column for quantitative or qualitative assessment, summarizing the comparative efficacy of different methods and techniques.
- Figure 1 (both top and bottom) displays AOIs for river ice presence, highlighting major rivers in the Northern Hemisphere.
- Figure 2 shows ice processes and represents ice information terms identified in the reviewed literature.
- Figure 3 outlines a methodological approach for extracting river ice information from observations.

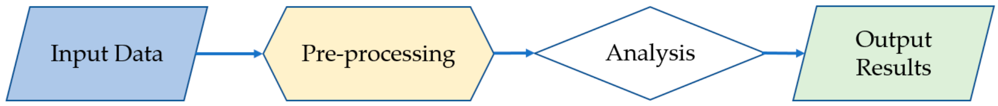

Figure 3. Flowchart of observation data processing and analysis process for river ice characterization.

3. River Ice Observation Technologies

3.1. Sensor

Several types of sensors and their combinations can be used for river ice observation. Each type possesses certain advantages and limitations. The following sensor types were previously demonstrated for river ice observation:

- **Electro-optical and infrared (EO/IR)**: EO/IR sensors, such as multispectral or hyperspectral cameras, acquire images of the surface in ultra-violet, visible, and infrared wavelengths. EO/IR imagery is valuable for monitoring and characterizing ice cover, dynamics, and conditions in clear weather. Thermal infrared images of river ice can be used to measure temperature, and estimate ice floe geometric and statistical characteristics, concentration, structure, and thickness. The resolution for EO/IR sensors spans from a few cm to about 1 km. Stereo imagery and motion videos can be used to extract digital surface models of river ice.
- **Synthetic aperture radar (SAR)**: SAR sensors operate in the microwave frequency range and can provide high-resolution images regardless of cloud cover or sunlight. SAR imagery acquired in X, C, L, and P bands in single (HH or VV), dual (HH-HV, HH-VV, or VV-VH), compact polarimetric, or Quad-Pol (HH-HV-VV) polarizations were used to extract river ice information. The resolution of SAR sensors ranges from sub-meter (e.g., 25 cm) to 100 m. Interferometric SAR (InSAR) technology can be used for change detection in ice cover [49] and for determining ice displacement [50].
- **Microwave radiometers**: microwave radiometers can measure brightness temperatures emitted by objects in frequencies of the microwave spectrum. They are useful for detecting the presence of ice on rivers and estimating ice thickness.
- **Ice penetrating radar or ground penetrating radar (GPR)**: GPR systems emit an electromagnetic signals down into the ice surface to measure ice thickness and detect internal ice structures, such as layers or fractures.
- **Radar altimeters**: radar altimeter measures the distance between the platform (aircraft or satellite) and the surface of the river.
- **LIDAR (light detection and ranging)**: LIDAR sensors emit laser pulses and measure the time it takes for the pulses to return after reflecting off a surface. Airborne, satellite, or terrestrial LIDAR can be used to map the topography of ice cover on rivers and measure water level or ice surface height in clear weather conditions.

- **GNSS-IR**: A global navigation satellite system-interferometric reflectometry (GNSS-IR) sensor exploits the interference between GNSS signals reflected off the observed surface and signals received directly from the GNSS satellite.
- **Gravimetry**: This sensor system measures changes in gravitational force to map gravitational fields.
- **Acoustic profilers:** Acoustic profilers are commonly used to measure water velocity and depth in rivers. They can also provide information on the presence of ice and its draft.
- **Ice thickness gauges**: these sensors/tools can utilize various principles (e.g., temperature or conductivity profiles) to measure the thickness of ice and snow covers.

The primary sensor specification which is important for river ice observation and characterization is spatial resolution. Increased resolution enables ice observation over small rivers and the detection of small-scale features and characteristics such as cracks, roughness, patterns, concentration, and individual ice floes.

3.2. Platforms

The above-mentioned sensors can be deployed on applicable remote sensing platforms to observe the river ice. The following different types of remote sensing platforms are used for river ice observation:

- **Satellites**: Satellites orbit the Earth at various (from 160 km and above) altitudes and can carry a range of sensors to observe rivers and provide geospatial data acquisition at various scales. While satellites require substantial initial investment, once launched, they can facilitate global data accessibility and provide near-real-time (NRT) access.
- **Aerial**: Airplanes, helicopters, and unmanned aerial vehicles (UAVs) (also known as unoccupied aerial systems (UAS), remotely piloted aircraft (RPA), or drones) are commonly used for river ice observation. They can carry a variety of sensors, including cameras, LIDAR, SAR, GPR, and hyperspectral imagers. Aircrafts are particularly useful for high-resolution imaging and targeted observations of specific areas of interest. UAVs are increasingly used for remote sensing tasks due to their versatility and relatively low cost. The cost efficiency of airborne observation compared to commercial SAR satellite data was highlighted in [9]. Air balloons could potentially be employed for river ice observation, but such examples were not found in the literature.
- **In situ (also referred to as ground-based)**: In situ sensors are instruments deployed on the ice, on the ground, underwater, or mounted on towers or other structures. In the case of river ice, ships (icebreakers) and vehicles moving on the ice surface can also be employed. In situ sensors are essential in collecting reliable ice information and are often used for the validation of remote sensing measurements collected from aerial or satellite platforms.

From the above listing, sensor technologies can be used individually or in combination to provide comprehensive monitoring of river ice conditions, including ice extent, thickness, dynamics, and associated hydrological parameters. The choice of sensor depends on factors such as the required spatial and temporal resolution, electromagnetic spectrum, environmental conditions, and available resources. Table 1 classifies different combinations of sensors and platforms into three categories (highlighted by different cell colors) with respect to river ice observation capability.

Table 1. Combination of sensors and platforms that can be used for river ice observation.

Sensor Type	Platform		
	Satellite [1]	Aerial	In Situ
EO/IR			
SAR			
Microwave Radiometer			

Table 1. *Cont.*

Sensor Type	Platform		
	Satellite [1]	**Aerial**	**In Situ**
GPR	[yellow]	[green]	[green]
Radar Altimeter	[green]	[green]	[yellow]
LIDAR	[green]	[yellow]	[yellow]
GNSS-IR	[yellow]	[yellow]	[green]
Gravimetry	[green]	[yellow]	[yellow]
Acoustic Profilers	[red]	[red]	[green]

[1] A green cell means that the combination of sensor and platform was demonstrated in the literature for river ice observation. A yellow color denotes that the combination may potentially be used for river ice observation, but the documented evaluation was not identified in the literature. A red cell indicates that the combination does not exist or cannot be used for river ice observation.

3.3. Satellites

Satellites are exceptionally well-suited for river ice observation due to their key advantages, such as remote area access, frequent and predictable acquisitions, and their ability to deploy a wide variety of sensors. Therefore, satellite-based technologies are analyzed with a high level of detail.

3.3.1. EO/IR

Optical images are visually intuitive and easy to interpret, enabling straightforward analysis of presence and changes in river ice cover. One of the main limitations is the visibility dependency on daylight and weather and atmospheric conditions such as cloud cover, fog, and haze. Additionally, the electromagnetic waves in the visible spectrum cannot penetrate through the snow surface, which limits imagery ability to detect ice properties beneath the surface layer.

As one of the first examples, a NOAA-4 satellite with a very high-resolution radiometer (VHRR) and a GOES-1 (Geostationary Operational Environmental Satellite) (visible images of 1 km resolution) were demonstrated [51] to be useful for monitoring changes in river ice and break-up on the Ottawa River in 1976. Table 2 provides a detailed analysis of the reviewed literature on river ice observation using EO/IR satellites. Satellites equipped with multispectral sensors included Landsat (MSS, ETM, OLI) and MODIS aboard Terra and Aqua satellites, and NOAA AVHRR, ASTER, Sentinel-2 MSI, PROBA-V, and Planet Scope. River ice observations were conducted relying on visible, near-infrared (NIR), and short-wave infrared (SWIR) bands, and indices were calculated (e.g., the normalized difference snow index (NDSI)). Ice information retrieved from EO/IR satellites included break-up detection and date estimation, ice presence and its concentration, extent, and tones (e.g., gray), and ice and surface water velocity. Validation sources used to verify EO/IR satellite-based river ice information ensuring the accuracy and reliability of observations included field observations, aerial photos, water and air temperature records, satellite data with higher resolution, ice bulletins, data from hydrometric stations (water levels, flow rates), and gauged discharge data.

Table 2. Review of the literature on river ice observation using EO/IR satellite imagery (1977–2023).

Year	Satellite, Sensor	Band	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
1977	Landsat 1–2, MSS [1], NOAAVHRR	Band 7 (NIR), Visible (0.6–0.7 µm), TIR (10.5–12.5 µm)	60, 1000	Break-up	Photointerpretation	Field observations at ground stations	High correlation (slope 0.98) of break-up dates	Proof of concept	Mackenzie River (Canada)	[52]
1990	Landsat 1–5, MSS, RBV, TM	MSS Band 2 (0.6–0.7 µm) RBV (0.58–0.68 µm and 0.505–0.75 µm) TM Band 3 (0.63–0.69 µm)	30, 60	Different 4 classes based on appearance tones: (1) ice-free, (2) partial gray ice, (3) complete gray ice, and (4) white ice	Visual photointerpretation	Areal photos, ground observations, water temperature records	Agreed 64–80% of time	Ice conditions, navigation, forecasting model	Allegheny, Monongahela, and Ohio rivers and Illinois Waterway (USA)	[53]
2004	MODIS; AVHRR	Visible and near-infrared bands	250–500, 1000	Break-up date	Visual interpretation	Ground-based observations;	Mean precision ±1.75 days	Confirm MODIS and AVHRR utility	Lena, Ob', Yenisey, and Mackenzie rivers (Canada, Russia)	[54]
2010	Landsat-7 ETM+	6 bands, NDVI and NDSI		Ice identification/ detection	Decision tree and fuzzy K-means clustering,	Visual image interpretation	83% of correct identification	Confirm capability	Yellow River (China)	[55]
2011	Terra, ASTER; ALOS, PRISM; IKONOS	Stereo NIR Bands 3N, 3B	15 2.5 1	Surface-water velocity based on ice debris tracking	NCC template matching	Cross-check with Landsat 5, 7 images	Accuracy ~0.5 pixels (1.3 m, 0.03 m s^{-1})	Demonstration	St. Lawrence and Mackenzie rivers (Canada)	[56]
2013	Terra, ASTER	Stereo device NIR Bands 3N and 3B	15	Ice velocity	NCC matching, manual coregistration	Investigation of matching result variations	Accuracy (0.04 m s^{-1}) and errors analysis	Demonstrate ice velocity over several 100 s km	Lena River (Russia)	[57]
2014	Terra, MODIS	Surface reflectance MOD09GQ Band 2 (841–876 nm)	250	Intraseasonal cycle from ice onset to ice break-up and total melting	Decision tree classification based on 4 thresholds	Landsat 7, in situ discharge measurements, aerial photographs and ice bulletins	PoD 91%, FAR 37%	River ice mapping system	Susquehanna River (USA)	[58]
2016	Aqua and Terra, MODIS	Snow products, radiance products	500 250	Break-up, ice-off dates, average ice velocity	Visual interpretation	WSC hydrometric stations	Difference of 5 days	Confirm MODIS utility	Mackenzie River (Canada)	[59]
2016	Terra MODIS	MOD09GQ surface reflectance Band 2 (841–876 nm)	250	Break-up dates (3 classes: ice, water, and mixed)	Automated classification based on threshold	Hydrometric records	Mean uncertainty ±1.3 days	Develop automated algorithm	Mackenzie, Lena, Ob' and Yenisey rivers (Canada, Russia)	[45]

Table 2. *Cont.*

Year	Satellite, Sensor	Band	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
2019	Aqua and Terra, MODIS	surface reflectance MYD09GQ and MOD09GQ products	250	Break-up	Semi-automated classification using optimal threshold	Gauge stations	Mean bias −2.0 to 6.7 days, MAE 3.4 to 6.9 days	Operational flood monitoring	Moose, Albany, Attawapiskat, Winisk and Severn rivers (Canada)	[60]
2019	Planet Scope	RGB, NIR	3.7	Velocity	NCC-based matching	Error budget and analysis of uncertainties, Landsat 8, Sentinel-2, ASTER stereo	Accuracy $\pm 0.01\ \mathrm{m\,s^{-1}}$	Introduce the satellites	Amur River (Russia) Yukon River (USA)	[61]
2020	Landsat 5–8, TM, ETM+, OLI	Green, SWIR, (for NDSI)	30	Ice spatial extent, multiyear maximum distribution	Calibrated threshold	Temperature, gauged discharge data	Average accuracy vs. visual interp. is 0.973	Ascertain spatial and temporal distribution	Babao River (Tibetan Plateau, China)	[62]
2021	Sentinel-2 MSI, PROBA-V	Red	10 100	Movement, velocity	Entropy filter, threshold, template matching	Error analysis	Able to generate product	Show the feasibility	Lena River (Russia)	[63]
2023	Sentinel-2 MSI, Landsat 8 OLI	Red, NIR, SWIR (for RDRI)	10 30	River ice extent, accumulation, melting, phenology	Threshold	Air temperature	Limitation analysis	Determine phenology and processes	8 rivers in Tibetan Plateau (China)	[64]
2023	NOAA-20, 21, SNPP, VIIRS	Red, NIR, and TIR bands (I01, I02, I03, and I05)	375	Ice extent, ice concentration, map with classes: ice, water, land, snow, vegetation, cloud and shadow	Semantic segmentation with U-Net CNN	Ground observations, Sentinel 1, 2, 3, river ice charts	PoD 77%, FAR 12%, CSI 0.697	Introduce operational system	Lat. [30 to 80], Lon. [−180 to −60] (USA and Canada)	[65]

[1] Acronyms: Probability of detection (PoD), false alarm rate (FAR), critical success index (CSI), mean absolute error (MAE), normalized difference snow index (NDSI), thematic mapper (TM), enhanced thematic mapper plus (ETM+), operational land imager (OLI), multispectral scanner (MSS), multispectral imager (MSI), RDRI is the reflectance of the red and near-infrared (NIR), normalized cross-correlation (NCC), advanced spaceborne thermal emission and reflection radiometer (ASTER), panchromatic remote-sensing instrument for stereo mapping (PRISM).

The research conducted by [66] demonstrated the feasibility of estimating river discharge during ice break-up by utilizing near-simultaneous time-lagged pairs of satellite images from ALOS PRISM. This method allowed for tracking ice displacement in the Mackenzie River. The estimation of river discharge during break-up processes is complicated by the presence of fractured ice sheets or moving ice rubble [66].

3.3.2. SAR

Independent of solar illumination, SAR can acquire data largely unaffected by atmospheric conditions, such as cloud cover, fog, and rain, providing all-weather, day or night imaging capabilities. The interpretation of SAR imagery may be challenging for water surfaces due to wind effects, which leads to backscatter values close to those observed for ice covers. In addition, ice and water are difficult to separate when the ice surface is wet and the wind speed is low.

The reviewed literature on river ice observation using SAR satellites (Table 3) describes the usage of ERS-1, RADARSAT_1/2, RCM, TerraSAR-X, ALOS PALSAR, and Sentinel-1 satellites. SAR data provided information on ice types, characteristics, and processes including frazil (pans, slush, and floes) ice, juxtaposed ice, columnar ice, snow ice, consolidated ice, brash ice, ice thickness, melting ice, tracking break-up events and freeze-up processes, ice jams, running ice, and thermal conditions. Ice extent can be monitored to track ice cover development and its characterization depending on ice surface roughness. Such an approach enabled the mapping of sheet and rubble ice as well as the detection of ice jams and ice-water classification. Validation methods for SAR-based river ice observation include the following:

- Ground-based (in situ) observations: drill holes for measurements of ice thickness and snow depth, ice typing, GPR for ice thickness measurement, runoff observations at gauging stations, photographs and videos on ice cover extent, dynamics and ice jams;
- Aerial photos and videos of ice conditions and extent;
- Remote sensing data from other satellite sources (e.g., Landsat and Sentinel-2);
- Environmental data including air temperature and precipitation.

While SAR data were found efficient [67], certain limitations were identified [68], including speckle noise, uncertainties arising from variations in incidence angles, and challenges associated with the approach to retrieve ice thickness. The thesis in [69] evaluated the utility of SAR (RADARSAT-1) satellite imagery to monitor river break-up progression on the Athabasca River (Canada), identifying the location and length of ice jams, and providing an understanding of ice texture or thickness. The study in [70] described a RADARSAT-2-based method to monitor the spatio-temporal variation in ice covers, as well as ice types during the freeze-up period, along the main channel of the Slave River Delta in the Northwest Territories of Canada. This method successfully discriminated open water, thermal ice, juxtaposed ice, and consolidated ice in the images captured between November and March.

Table 3. Review of the literature on river ice observation using SAR satellite imagery (1993–2023).

Year	Satellite Sensor	Band; Polarization	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
1993	ERS-1	C; VV	26 30	Monitor/differentiate ice conditions (snow ice, clear ice, thin ice, new ice, broken ice, navigation track, cracks and ridges)	Visual interpretation, pre-processing by contrast stretching, despeckling and brightness adjustment.	Ground observations and photos, ice thickness, aerial photos	Analysis of SAR limitations, potential utility	Evaluate utility for navigation and engineering applications	St. Marys, Connecticut and White rivers (USA)	[71]
2001	RADARSAT-1	C; HH	8	Frazil pans and floes, juxtaposed, secondary consolidated, shore ice (frazil slush, melting ice, and brash ice), thermal break-up	Fuzzy K-means classification	Aerial photographs and videos	Most of the ice types can be visually identified and distinguished	Ice formation, ice types, and ice strength are necessary for the operation of hydropower-generating facilities	Peace River (Canada)	[9]
2003	RADARSAT-1	C; HH	8	Ice cover (7) types (frazil pans, juxtaposed ice, a juxtaposed ice cover with moderate consolidation, consolidated ice cover)	Visually and Fuzzy K-means classification	Aerial videos	Qualitative assessment shows good agreement	Ice cover maps for hydroelectric operations	Peace River (Canada)	[72]
2003	RADARSAT-1	C; HH	8	Ice thickness, sail height, ice classes (open water/skim ice/smooth border, low- or high-concentration ice pans, juxtaposed, consolidated)	Fuzzy K-means classification, ice thickness regression	Field data: drill holes, cross-sectional surveys, air photos	Thickness R^2 0.75–0.89	Measure spatial differences in ice cover for hydroelectric operations	Peace River (Canada)	[73]
2004	RADARSAT-1	C; HH	100	Ice front, dark and bright ice classes	Visual interpretation	Predictive model, feedback from users	Good agreement	Reduced uncertainty in flood forecast	Exploits River (Canada)	[74]
2006	RADARSAT-1 Envisat ASAR	C; HH C: HH-VV	8 25	Ice classes (open water border, frazil pans, juxtaposed, consolidated)	GLCM texture and backscattering, fuzzy K-means	Aerial photos, manual labeling	High degree of confidence	Develop mapping procedure, compare satellites	Peace River (Canada)	[75]
2007	RADARSAT-1	C; HH	8	Columnar ice, snow ice and frazil ice	Scattering model	Cores: ice thickness, ice type, ice densities	Model results proved	Understand interaction radar signal with the different ice types	Athabasca River (Canada)	[76]

Table 3. *Cont.*

Year	Satellite Sensor	Band; Polarization	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
2007	RADARSAT-1	C; HH	9	Ice classes: consolidated frazil, columnar (thermal) ice, heavily consolidated ice, juxtaposed	Fuzzy K-means, object-oriented classification, backscatter, texture	Field and aerial surveys	OA 69–92%	Validate river ice maps and assess classifiers for hydropower companies or flood forecasters	Peace and Saint-François rivers	[77]
2009	TerraSAR-X RADARSAT-2	X, C; HH-VV, QP	5.2 × 7.6	Extent of intact frazil and consolidated ice classes	SVM classifier	Ice cores and ground photos, GPR	Mapping accuracy—CI 80.1%, II 64.8%	Evaluate utility of DP SAR	Saint-Francois River (Canada)	[78]
2009	RADARSAT-1	C; HH		II, jam, running ice, ice thickness, thermal, juxtaposed and hummocky ice covers	Backscatter analysis	Field study: holes, helicopter, photographs	plots	Explore application of SAR for river ice characterization	Athabasca River (Canada)	[79]
2010	RADARSAT-2	C, HH-HV	25	Ice thickness	HH backscatter	Field data: ice thickness and snow depth	R^2 = 0.43–0.6	Ice thickness for ice break-up forecasting	Red River (Canada)	[80]
2011	RADARSAT-2	C, QP		Freeze-up process, floes, columnar, consolidated, border ice, ice bridging, frazil, or snow ice	HH-HV-VV RGB color composite interpretation	Field data: roughness, snow properties, ice thickness, and ice stratigraphy, GPR	Successful ice type map	Basis for exploring differences in ice strength and thermal characteristics between the various ice cover types	Red River (Canada)	[81]
2011	RADARSAT-2 ALOS PALSAR	C; QP L; QP		Ice cover (columnar, frazil) characteristic, thickness, classification	Linear regression, polarimetric parameters	Field data: surface roughness, snow properties, ice thickness, and ice cover composition	Coefficient of variation is better for R2, Thickness $R^2 \leq 0.7$	Study potential of R2 and ALOS	Mackenzie River (Canada)	[82]
2013	TerraSAR-X RADARSAT-2	X; HH C; QP	3.74 10.96	Extent, estimation of decay	K-means classification	Comparison to manually derived reference	Mean error 10–16%	Analyse classification performance	Lena River (Russia)	[83]
2013	RADARSAT-2 MODIS	C; DP, QP	10, 25	Ice type identification: consolidated frazil pans, juxtaposed frazil pans, skim ice, thermal ice	Fuzzy K-means classification using backscattering and texture	Photographs, visual data interpretation, cross-satellite comparison	92% global accuracy	Improve IceMAP-R algorithm for automated ice classification	Peace River (Canada)	[84]
2012, 2014	RADARSAT-2	C; QP	5.2 × 7.6	Ice thickness	Polarimetric entropy	Field data: cores, GPR	for some types RMSE 16.6%	Develop methodology	Saint-François, Koksoak, and Mackenzie rivers (Canada)	[85] [86]

Table 3. *Cont.*

Year	Satellite Sensor	Band; Polarization	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
2014	RADARSAT-1, ERS-2	C; HH VV	12.5 (PS)	Break-up process monitoring	Image brightness, its variance, sum of rank order change	Field runoff observations, gauging stations	Successful SAR variables were identified	Determine SAR potential	Kuparuk River (USA)	[87]
2014	ALOS; PALSAR,	L; QP	30, 50	Freeze/thaw conditions of surrounding fores area	HV backscatter analysis	AVNIR-2 brightness temperature and AMSR-E as ancillary data	Brightness temperature supports SAR results	Detecting thaw/freeze conditions on the ground	Lena River (Russia)	[88]
2015	RADARSAT-2	C; DP and QP		Ice variation and formation, 4 types classification (open water, thermal, juxtaposed, and consolidated ice)	Texture, fuzzy K-means classifier, CV	Field data: time-lapse photos, holes, visual SAR interpretations	River-ice maps were compatible with validation sources	Introduce SAR-based methodology for ice monitoring and mapping	Slave River (Canada)	[70]
2015	RADARSAT-2	C; DP, QP	8, 25	Freeze-up process, different types of ice	Visual data interpretation	Field data: time-lapse cameras, thickness, ice types, etc.	Qualitative analysis	Describe mechanism of ice cover formation	Slave River (Canada)	[89]
2016	RADARSAT-2 TerraSAR-X	C; QP X; HH-VV	5–11 3 (PS)	Skim, juxtaposed skim, agglomerated skim ice, frazil run and consolidated ice	Wishart classification	Landsat	OA TSX 81.3–87.5%, R2 83.8–99%	Compare and evaluate TerraSAR-X with RADARSAT-2	Peace River (Canada)	[90]
2017	Sentinel-1	C; VV + VH	20	Ice cover	Log likelihood change statistic on optimal thresholds	Landsat 8, Sentinel-2, air temperature, precipitation	Visibility analysis	Monitor ice cover changes	Vistula River (Poland)	[91]
2018	RADARSAT-2	C; SLA HH QP	1.6×0.8 5.2×7.7	Monitor ice cover development	Freeman–Durden polarimetric decomposition	Field data: snow depth, ice thickness, crystallography analysis; environmental data	Polarimetric product assessment and comparison with ice structure	Understand interactions between SAR signals and river ice covers to select transportation routes	Slave River (Canada)	[92]
2019	RADARSAT-2	C; QP	4.7, 8	Classification of thermal ice, frazil ice, and consolidated ice	Minimum distance, Fisher and Wishart classifiers	Field data on ice typing and thickness measurement	OA 95%	Provide basis for modeling and ice thickness retrieval	Yellow River (China)	[93]
2019	RADARSAT-2	C; QP	PS 10	Ice thickness	"IceThick-RS" model and polarimetric parameters	Field data: thermal conditions, snow properties, measurements, and cores	Snow depth R^2 0.93, 0.97	Demonstrate utility of framework	Slave River (Canada)	[94]

Table 3. *Cont.*

Year	Satellite Sensor	Band; Polarization	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
2021	RADARSAT-1/2	C; HH		Six classes of sheet ice and rubble ice	Two-step supervised classification model IceBC based on thresholds	Oblique aerial and time-lapse photography	OA water 97%, sheet ice 69–85%, and rubble ice 97–99%	For operational IceBC prototype	Mackenzie, Athabasca, Saint John, Moose, Albany rivers (Canada)	[95]
2021	Sentinel-1	C; VV-VH	PS 15	Ice classes: sheet and rubble ice, ice jam	Random Forest classifier, pseudo-polarimetric decomposition and GLCM texture	On-site measurements by permanent cameras and observation flights, Sentinel-2	Confusion matrix, Kappa coefficient 0.87, OA 91%	Assess utility of Sentinel-1 data for operational monitoring of river ice during break-up	Athabasca River (Canada)	[96]
2022	Sentinel-1	C; VV-VH	PS 10	Ice surface roughness (sheet, rubble)	Random Forest and regression models	UAV-based 3 cm DEM	STD MAPE 5–113%	Investigate effect of roughness on backscatter	Yellowstone River (USA)	[46]
2022	Sentinel-1	C; VV-VH	5 × 20	Ice thickness	Regression, inversion	Field data	RMSE 0.109 m, 0.258 m	Evaluate retrieval methods	Babao and Binggou rivers (China)	[97]
2022	Sentinel-1	C; VV-VH	PS 10	Ice detection, analysis of border, frazil, consolidated ice	Three binary classification models based on thresholds	In situ observations of ice types, Sentinel-2	Agreement 68–91%	Evaluate SAR potential to detect ice in narrow rivers	Nemunas and Neris rivers (Lithuanian)	[47]
2022	Sentinel-1	C; VV-VH	PS 10	Ice jam detection, ice-water classification	Ice classification based on threshold	RLIE, LIE, Sentinel-2	F1, Precision, Recall 0.77	Develop algorithm	Kemijoki River (Finland)	[98]
2023	Sentinel-1	C; VV-VH	20	Ice thickness	Inversion from VV backscatter	Field measurements, water level, and discharge station data	R 0.702, 0.437 (for snow-covered ice), RMSE 11.75 cm	Analyse correlation and long-term trend, compare with model based on temperature	Yellow River (China)	[99]

Acronyms: Dual-polarized (DP), Quad-Pol (QP), support vector machine (SVM), intact ice (II), which contains thermal ice or fused layers of thermal (TI) and frazil ice, consolidated ice (CI), which is a mix of different ice types, frazil ice (FI), which include slush, pans, and floes, overall accuracy (OA), mean absolute percentage errors (MAPE), coefficient of variation (CV), pixel spacing (PS), coefficient of determination (R^2), Pearson correlation coefficient®, overall accuracy (OA), river lake ice extent (RILE), lake ice extent (LIE), grey level co-occurrence matrix (GLCM), ice break-up classifier (IceBC).

3.3.3. Other Satellites Technologies

Other satellite technologies are analysed separately from SAR and EO/IR to differentiate the less commonly used technologies specifically employed in river ice monitoring. This separation allows for a focused discussion on these niche technologies, which may offer unique advantages or applications not covered by mainstream satellite systems. Table 4 provides details of the reviewed literature on river ice observation using other satellites: altimeters, microwave radiometers and gravimetry.

- **Altimeters**

Satellite radar altimetry was used to monitor river water levels [100–104]. The results were compared with river level and discharge measured at gauging stations, showing a good agreement. The results of using ICESat-2 laser altimetry data [105] demonstrated that satellite-based estimations of water levels of the Yangtze River were in good agreement (average water level estimation error was 0.27 m) with in situ observations.

- **Microwave Radiometers**

Time series data from the European Space Agency Soil Moisture and Ocean Salinity (SMOS) mission were utilized for a collection of 31 satellite gauging reaches (SGRs) located above 65° N from 2010 to 2020, allowing them to observe decrease of 3.4 days in theaverage annual river ice duration [106].

- **Satellite Gravimetry**

Peak river flow and snow mass at coarse resolution were estimated for the basins of Mackenzie and Red rivers (Canada) [107].

Table 4. Review of the literature on river ice observation using other satellites (2005–2020).

Year	Satellite, Instrument	Sensor Type or Band	Resolution, m	Ice Information	Retrieval Method	Validation Sources	Quantitative or Qualitative Assessment	Main Purpose	AOI	Reference
2005	TOPEX/Poseidon	C, Ku	(GS) 596	River discharge	Relation between water level and river discharge	River level and discharge measured at gauging station	Good agreement, average error up to 17%	Identify potential solutions and benefit for hydrological studies	Ob' River (Russia)	[100]
2014	Jason-1, 2; Altimeter, JMR, AMR	Ku 18.7, 23.8, 34 GHz	10 km	Determine freezing time	Backscatter coefficient and brightness temperatures histograms	In situ observation data	Good agreement with in situ data	Develop method for distinction between open water and ice cover	Volga and Don rivers (Russia)	[108]
2017	GRACE	Gravity	330 km	Peak river flow and snow mass estimation	Modeling	Global Land Data Assimilation System (GLDAS) datasets	Snow mass is 20% higher than GLDAS, $R^2 > 0.5$, R 0.83	Evaluate, assess, and examine basin scale performance	Basins of Mackenzie and Red rivers (Canada)	[107]
2020	Jason-2, 3; Altimeter, AMR	Ku 18.7, 23.8, 34 GHz	Few km 22–42 km	Ice phenology (freeze-up, break-up) and thickness	Backscatter coefficient behavior and brightness temperature difference	Landsat 8 and Sentinel-2, water level gauging stations, in situ observations	Ice phenology ±10 days in 90% of cases, thickness RMSE 0.07–0.18 m	Demonstrate potential for retrieval of river ice phenology and ice thickness for ice roads	Ob River (Russia)	[109]

Advanced microwave radiometer (AMR), Jason microwave radiometer (JMR), radar altimeter (RA), ground spacing (GS).

3.3.4. Multi-Sensor Observations

Multi-sensor river ice observation involves the integration of various sensing technologies. The usage of a combination of sensors such as satellite imagery, aerial surveys, and in situ instruments enables the diversity of data sources to enhance understanding and analysis of river ice information.

An integrated automated approach was developed and applied to characterize river ice processes along the Slave River, Canada, using MODIS time series to detect the dates of river ice freeze onset and water clear of ice, while RADARSAT-2 imagery successfully characterizes and maps four classes of water and ice covers [110]. The comparison of satellite-based results with time-lapse photos and aerial surveys demonstrated a good agreement. Space-borne data acquired by RADARSAT-1 and RADARSAT-2 and optical SPOT-5 were successfully used to track the ice cover formation along the Dauphin River (Canada) for the geospatial model [111].

A method for river ice extraction and change detection using multi-temporal SAR and multi-spectral EO/IR images [112] used adaptive threshold segmentation for ice detection in SAR imagery and Fuzzy C-means clustering using infrared bands for ice, water, and shore discrimination over the Yellow River (China). Ref. [22] conducted research to map the spatiotemporal changes in ice and open water coverage using multispectral and synthetic aperture radar (SAR) imagery from historic (1973 to 2021) Landsat and recent Sentinel-2 and Sentinel-1 satellites, aiming to identify ice cover in the Copper River Basin (USA) for river ice crossing. The usage of data from four satellites EO/IR (Landsat-8 and Sentinel-2) and SAR (Sentinel-1 and RADARSAT Constellation Mission (RCM)) over a segment of the Churchill River, Canada [113] demonstrated the potential of spaceborne solutions for automated river ice detection and frequent monitoring.

3.3.5. Summary of Satellites Observations

Satellite-based river ice observation utilizes various satellite sensors, with prevalence of SAR and EO/IR systems, to detect and monitor ice cover over river systems. These observations provide information on ice extent, thickness, and dynamics, aiding in the assessment of potential hazards and impacts on various sectors such as transportation, infrastructure, and ecosystems. Optical sensors, such as Landsat-8 and Sentinel-2, capture imagery in visible and near-infrared bands, offering high spatial resolution and detailed surface information. SAR systems, such as Sentinel-1, TerraSAR-X, RADARSAT-2, and RCM, provide all-weather imaging capabilities. By combining data from multiple satellite sensors, satellite-based river ice observation offers a comprehensive and effective means of monitoring river ice conditions over large spatial scales and extended periods, contributing to improved understanding and management of river ice. Satellite data archives (e.g., Landsat since 1972) can provide long-term records of river ice observations, allowing us to analyse trends, variability, and patterns in ice cover and behavior.

3.4. Airborne Instruments

The history of aerial river ice monitoring goes back to the early 20th century when aviation technology significantly advanced. Aerial reconnaissance flights provide information on river ice conditions and environment monitoring for the military, navigation, hydroelectric power operation, and other purposes. Observation flights can provide important details on ice, water, and snow conditions (e.g., [114]) the position of the river ice front, ice deterioration and melt, break-up, hanging dam, ice deformation, ice jams and their magnitude, open water leads, runs and water on ice, and documentation of weather conditions. Daily observations of river ice conditions on the St. Lawrence River were conducted through helicopter flyovers by Environment Canada ice observers, who generate maps for transmission, and real-time ice observation systems using cameras and radars mounted along the river [115]. Daily updates on river ice conditions are accessible through the Canadian e-Navigation Portal (www.marinfo.gc.ca (accessed on 5 April 2024)).

3.4.1. EO/IR Cameras and Scanners

Aerial surveys equipped with cameras operating in the visible and infrared spectrum were used to collect data on river ice cover extent and its types, as well as water temperature [34,42]. These surveys played an important role in understanding the spatial distribution of river ice and assessing ice-related hazards such as ice jams and flooding. However, as it was discussed in [34], such remote sensing systems for the surveillance of ice and snow (e.g., aerial photography, multispectral scanners) suffer from the following:

- their restriction to the visible and infrared portions of the electromagnetic spectrum to operate in low visibility conditions (e.g., clouds, fog),
- difficulties in ice characterization in the presence of snow cover, and
- challenges of aircraft navigation in poor meteorological conditions.

Currently, aerial river-ice monitoring continues to evolve with advancements in sensor and platform technologies and data processing techniques. Aerial photos and videos serve as valuable sources of information for river ice observation, documenting ice cover characteristics, dynamics, and patterns. Deployed on suitable altitudes, aerial cameras operating in the visible electromagnetic spectrum can provide up to ultra-high (few cm) resolution (UHR) and multispectral data that enable detailed analysis of ice conditions, extent, and classification. Aerial photos and videos also allow for the identification of features such as ice jams, cracks, and leads, providing information on ice movement and potential hazards. In many studies, aerial EO/IR data complemented ground-based measurements for the validation of satellite-based observations and image classification methods [72].

UAV remote sensing was used for several river-ice applications [48], allowing efficient access to a large amount of high quality of data that cannot be matched by manual measurements. The results from study [116] demonstrated that employing a fixed-wing UAV system was feasible and that this was an effective technology for rapid observation and risk assessment of ice jam formation over the Yellow River (Inner Mongolia segment, China) in challenging weather conditions characterized by low temperatures and strong winds.

UAV-based UHR video footage and photogrammetric digital surface models (DSMs) generated for a structure from motion (SfM) method allow us to observe important river ice characteristics:

- surface roughness [46];
- topographic mapping of ice jams in the Mohawk River [117,118], including its extent, thickness estimation, severity, and evolution;
- broken anchor ice dams [118];
- shear wall height [119], identify and measure floe sizes, thickness and volume, and floe size distributions (which can be useful information for estimating loads on structures);
- ice jam, its state and elevations [120],
- ice thickness estimation at various stages of freeze-up on the river Sokna, Norway [121].

Airborne thermal infrared (TIR) observations were found useful for the retrieval of information on surface ice characteristics including superficial concentration and temperature over the St. Lawrence River [122]. Ice floe geometric and statistical characteristics, concentration, structure, and thickness were also successfully deduced. However, the retrieval of ice floe thicknesses from TIR observation was difficult since it required certain assumptions regarding thermal history and estimates of ice properties and near-surface turbulent processes. The results of the study [123] revealed that drone-based thermal infrared imagery can be useful for characterizing river flow temperature heterogeneity and identifying the location and extent of discrete thermal inputs to rivers. However, the quality of the acquired thermal imagery was affected by temperature drift-induced bias, which prevented the extraction of accurate temperature data.

3.4.2. LIDAR

Airborne LIDAR technology enables surveying large areas to obtain surface elevations, thereby enabling high accuracy output (error within a few centimeters [124,125]). There were no references identified for LIDAR-based river ice observation. However, the bathymetry data collected using green LIDAR (LIDAR with the ability to penetrate the water surface) provided a very precise basis for modeling and for incorporating the river ice DSMs into the hydraulic model for the Gaula River in Norway [119].

3.4.3. Radars

With the technology progress in the 1960s–1980s, aerial observation of river ice evolved [35] towards radar demonstration, evaluation, and utilization in tasks:

- ice thickness measurement with nadir-looking impulse radar [126,127] and frequency-modulated continuous wave (FM-CW) radar [128,129]; and
- ice type and drift determination with side-looking radar (SLR, also called SLAR), microwave scatterometers and SAR.

- **Ice Penetrating Radar**

An ice penetrating radar measures ice thickness by distinguishing signals from the air/ice and the ice/water interfaces. River ice thickness measurement using the penetrating radar was conducted using different aerial platforms: helicopters, airplanes, and UAV. The operational ice thickness radars for deployment on helicopter or airplane (up to 150 m altitude) were developed in the the 1970s–1990s at the Riga Institute of Civil Aviation Engineers [127,130] with two modifications: (i) the impulse and (ii) FM-CW radars. The impulse radar is able to measure freshwater ice thickness from 10 to 200 cm with an error of less than 5%. The FM-CW is able to measure ice thickness from 20 to 250 cm with an error less than 2 cm for ice 20–60 cm thick and less than 3% for ice 60–250 cm thick. This device also allows to determine the type of environment under the ice (water, soil, air).

The FM-CW ice thickness radar deployed on a helicopter with a flying height of up to 10 m at 15–20 km/h operated in the 26.5–40 GHz frequency range [128,129]. Ice thicknesses less than 5 cm were successfully resolved over the Connecticut River, USA. In the region of rubble ice, the radar return has a characteristic "fuzzy" appearance because of scattering from the rough surface.

A study with an impulse radar (frequency of 500 MHz), [37] demonstrated the possibility of determining freshwater ice thickness in most temperate climate winter conditions when surface water (melt or rain) is about 8 mm. The performance of the helicopter-borne impulse radar flying at a speed of 1.8 to 9 m/s and an altitude varying from about 3 to 12 m was assessed by [36] over the Yukon River. The minimum ice thickness resolved from the raw data was about 0.2 m with the 600 MHz antenna and less than 0.15 m with the 900 MHz antenna.

Investigations of ice jams were performed by [131] using the helicopter-borne GPR (antenna center frequency 150 MHz) flying at 20 m altitude with 20 km/h speed over the Lena River (Russia). The possibility of ice thickness profiling to calculate ice volume was demonstrated for the broken ice accumulations 2–4 m thick and for the ice heaps up to 10 m thick.

Investigations with UAV-mounted GPRs over the Songhua River basin (China) demonstrated [132] an ice thickness detection system that enable automatic tracking of the ice layer, overcoming the altitude fluctuations.

- **SAR**

In preparation for the RADARSAT-1 mission, helicopter-based flights with C/X-bands SAR were conducted [133] over the Burntwood River (Canada). Results with HH and HV polarizations have shown that airborne SAR can be used to differentiate and identify various freshwater ice types, such as juxtaposition ice, refrozen slush, river ice runs, lake ice, and open water leads.

Quad-Pol data with a resolution of 1.7 × 4.0 m were acquired over the Saint-Francois River (Canada) using Airborne Convair-580 C-band SAR, which was complemented by field data collection [134]. Ice types (frazil, thermal, and open water) classification was performed using rule-based hierarchical and Wishart classifiers, showing the advantages of hierarchical classifier and full polarimetric data.

- **Microwave Radiometer**

The scanning microwave radiometer, deployed aboard NASA's Convair 990 aircraft flown over the Alaskan tundra, demonstrated [135] the viability of radiation measurements spanning from infrared to microwave wavelengths (1.55 cm). The observed contrast in radiance facilitated the mapping of a diverse range of partially frozen and partially melted lakes and rivers, even under cloud and rain conditions.

The Ka-band radiometric mapping system, which is an airborne passive microwave imager at a center frequency of 33.6 GHz (wavelength of 0.89 cm) with a footprint, of approximately 26.6 m in diameter at nadir 1500 m flight altitude, demonstrated an ability to distinguish large-scale freshwater ice and snow conditions [136,137].

3.5. In Situ Observations

The previous surveys, including [41,42], provided detailed information on the in situ instrumentation and observation methods, which remain relevant today. We provide a brief overview of in situ technologies highlighting recent advancements.

3.5.1. Method Implementations

The observation of river ice characteristics can be performed through different in situ methods implemented from the following:

- **Shore:** including towers, bridges, or other structures which have elevation, and tramway,
- **Ice surface:** stationary or moving on ice surface such as sled or vehicle (e.g., snowmobile, car, air cushion vehicle (ACV) [138]),
- **Ship** [126],
- **Underwater:** submersibles or remotely operated vehicles (ROVs),
- **Frozen in ice** (gauges and buoys).

Certain ground-based observations share similarities with aerial observations conducted from low-flying helicopters or UAVs, as both occur at altitudes measured in meters. However, the key differences lie in the following:

− safety considerations favor the aerial platform over measurements taken from the ice surface,
− additional equipment requirements differ for deployment on aerial platforms,
− aerial platforms offer the potential for remote sensing over vast distances and areas, spanning many kilometers.

3.5.2. Observation Technologies

- **Visual observations**

Visual observations and measurements conducted from ships are widely used to determine ice characteristics and processes [34,126]. The National Weather Service, NOAA (USA), actively promotes public engagement in reporting ice jams or river flooding through social media channels or via email or phone (https://www.weather.gov/bgm/hydrologyRiverIce (accessed on 5 April 2024)). Ice observers gather data and upload information on ice jams and river conditions via the New Brunswick (Canada) River Ice Observation System (https://mreac.org/projects-2/ice-observation/ (accessed on 5 April 2024)). Ice on/ice off conditions in the Ottawa River Watershed (Canada) can be reported via an online form (https://ottawariverkeeper.ca/what-we-do-2/initiatives/watershed-health-assessment-and-monitoring/ice-observations/ (accessed on 5 April 2024)).

- **Photography and Video**

Photographs and videos are essential tools for gathering river ice information due to their ability to visually document the ice state and characteristics. By capturing images and footage of river ice formations, observers can document various aspects such as ice type, texture, color, and the presence of various features like jams, cracks, or floes and their shape. These visual records provide valuable data for analysing changes in ice conditions over time. Additionally, photographs and videos can help communicate findings to a wider audience, including policymakers, scientists, and the general public, facilitating a better understanding of river ice conditions and the need for ice monitoring and management. The historic photograph of aufeis on the Canning River in June 1908 was reported [139]. The river ice concentration and velocity of the ice in Hungarian rivers were observed using a shore-based photo camera for characterizing the development of an ice jam [34].

The paper [140] described the use of low-light-level television (LLLT) video cameras located at the New York Power Authority and Ontario Hydro intakes for observation of ice conditions measuring ice concentration on the Upper Niagara River. This observation technique was found ineffective during periods of darkness and/or blowing snow.

Webcams (connected to the Internet) installed along riverbanks or bridges are widely used for river-ice monitoring, capturing real-time images or videos of ice conditions, offering continuous visual monitoring and allowing observers to track changes in ice cover. River ice monitoring can also be performed in remote areas using a ruggedized camera system (https://www.nupointsystems.com/aerimis-camera-system/ (accessed on 5 April 2024)) connected via satellite and cellular networks. Automated algorithms were developed [141] for the identification and measurement of key characteristics of river ice cover, including the ice-covered area percentage, leading edge location, and the rate of border ice growth and recession using a time-lapse camera system on the Lower Nelson River, Canada.

- **Thermal Sensors**

Net radiation can be measured with a radiometer which helps estimate the potential for frazil ice formation [140]. Thermal infrared images of river ice can be captured using FLIR IR which measures temperatures ranging from −40 to +10 °C [142].

The utilization of portable pressure/temperature loggers has proven to be an effective and reliable method for gathering quantitative information to develop predictive modeling capabilities for hydraulic and ice jamming processes in the Mackenzie Delta [143].

- **Gauges and buoys**

Ice gauges are important tools for river ice thickness measurement and monitoring as well as measuring ice motion during break-up [144] and vertical surface movement [145]. "Hot wire" and conductivity (frozen in ice) gauges provided low-cost river ice thickness measurements with an accuracy of 0.5 cm [146]. A sensor for ice and snow thickness measurement was developed [147] using temperature gradient differences in air, ice, and water and a snow depth detection with an array of infrared diodes. The experiments on the Heilongjiang River (China) demonstrated a measurement accuracy of 1 cm for both the ice thickness (in the range of 0–2 m) and snow depth detection (in the depth range of 0–0.5 m).

The apparatus for freshwater ice thickness monitoring, which is performed by an array of electrodes measuring the differences in the electrical resistance and the temperature of air, ice, and water, was developed and tested in the Wanjiazhai Reservoir in the upper Yellow River (China) [148]. The depth of ice thickness measurements was up to 2 m with accuracy of 1 cm. The ice thickness data can be uploaded to a remote monitoring center through GPRS mobile communication and internet networks.

Snow and Ice Mass Balance Array (SIMBA) [149] was developed based on Ice Mass Balance Buoy (IMB) by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). SIMBA measures vertical temperature profiles through the air–snow–ice–water column using a thermistor chain. For the lake ice and snow thickness the mean absolute error (MAE) was about 3 cm and the coefficients of determination (R^2) were 0.98 for ice and 0.8 for snow [150]. SIMBA is also used for operational river ice thickness monitoring in Canada [151].

River ice motion detector sensors based on the principle of breaking wire were developed [144] to provide a near-real-time indication of ice-cover movement.

- **Acoustic**

Real-time measurements of ice draft and concentration were performed [152] using upward-looking ice profiling sonar (IPS) and velocity with an Acoustic Doppler Current Profiler (ADCP). The IPS and ADCP were installed at 13 m depth in the St. Lawrence River (Canada) and connected to headquarters for managing navigation and detecting ice jams in real-time. Such instruments were previously used to observe the characteristics of brash ice and ice congestion [153].

Mini-Acoustic Doppler Profilers (ADP) (3.0 MHz and 1.5 MHz with the range of 25 m and 6 m) were deployed [154] from above the ice cover to collect water velocity data in the Mackenzie River (Canada). Velocity profiles were sufficient to resolve most of the flow, showing a good agreement with a mechanical current meter.

The feasibility of conducting acoustic (25 kHz) tomography experiments under ice has been demonstrated using three stations in the Songhua River, China [155]. The sectional velocity of the river was about 0.95 m/s with flow error ranging from 0 to 8%.

- **Ice Penetrating radar**

The results achieved using a 50 MHz centre-frequency GPR system from the ice surface [156] demonstrated the possibility to measure the thickness of both fragmented thermal ice as well as slush ice. It documented an ice jam up to a 7 m thick in the Saint John River. A survey of ice thickness using surface-based GPR with the frequency of 800 MHz was performed [157] over the Pulmanki River (Finland), demonstrating the possibility of measuring thickness, with a mean absolute error of ±3 cm and a relative error of 5%, in 35–75 cm thick ice.

- **Imaging Radars**

A trial installation of a marine radar system was tested in 1987–1988 to evaluate its capability to estimate ice concentration [158]. A standard 25 kw X-band radar was mounted at a height of 14 m on the roof of the River Control Centre and data were recorded every 15 min during much of the winter. Analyses of the data revealed that the radar could detect the presence of ice in the river and could discriminate ice types based on the surface roughness of the ice. Because of the height of the radar antenna, ice could only be observed to a range of up to 3 km. The icebreakers also had marine radars that could help identify the extent of the ice cover within a limited range.

- **Seismic Sensors**

Three geophones were deployed along the Sävar River in Sweden to assess the effectiveness of seismic methods in detecting ice-cracking events and distinguishing between thermal and mechanical ice break-up [159], revealing a potential adaptable approach for extracting and characterizing ice-cracking signals and determining ice break-up modes in northern rivers.

- **GNSS-IR**

An application of L-band frequency Global Navigation Satellite System (GNSS) Interferometric Reflectometry (GNSS-IR) for the estimation of lake ice thickness demonstrated [160] a good agreement (MAE 5 cm and RMSE 7 cm) with in situ thickness measurements. The recent publication in [161] on GNSS-IR observations of river ice break-up demonstrated ice detection accuracy of up to 94%, using a shallow neural network as a classification algorithm.

4. From Observations to River Ice Information

4.1. Observation Data Processing and Analysis

Retrieval of river ice information for various applications may involve the methods of raw data pre-processing, analysis, interpretation, and analytics, depending on the data source, analysis method, and required information. Figure 3 shows the common steps.

The data and image pre-processing step aims at preparing raw data or images for analysis. It may involve multiple techniques, such as calibration, noise reduction, improving contrast, enhancing features and texture, decompositions (e.g., polarimetric for SAR and index calculation for multispectral data), geometric correction, co-registration, land masking, atmospheric correction, and cloud masking for EO/IR.

The data analysis step is focused on extracting river ice information regarding dynamics, processes, types, and characteristics. Initially, data analysis relied on manual image interpretation, but since the early 2000s, it evolved to incorporate various machine learning (ML) techniques. The most common ML techniques for satellite data analysis (listed in Tables 2 and 3) are as follows:

− decision tree (DT) based on threshold and K-means classification methods for river ice classification,
− NCC for ice movement estimation, and
− SAR backscatter modeling, regression, and inversion for ice thickness retrieval.

The output results step facilitates the export of analysis results to diverse product formats, serving dissemination, further analysis, quality evaluation, and utilization for decision-making and presentation purposes.

4.2. ML Technologies for River Ice

Several publications described a semi-automated classification process that involves a combination of (i) the manual input to guide the adjustment of parameters (e.g., threshold) or validate the results and (ii) automated processing using algorithms or software tools. Semi-automated classification combines the efficiency of automated methods with the accuracy and expertise of an analyst's judgment, resulting in a more efficient and reliable classification process, which is valuable when a fully automated classification is not feasible.

Various ML techniques are used for the analysis of river ice observations to identify patterns, trends, and relationships. ML algorithms are computational models that are able to learn from data and make predictions, decisions, or classifications. In the context of river ice analysis, ML can be used for tasks of ice detection, classification of ice types, prediction of ice break-up or freeze-up dates, ice thickness estimation, and others.

In addition to DT and K-means classification methods widely used in reviewed publications, the use of support vector machines (SVM) and Random Forest have gained popularity for river ice classification. The relevance vector machine (RVM) was applied to HJ-1B satellite images of 30 m resolution to detect ice in the Yellow River (China). Depending on the image, the detection accuracy (correct rate) varied from 87.6 to 98.7%. In specific scenarios, combining multiple algorithms can enhance accuracy. For instance, the integration of texture segmentation with a Gabor filter, K-means clustering, and a probabilistic neural network (PNN) classifier achieved a 95.5% accuracy when applied to hand-held thermal infrared camera data [142].

In recent years, there has been a growing trend towards the usage of deep learning (DL) techniques, particularly semantic segmentation, for river ice analysis. This DL approach enables the identification of various ice features and types directly from images with minimal pre-processing requirements. The process typically involves training a deep learning model, such as a convolutional neural network (CNN), on a large dataset of labeled images containing various examples of river ice. The trained model processes each pixel in the image and predicts the class label for that pixel based on its visual characteristics. The UNet semantic segmentation model is useful for river ice analysis tasks such as delineating ice boundaries, identifying ice types, and quantifying ice coverage in satellite, aerial, or webcam images of rivers. The UNet model was applied to publicly available webcam images acquired over the North Saskatchewan River (Canada) to calculate ice concentration and the size and shape of ice pans. It achieved a mean accuracy of 77% [162].

The Alberta River Ice Segmentation Dataset with RGB images and videos of surface ice conditions was collected from bridges in Edmonton and with UAVs in 2016–2017 over the Peace River and North Saskatchewan River (Canada) [163]. This freely available dataset includes 50 manually labeled images with pixel-wise labels for three classes: anchor ice, frazil ice, and water. This dataset was used in several studies to develop and compare different ML and DL models. The comparison of SVM, UNet, SegNet, Deeplab, and DenseNet [164] showed better Precision (77–84%) and Recall (86–91%) for frazil ice and open-water classes with Deeplab. However, for anchor ice, the Precison and Recall with Deeplab were lower: 53% and 74%, respectively.

Using the Alberta River Ice Segmentation Dataset, the modified UNet architecture [165] was compared to the efficient segmentation network LR-ASPP (with a MobileNetV3 backbone), achieving better performance (a mean pixel accuracy of 76.8% vs. 62.8%) and 91% faster computation times. Another study [166] used this dataset to compare UNet, UNet3+, CCNet, DeepLabV3+, DMNet, PSPNet, K-Net, SegFormer, and IceHrHet, showing better accuracy (93%) with the DeepLabV3+ model.

The UAV-based dataset NWPU_YRCC from the river ice on the Yellow River contains 814 labeled video frames with three classes: ice, water, and shore [167]. The semantic segmentation CNN ICENET (using ResNet as the backbone) achieved pixel accuracy of 96% [167], which was higher by 0.7–3.8% than in other CNNs (such as DeepLabV3, DenseASPP, PSPNet, RefineNet, BiseNet, and GCN). Subsequently, an improved ICENET architecture, ICENETv2 model [168], was applied to a new river ice dataset named NWPU_YRCC2, which contains four classes (drift ice, shore ice, water, and others), achieving a pixel accuracy of 91.94%, slightly outperforming ICENET by 0.1%.

TerraSAR-X Dual-Pol (HH-HV) satellite data acquired over the Mackenzie River (Canada) were used for ice and non-ice mapping with UNet, achieving an overall accuracy of 94% [169].

The study in [170] focused on addressing the challenge of ice-tracking and velocimetry using the IPC_RI_IDS dataset collected in the Nenjiang River (China) with on-shore camera imagery. It utilized the derivation of parameters such as ice concentration, area, and motion intensity to enable monitoring of river ice regimes and provide short-term warnings for ice floods. Ice concentration accuracy estimated with different semantic segmentation methods (FastScnn, MobileSeg, PPLiteSeg, PPMobileSeg) was about 98%.

Development of efficient methods for river ice classification and application of novel achievements from sea ice classification [171] may improve accuracy compared to conventional and deep learning classifiers by up to 15% for satellite SAR and multispectral data.

4.3. Reporting and Product Dissemination

Current technologies for river ice product visualization, analysis, and dissemination include the following:

1. Generation of output products in mapping formats (compatible with Geographic Information Systems (GIS) software, such as ESRI shapefiles, GeoTIFFs, KML/KMZ files), and in data formats (such as CSV, JSON, Excel) for sharing and integration with other software tools, supporting statistical analysis and visualization.
2. Database storage allowing for easy access, retrieval, and querying, facilitating further analytics and data processing.
3. Web-based platforms or portals enabling users to access and interact with the data online, providing interactive maps, visualization tools, and download options.
4. Application Programming Interface (API) endpoints, which enable programmatically accessing and integrating river ice data into custom applications or systems, enhancing accessibility and interoperability.
5. Social media platforms and media coverage, which can provide real-time updates and raise awareness about river ice conditions.

6. Mobile applications, which can provide convenient access to river ice information, including alerts, maps, and crowd-sourced observations.
7. Email alerts and newsletters, which deliver updates on river ice conditions, forecasts, and advisories to subscribers.

Examples of ice maps (charts) from different sources compared to automated product-based U-Net deep learning techniques applied to near real-time VIIRS sensors onboard the NOAA-20 and NPP satellites are provided in [65].

4.4. River Ice Observations for Hydraulic Models

Hydraulic models for river ice [172] are used to simulate ice behavior and characteristics for a better understanding, forecast, and management of the river ice phenomena, flood risks and their impacts on infrastructure, activities, and the environment, as well as for climate research.

These models may incorporate data from various sources, including satellite, aerial, and in situ observations, to improve the accuracy and reliability of parameter extraction. Aerial or satellite data (e.g., RADARSAT-2) were used to initialize (provide the initial location and length of a jam) the River1D model for the Peace River in Canada [173]. Ice volume determined using MODIS satellite data was used as an input parameter for the RIVICE model [174] to simulate and explore ice jam formation in the Slave River Delta (Canada). A UAV was used [120] for collecting high-resolution images over the Aux Saumons River (Canada) to observe an ice jam and extract DEMs for calibrating and validating a 1D numerical ice jam model (HEC-RAS).

A global conceptual river ice model was developed [5] to predict six ice cover types (ice shells, suspended ice cover, surface floating ice cover, surface-confined ice cover, solid ice, and no ice) and to identify five ice processes (active frazil ice and anchor ice, hanging dams, ice dams, aufeis, and ice jams) potentially affecting cold region channels. The classification of channel morphology, plan-view patterns, and sizes can be performed visually (e.g., using aerial or satellite images). The model can assist in determining the potential impacts of specific ice cover types and processes on hydraulics, hydrology, and infrastructure.

The study by Turcotte [175] provided observations on river ice formation along 300 km of the Yukon River to understand the potential cause of the change in freeze-up dynamics. This was completed by introducing an empirical freeze-up model.

4.5. Existing Operational River Ice Monitoring Services

Existing operational river ice monitoring services are provided through governmental agencies, research institutions, and private companies, which deploy a range of observational technologies such as satellite imagery, aerial surveys, in situ sensors, and visual observations as well as numerical models to monitor and forecast river ice processes. These services provide information to support various sectors including transportation, water resource management, energy production, and public safety, aiding in decision-making and mitigating risks associated with river ice and flood hazards.

4.5.1. Canada

In Canada, multiple organizations conduct research and provide expertise and services on river ice monitoring. The INRS (Institut National de la Recherche Scientifique) contributes to the understanding of river ice dynamics through its research initiatives. An example of such efforts is the development of the FRAZIL GIS-based system, aimed at providing specific physical attributes of river channels and facilitating data preparation for hydraulic flood routing [176]. Tailored for winter conditions, this system incorporates tools to extract information on ice cover from satellite radar images, which can subsequently be integrated into modeling processes. The SAR-based ice mapping technology [177] produced weekly maps during the freeze-up and break-up seasons and distributed results through the Web.

At the University of Saskatchewan, research on river ice is focused on understanding and addressing the complexities of ice processes in river environments involving interdisciplinary studies that span various facets of river ice dynamics, hydrology, and climate change impacts. Through field observations, laboratory experiments, and numerical modeling, they study the mechanisms governing the formation, movement, and evolution of river ice in practical implications for managing water resources, mitigating flood risks, and sustaining ecosystems. An example of this research is the development of an integrated and automated approach, utilizing data from both active and passive remote sensors [50]. This approach was applied to characterize river ice processes along the Slave River, Northwest Territories, Canada. The analysis of the MODIS Band 2 time series revealed the capability to detect the dates of river ice freeze onset and water clear of ice with deviations of up to 12 days and 3 days, respectively, while RADARSAT-2 imagery successfully characterized and mapped intact ice, smooth rubble ice, rough rubble ice, and open water during the break-up period. Several other Canadian universities are also actively engaged in river ice research. The Université Laval (Quebec City) has a long history and notable achievements in studying river ice processes (https://centreau.org/ (accessed on 5 April 2024)). The University of Alberta conducts research on river ice hydraulics and morphology, contributing to advancements in ice monitoring and prediction (https://www.riverice.ca/ (accessed on 5 April 2024)).

Additionally, organizations like BC Hydro are actively involved in managing ice-related risks associated with hydropower operations in British Columbia, employing various technologies and strategies to ensure the safety and reliability of power generation.

C-CORE's operational experience in satellite-based river ice mapping has been ongoing since 2003 [74,178,179] and provides advance warning of flooding for several rivers across Canada [180]. This service has been provided to several provincial and territorial water resource departments and emergency measurement organizations in Canada and internationally. SAR image analysis results are provided in three products: ice cover, ice classification, and ice cover changes. There are three ice classes during freeze-up and mid-winter monitoring: open water, non-consolidated ice, and consolidated ice. For break-up, the three classes are augmented by a fourth class: water on ice [181]. The primary data sources include the RCM and Sentinel-1 (S1) SAR imagery. Imaging modes include S1 Interferometric Wide Swath (IW) and RCM 16M, 30M, and 50M. Cloud-free, optical imagery from Landsat 8/9, Sentinel-2 and Planet are used to aid in the interpretation of ice conditions. The data products are delivered through IceSight (https://www.churchillriver.app/ (accessed on 5 April 2024)), C-CORE's web-based platform, which offers additional analytics and facilitates inter- and intra-annual comparisons.

In addition, C-CORE integrates in situ devices and collects aerial ice-penetrating radar data to measure ice thickness [182]. Work has focused on automating and operationalizing the analysis process and, more recently, developing a scientific basis to help decide when ice roads built on rivers, lakes, and river crossings are no longer safe for crossing. Since 2019, the Sea Ice Mass Balance Array (SIMBA) buoys have been adapted for deployment on the river [183]. The SIMBA buoys measure and transmit, via Iridium, an ice temperature profile from which ice thickness can be derived. The buoys are deployed at key locations on the river once the ice is thick enough to safely support installation. Manual ice thickness measurements are acquired opportunistically to validate the ice thickness measurements. C-CORE's satellite-based river ice monitoring service further supports river ice modeling and flood forecasting [184,185].

Canadian provincial governments (e.g., New Brunswick and Newfoundland and Labrador (https://www.gov.nl.ca/ecc/waterres/flooding/lc-flood-warning/ (accessed on 5 April 2024))) cooperate with various organizations to implement comprehensive monitoring programs to assess ice conditions, predict and mitigate ice-related hazards, and ensure public safety. In British Columbia, river ice services are overseen by the River Forecast Centre, ensuring real-time updates on ice conditions and flood preparedness resources, and producing bulletins, maps, and warnings to inform emergency managers and the public about current and upcoming streamflow conditions. The Alberta River Forecast Centre provides information and forecasts on river ice conditions. The Alberta Government offers river ice services (https://rivers.alberta.ca/ (accessed on 5 April 2024)), providing access to observation reports and photos. In Saskatchewan, the Water Security Agency (WSA) (https://www.wsask.ca/ (accessed on 5 April 2024)) coordinates river ice services, as well as the monitoring and forecast of ice jams and spring runoff.

In order to mitigate ice jam-induced flood risks, the Natural Resources Canada (NRCan) Emergency Geomatics Service (EGS) may be activated by Canada's emergency management authorities. Evaluation of RADARSAT-2 multi-polarimetric data and parameters [186] demonstrated the potential for improvement in river and lake ice mapping based on unsupervised classification. As new satellite imagery (RADARSAT-2 and RCM) becomes available, NRCan will produce river ice roughness maps and update the dataset in near real-time (within 4 h) (https://open.canada.ca/data/en/dataset/7b210c58-2fc7-47c5-8b8a-2605c77d725c (accessed on 5 April 2024)). This ice cover condition map discriminates between 'water' and two ice cover conditions classes labeled as 'sheet ice' and 'rubble ice'. Each of the ice classes contains three sub-classes [187]. Sheet ice covers are characterized by smooth textures, whereas rubble ice covers have rough textures. Because ice jams are formed of rubble ice with rough to very rough textures, potential ice jams are expected to be represented in the ice products. Spatial resolution varies depending on the source imagery between 5 m and 16 m pixel size. It can be noted that pixel size and resolution can be different for SAR due to oversampling. Van der Sanden, Drouin, and Geldsetzer [95] described the algorithm and C-band HH backscatter intensity distributions for rubble ice, sheet ice, and water.

4.5.2. European Products

The Copernicus Land Monitoring Service (CLMS) provides River and Lake Ice Extent (RLIE) products for the entire European Economic Area (EEA) zone, shown in Figure 1 (covering 39 countries including the UK) (https://collections.sentinel-hub.com/hrsi-rlie-s1/ (accessed on 5 April 2024)). The RLIE S1 product, based on the revisit time of the Sentinel-1, provides the river and lake area (ice and open water rasters) covered by snow or snow-free ice with a spatial resolution of 20 m $\times$ 20 m, and it is released in near-real time (within 6–12 h after image acquisition). RLIE S1 is generated with the ICE algorithm [188,189], which detects ice/snow extent using inland waters based on the threshold of backscatter in VV and VH polarization images. The overall classification accuracy of the ICE algorithm is 76.7% against in situ data and 74.9% against classified EO/IR Sentinel-2 images.

The RLIE S2 product (20 m resolution) is based on Sentinel-2 data. The ICE algorithm classifies the multiband image with 10 flat surface reflectance bands and the four spectral indices (normalized difference water index (NDWI2), (NDSI) normalized difference snow index, (NDVI) normalized difference vegetation index, and (BSI) bare soil index) into the following classes: snow, ice, water, vegetation, and soil [190]. According to the quality assessment against in situ data, the ICE algorithm provides Sentinel-2 classification results over the expected 85% accuracy level. However, the comparison with six very high-resolution images demonstrated the estimated overall accuracy of 96%.

The Copernicus Aggregated River and Lake Ice Extent (ARLIE) product is enriched every day based on the revisit time of the Sentinel-1 and Sentinel-2 satellites. It provides percent coverage of snow-covered or snow-free ice on lakes and on 10 km river sections described by the EU-HYDRO river and lake network database. The RILE and ARILE products can be viewed via the EO Browser platform (apps.sentinel-hub.com (accessed on 5 April 2024)) or downloaded from the geodatabase using REST API.

4.5.3. USA

The National Weather Service monitors the rivers and streams and issues ice statements and flood potential outlooks on a periodic basis (https://www.weather.gov/phi/ice (accessed on 5 April 2024)). The statements, reports, and flooding warnings can be viewed via an interactive map of the Web Portal. The Alaska-Pacific River Forecast Center shows the web map with the break-up status of major rivers in Alaska (https://www.weather.gov/aprfc/ (accessed on 5 April 2024)). The automated, multi-source remote sensing system recently demonstrated [191] near real-time capabilities for the monitoring of river ice, relying on satellite observations and citizen science data collected via the GLOBE Observer platform (https://observer.globe.gov/ (accessed on 5 April 2024)). Its integration using Google Earth Engine, cloud computing, and deep learning technologies has shown its effectiveness in capturing the spatial and temporal evolution of snow and ice conditions in challenging regions of Alaska.

4.5.4. International Projects

The Arctic Great Rivers Observatory project (https://arcticgreatrivers.org/publications/ (accessed on 5 April 2024)) offers freely accessible datasets on biogeochemistry, water quality, and discharge for the largest Arctic rivers, including Ob, Yenisey, Lena, Kolyma, Yukon, Mackenzie, Mezen, Northern Dvina, Onega, Pechora, Nadym, Yana, Indigirka, Olenek, and Pur rivers. Figure 1 (top) highlights these rivers with thicker lines.

The Polar Prediction Project (PPP) (2013–2022) initiated by the WMO helped promote cooperative international research to develop improved weather and environmental prediction services and operational support for the polar regions, covering user needs in forecasting and access to weather, water, ice, and climate information services. This included addressing specific challenges related to river ice formation and break-up processes [192]. In addition to the North American and European participating organizations, the river ice hydrological services from the National Marine Environmental Forecasting Center (China), and the Federal Service for Hydrometeorology and Environmental Monitoring (Russian Federation) contributed to the PPP by bringing in their expertise and capabilities in hydrological and environmental forecasting (https://www.polarprediction.net/services/operational-support/ (accessed on 5 April 2024)).

Beginning in 2005, satellite-based river ice monitoring services were implemented for rivers in Canada, the United States, and Russia by Polar View, an international consortium of companies, research organizations, and government agencies funded under the European Space Agency's Global Monitoring for Environment and Security (GMES) Services Element (GSE). Rather than research, it was the focus of these efforts to build operational services based on available technologies and current science output. This required the close collaboration of service providers and end users in a flexible and agile development environment. River ice monitoring services pioneered under Polar View continue to be delivered across Canada [179].

5. Discussion

Various observation technologies relying on satellite, airborne, and ground-based data and numerical modeling offer a comprehensive approach to monitoring and understanding river ice processes. Satellite technology has experienced significant advancements, leading to increased utilization and effectiveness in the field of river ice observation due to improved spatial and temporal resolution, enhanced data processing techniques, global coverage, and free access to many satellite data sources and long-term archives (e.g., Landsat since 1972). The trend of the increasing number of publications on UAV usage and decreasing publications on airplane-based observations for river ice monitoring can be attributed to several factors, including cost-effectiveness, advancements in instrument technology, flexibility, maneuverability, and ease of UAV use. As the technology continues to evolve and so do regulatory frameworks (to make it easier to fly beyond the line of sight), we can expect to see the further expansion of UAV-based applications in river ice observations. In situ river ice observation methods employ cutting-edge technologies such as underwater acoustic and buoy sensors, facilitating real-time access to data on ice thickness.

5.1. Gaps

Our review revealed several technology gaps in river ice observation. A systematic analysis of current advancements in the river ice observation field considered all possible sensors, platforms, and their combinations (Table 1). This approach helped generate new ideas for river ice observation, including the use of LIDAR, radars, gravimetry, and GNSS-IR, from various platforms, as indicated by the yellow cells in Table 1. There is a lack of records on the utilization of hyperspectral imaging technology (e.g., PRISMA), which could provide information on the spectral characteristics of river ice and improve river ice type classification and condition assessment. The Surface Water and Ocean Topography (SWOT) mission, despite its potential to enhance understanding of river flow, has not been investigated for studying floods and river ice. There has been no application of single-pass (SP) InSAR technology using TanDEM-X data for river ice observation. SP InSAR has the capability to provide high-resolution measurements of ice thickness and characterize ice deformation features [193], which could greatly benefit river ice monitoring efforts. The usage of LIDAR was not described in the literature, but it could potentially be helpful to characterize river ice topography and identify ice features (e.g., floes, jams). There is a notable need for further research on the application of artificial intelligence (AI) and wider use of deep learning (DL) techniques in river ice observation and forecasting. Furthermore, there is a lack of integration of Internet of Things (IoT) devices enhanced with edge-computing performance for real-time monitoring of river ice conditions, which could improve the spatial and temporal coverage of observations, leading to a better understanding of ice dynamics and conditions and enhanced early warning systems for ice-related hazards. The gap in effectively assimilating observational data into numerical models to improve the accuracy of river ice predictions requires interdisciplinary collaboration and efforts between observational and modeling frameworks.

Addressing these gaps is basic for advancing our understanding of river ice processes and improving our ability to mitigate risks associated with river ice hazards.

5.2. Challenges

The low accuracy of some automated techniques, machine learning (ML), and deep learning (DL) algorithms poses a significant challenge to the quality of river ice information. While these technologies offer great potential for automating data analysis processes and extracting valuable information from large datasets, they often struggle to achieve the required level of accuracy and reliability. This can be attributed to various factors, such as the complexity of ice features, variations in environmental conditions, and the limited availability of high-quality training and validation data. Accurate river ice information derived from observations with low uncertainty provides valuable input data for numerical models and forecasting systems for the prediction of river ice formation, thickness, movement, and break-up and jamming forecast. Additionally, integrating complementary methods and expertise from different domains, such as remote sensing, hydrology, and computer science, can help address these challenges and enhance the accuracy and effectiveness of river ice observation techniques.

5.3. Future Directions and Opportunities

In order to maximize the utility of river ice information derived from remote sensing technologies for practitioners, several recommendations can be made. There is a need for efficient data processing and analysis techniques to ensure consistency of results and comparability across different datasets. This includes the development of automated algorithms for ice characterization with high confidence (>95% accuracy), which could process and extract relevant information from remote sensing imagery.

In addition, practitioners can benefit from incorporating new sensor technologies and their fusion to enhance river ice observation. Advancements and innovations in sensor and platform technology promise to offer enhanced capabilities for capturing detailed ice characteristics and processes. Emerging satellite constellations, such as hyperspectral (e.g., Dragonette) and Very High Resolution (VHR) SAR (e.g., Cappela, IceEye), can provide detailed, frequent, and timely inputs in operational ice-monitoring practices. The hyperspectral characteristics of river ice could enable a more accurate classification of ice types and the assessment of ice conditions. On the other hand, VHR SAR satellites will offer enhanced spatial resolution, allowing for the detection of smaller-scale ice features, as well as estimates of ice thickness and movement.

New concepts, such as the IoT, present opportunities for deploying sensor networks along riverbanks or bridges to collect real-time data on ice conditions. These IoT devices can complement satellite observations and provide continuous monitoring capabilities, enhancing the spatial and temporal resolution of river ice monitoring systems. Furthermore, practitioners should consider the integration of EO-derived information with ground-based observations and hydrological models. This can enhance the accuracy and reliability of river ice monitoring systems, providing a comprehensive understanding of ice dynamics and associated hazards. Crowd monitoring for river ice involves harnessing the collective efforts of individuals and remote communities to observe and report on ice conditions in rivers. This approach takes advantage of citizen science initiatives, community engagement, and crowdsourcing platforms to gather real-time data on river ice, thereby contributing to improved safety and resilience in cold regions.

Edge computing for river ice involves deploying computational resources closer to the source of data collection (e.g., cameras). It can enable real-time processing and analysis of data related to river ice dynamics, thickness, and movement. By accessing real-time high-quality data, the users can cross-validate and enhance their confidence in satellite-derived products and refine algorithms used for analysing river ice processes. Edge computing can potentially facilitate the rapid generation of actionable river ice information for timely decision-making and response to changing ice conditions.

Advancements in big data analytics enable the processing, interpretation, and dissemination of large volumes of EO data, facilitating real-time monitoring and predictive modeling. Artificial intelligence (AI) algorithms can also be leveraged to automate the analysis of satellite imagery and in situ sensors to identify patterns or anomalies indicative of ice cover change and dynamics.

6. Conclusions

Our paper provides a systematic review of the literature on river ice observation and analysis technologies. By analysing 200 publications from 1919 to June 2024, we have evaluated the utility of various in situ, aerial, and satellite platforms in monitoring and characterizing river ice covers. The study holds the significant value of river ice information in enhancing infrastructure resilience against climate change.

Our review highlights the advantages of satellite technologies, such as EO/IR, SAR, and other systems, allowing river ice characterization and reliably delineating open water and ice boundaries. These technologies, supported by both current and forthcoming sensors, offer benefits for river ice monitoring.

The paper also discusses various data analysis methods for river ice observation, including retrieval techniques and their accuracies. We recognize the growing importance of artificial intelligence, especially DL techniques, in enhancing the precision of automated systems for river ice analysis. The increasing availability of high-quality satellites, UAVs, and in situ data signals a promising future for operational river ice observation.

Additionally, we identify gaps in current capabilities and provide recommendations for improving data analysis and interpretation. This includes integrating the latest technological advancements and addressing limitations in existing methodologies.

To improve clarity, we have included several visual elements in the review, such as tables and figures, which provide a comprehensive overview of different sensor and platform combinations, areas of interest, and methodological approaches. These visual aids are intended to enhance the understanding of our research methodologies and findings.

Our analysis of river ice observation technologies also presents novel contributions to the field and identifies potential ideas for future work. We have summarized the advancements in sensor technologies and their applications, providing a detailed account of the methods, validations, and practical importance of river ice information. This comprehensive review can serve as a practical resource for advancing river ice observation and addressing the challenges posed by climate change.

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Data Availability Statement: River and lakes centerlines dataset from Natural Earth (used to plot Figure 1) are freely available at https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-rivers-lake-centerlines (accessed on 1 August 2024)). Monthly reanalysis maps from the EMCWF can be freely accessed at https://climatereanalyzer.org/research_tools/monthly_maps (accessed on 1 August 2024).

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Appendix A. River Ice Terms Representing the Observed River Ice Information

The following river ice terms representing the observed river ice information, including ice types/classes, features, characteristics, and processes, were identified in our literature review. The majority of river ice terminology definitions can be found in [33]. However, if a specific term is absent from IAHR's river ice terminology, its definition is provided from the referenced source.

1. **Agglomerate ice** [194]
2. **Agglomerated skim ice** (ASI) is more packed than juxtaposed skim ice and therefore has higher SAR backscatter [90]
3. **Anchor ice** [163]
4. **Aufeis** is a deposit of ice on the surface of the ground or exposed structures, produced by the freezing of periodically flowing water [32]
5. **Black ice** [70]
6. **Break-up** (e.g., [52,59])
7. **Border ice** [73,75,81]
8. **Brash ice** [9]
9. **Broken ice** [71]
10. **Candled ice** [195,196]
11. **Columnar ice** [81,82,197]
12. **Congestion** is stagnation of the ice cover at choking locations [175]
13. **Consolidated ice** [70,72,73,75,81]
14. **Clear ice** is a smooth ice sheet, appears in gray tone in SAR image [71]
15. **Crack** [71]
16. **Frazil ice** in different forms (slush, clusters/flocks, pans/pancake, hanging dam) [32,195,196]
17. **Frazil floes** [9]
18. **Frazil pans** [72,75]
19. **Frazil run** [90]
20. **Hanging dams** are made of frazil ice transported under an existing surface ice cover and depositing under the ice surface in slow-flowing locations (e.g., [198])

21. **Ice bridging** [81]
22. **Ice concentration** [65]
23. **Ice decay** is the changes in ice-covered areas with melt onset and start of break-up [83]
24. **Ice extent** (spatial) is the area (in km^2) of river ice [62]
25. **Ice floes** [81]
26. **Ice flow choking points** are locations with 100% ice concentration at the water surface [175]
27. **Ice-free** [53]
28. **Ice front** is defined by two criteria: (i) the ice front is the boundary between partial and complete ice coverage; and (ii) the frazil pans and floes must be static [72]
29. **Ice heap**: agglomeration of broken ice up to 10 m thick [131]
30. **Ice velocity** is dividing the measured displacements to the time difference [57]
31. **Icing shell** [5] forms horizontally, close to the water surface, and develop from waves that repeatedly flood cold surfaces (observed along the banks of turbulent channel segments such as rapids or riffles)
32. **Intact ice** is ice with a relatively smooth surface [79,110]
33. **Intraseasonal cycle** from ice onset to ice break-up and total melting [58] (i.e., duration of ice cover including time of ice clearing)
34. **Jam** [79], including break-up jam and freeze-up jam [199,200]
35. **Juxtaposed ice** is formed when ice floes gradually thicken and adhere to each other [70]; its rough ice–water interface and a coarse ice structure cause the medium to moderately strong SAR backscatter
36. **Mixed ice/water** is the ice cover condition after beginning of break-up until open water. It was defined based on the reflectance (values 0.1–0.5) of MODIS Band 2 [45]
37. **Navigation track** is an ice opening for ship navigation pathway, may contain brash ice [71]
38. **New ice** is ice which was recently formed [71]
39. **Phenology** is the duration of ice period and time of its appearance, accumulation, and disappearance for a certain river reach [64]
40. **Ridge** [71]
41. **Rubble ice** is resulted from mechanical break-ups and it has a rough top surface (texture) [95]
42. **Rough ice** [71]
43. **Sail height** serves as a measure of the surface roughness of the ice cover, determined from the thermal ice surface up the average tops of larger protruding ice pieces of ice by visually lining them up with the horizon [75]
44. **Shore ice** [72] composed of frazil slush, melting ice, and brash [9], shore-fast frazil ice [73]
45. **Skim ice** [3,4,84]
46. **Smooth ice cover** is represented by consolidated frazil or columnar (thermal) ice [77,95]
47. **Snow ice**, also known mainly as white ice [198], is always formed on an established ice cover from an overlying snow cover saturated with rain or river water infiltration that has refrozen subsequently (has small and granular crystals) [81,197]
48. **Spray ice** is made by water splashing and freezing and it is generally observed close to waterfalls, cascades, or steps [5]
49. **Thermal ice** is formed mainly near the shore, where water is slow moving. Thermal ice crystals are large and display a tubular form [70]
50. **Thickness of ice cover** is the distance between the air–ice (or snow–ice) and ice–water interfaces [85]
51. **White ice** [53].

In addition to these ice-related items, classification and mapping products often include the **open water** class. Also, certain technologies provide classes with vegetation, soil, snow, and other environmental variables as well as infrastructure present along the rivers.

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