



Changes in river ice cover in the context of climate change and dam impacts: a review

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Abstract

This article presents a review of previous studies on the impacts of climate change and the operation of dam reservoirs on the characteristics of river ice cover. Based on a review of the existing literature, the spatial and temporal variability of trends in individual river ice cover conditions and their relationship to both climate change and the operation of dam reservoirs is explored. From this analysis, climate change is identified as the main determinant of the river ice cover disturbances observed since the start of the twentieth century. The study found that in the twentieth century, climate change contributed to a decrease in the duration of ice cover on rivers. The shortening of ice cover duration occurs primarily through earlier breakup rather than later formation. The trends in ice cover freeze-up and breakup are less spatially variable across Eurasia than in North America. The analysis indicates that dam reservoirs can exert a significant control on the spatiotemporal distribution of ice cover occurrence on rivers, even on a global scale. The first quantitative estimate of the number of dam reservoirs in river ice cover areas was also presented based on climatological and reservoir location data. The obtained results highlight the need to research river ice cover changes based on remote sensing data; such studies will make it possible to recognize the temporal-spatial distribution of trends in river ice cover parameters and the strength and extent of the influence of dam reservoirs.

Keywords River ice cover · River ice phenomena · Climate change · Global warming · Dam reservoirs · Earth river systems

Introduction

Ice cover is a phenomenon observed on more than half of Earth's rivers (Fig. 1; Bennett and Prowse 2010; Yang et al. 2020). As defined by the International Association for Hydraulic Research, ice cover is "a significant expanse of ice of any possible form on the surface of a body of water" (IAHR 1980). It is estimated that river ice periodically occupies an area of around 120,000 km² and a volume of up to 140 km³ (Brooks et al. 2013). Its freeze-up and breakup is closely linked to the timing of the 0 °C isotherm (Fig. 1; Bennett and Prowse 2010).

Ice cover occurrence exerts a major impact on the course of hydrological and geomorphological processes within rivers and their channels (Prowse 2001; Thellman et al. 2021). Ice covers change the velocity and dynamics of water flow

by physically altering the cross-section of the riverbed (as part of the cross-section is taken up by ice) and increasing turbulent water flow (Thellman et al. 2021). In extreme temperatures, small rivers and streams can freeze completely (Prowse 2001). The presence of ice also reduces the amount of solar radiation reaching the water (Thellman et al. 2021). This effect is controlled by the thickness and type of ice and can reduce the solar radiation input to the water by up to 95% when there is fresh snow on the ice (Prowse 2001). Changes in light availability directly affect the river's thermal characteristics, causing a decrease in the water temperature under the ice (Beltaos and Burrell 2006). The presence of ice also controls the oxygenation of river waters by blocking gas exchange between the water and the atmosphere (Prowse 2001). This effect is particularly important in areas with persistent ice cover during several months of the year.

Ice cover-induced changes in water flow patterns within the channel affect the river's ability to transport suspended and trailing material. Studies have shown that ice-covered rivers have lower transport capacity compared to rivers without ice cover due to the fact that ice affects flow dynamics (Sayre and Song 1979; Knack and Shen 2018). Ice cover also

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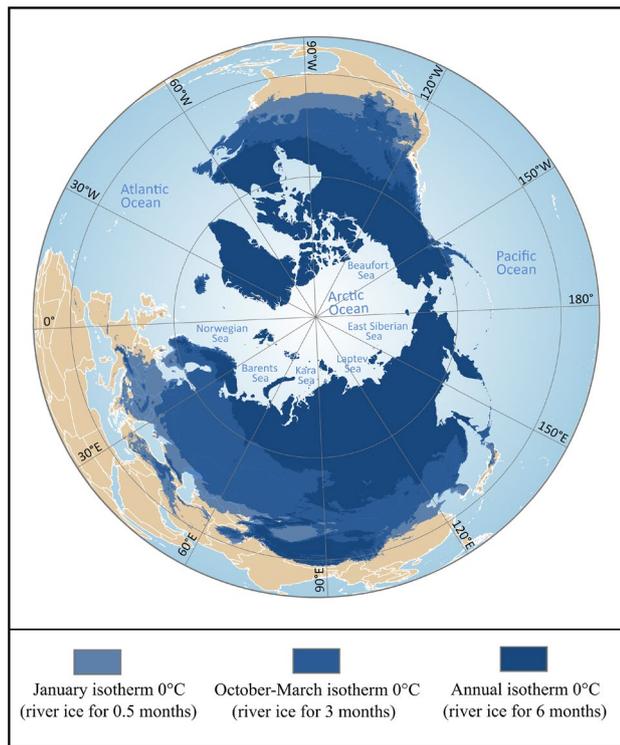


Fig. 1 Extent of periodic ice cover on Earth's rivers (determined from 0 °C isotherms for the period 1970–2000, developed from the methodology presented by Bennett and Proxse 2010)

plays an important role in erosion and deposition processes: some studies have shown that mobile ice from ice cover breakup significantly increases lateral erosion in the river channel (Martinson 1980; Chassiot et al. 2020).

The occurrence of river ice cover also affects biotic elements of the surrounding natural environment. Most previous studies have investigated the impacts of river ice on fish habitats (e.g., Bodensteiner and Lewis 1992; Cunjak 1996; Cunjak et al. 1998; Huusko et al. 2007; Heggenes et al. 2018; Andrews et al. 2019). The presence of ice is an important factor influencing fish winter habitat choices (Cunjak et al. 1998; Huusko et al. 2007). Extensive ice within the channel can also affect food availability by reducing the ability of organisms to migrate (Thellman et al. 2021). The presence of ice within the channel is also important for invertebrates; for example, as identified by Bogatov and Astakhov (2011), the presence of ice affects the migration of mayfly nymphs (Ephemeroptera).

In the last 30 years, ice cover duration on rivers has declined globally (Newton and Mullan 2020; Yang et al. 2020). On many of the world's rivers, later freeze-up and earlier breakup are recorded, which translate to shorter ice cover duration (Janowicz 2010; Helama et al. 2013; Shiklomanov and Lammers 2014; Takács and Kern 2015; Ionita et al. 2018; Rokaya et al. 2019; Newton and Mullan 2020;

Yang et al. 2020). In addition, a decrease in ice cover thickness has been observed (Vuglinsky 2017; Vuglinsky and Valatin 2018; Nalbant and Sharma 2022). The vast majority of the cited studies highlight global warming as the main reason for the observed changes in the ice regime of rivers. In some studies, temporal and spatial changes in river ice formation are explained solely by the climate factor, while other potential factors are ignored. This approach seems wrong given that the freeze-up process is complex and influenced by many factors in addition to climatic and meteorological conditions. These factors include the riverbed morphology, the volume and pattern of water flow, water supply mechanism, the presence of vegetation around the riverbed, the land cover around the river, thermal pollution, and the presence of hydraulic structures. While climatic factors may exert the strongest control on ice cover formation on large rivers, other factors may also play an essential role on medium and small rivers. As the majority of studies on ice cover formation disturbance to date have focused on large lowland rivers, the factors controlling ice cover formation on medium and small rivers are not fully understood (Thellman et al. 2021).

An additional element that can specifically affect ice cover formation is the presence of reservoirs. The operation of these facilities alters the natural thermal regime of the river downstream of the dam by releasing bottom water (warmer in winter) from the reservoir (Olden and Naiman 2010; Kędra and Wiejaczka 2016; Maheu et al. 2016). Reservoirs also reshape the flow hydrograph of rivers downstream, which can affect the freezing and breakup process of the ice cover, act as a barrier to mobile ice from higher in the catchment, and reduce the amount of suspended sediment in the water which can be a source of nucleating particles (Tuthill 1999; Takács and Kern 2015). Consequently, dam reservoirs limit the occurrence of ice cover on the rivers below their location.

Currently, there is a lack of studies in the existing literature on the impact of reservoir operations on the formation of ice cover on rivers. The available studies usually deal with specific cases; thus, it is difficult to draw globally applicable conclusions from them. Therefore, the impact of the construction and operation of dam reservoirs on the occurrence of river ice cover at a global scale is currently not recognized.

Given these research gaps, this study reviews research regarding the impact of (i) observed climate change and (ii) the construction and operation of dam reservoirs on the occurrence of ice cover on Earth's rivers. The paper is limited to the analysis of the impact of dam reservoirs and climate change on ice cover parameters such as freeze-up, onset of breakup, duration, and thickness of the ice cover. The review mainly considered papers that analyzed the variability in these parameters based on long (> 1 year)

measurement series. Despite the extensive number of papers cited, it is not possible to cover all aspects of the impact of dam reservoirs and climate change on river ice cover in a paper of this type. The paper lists articles where the reader can find detailed information on particular aspects of ice cover research. The results obtained were critically analyzed, and on this basis, limitations in the current understanding of the processes guiding the freeze-up, breakup, and duration of river ice cover were identified, and corresponding areas for future research were proposed.

Data and methods

The literature review in this study was based on online databases of scientific papers: Web of Science, Scopus, and Google Scholar. In the first stage of the literature review, an index of titles and abstracts of scientific articles was obtained, with studies on the impact of climate change and the operation of dam reservoirs on the occurrence of ice cover on rivers compiled separately. In terms of the impact of climate change, the database was searched using the following keywords: *river ice*, *river ice cover*, *river ice phenology*, *frazil ice*, *ice floe*, *river ice breakup*, *river ice freeze-up*, *river ice duration*, *river ice processes*, *climate change*, and *global warming*. In terms of the impact of dam reservoir operations on river ice cover, the database was searched using the following keywords: *dam reservoir*, *river ice cover*, *river ice hydropower plant*, *ice in regulated rivers*, *flow control river ice*, *river ice phenology*, and *river water temperature*. In addition, databases were searched for the use of remote sensing data in river ice cover studies. Articles were searched based the following keywords: *river ice*, *remote sensing*, *SAR*, *radar*, *optical*, *multispectral*, *Landsat*, *Sentinel*, *Radarsat*, *TerraSAR-X*.

In the second stage, the resulting article databases were manually filtered. This step involved rejecting all papers that

- (a) were not thematically related to the impact of climate change, or the operation of dam reservoirs on river ice cover, and
- (b) were in a language other than English.

The two article databases were reduced based on the titles and abstracts of papers. The research in the resulting filtered databases was then reviewed, the results of which are described in the third and fourth sections. On the basis of the data extracted from the articles, such characteristics as timing of freeze-up and the onset of breakup, duration, thickness, and volume of the ice cover in the study areas were collected.

In the next stage, the number and spatial occurrence of dam reservoirs in areas of periodic ice cover on rivers were

analyzed. Dam reservoir locations were obtained from the GeoDAR [Georeferenced global Dams And Reservoirs] database, which is currently the most complete database of its kind, containing details of the locations of 24,783 dam reservoirs (Wang et al. 2022; Zenodo repository: <https://zenodo.org/record/6163413>). The main concept behind the creation of this database was to geolocate dams and reservoirs that are also included in the World Register of Dams (WDR) maintained by the International Commission on Large Dams (ICOLD). The WDR is a registry listing dams that are 15 m or taller from the lowest foundation to the top or dams between 5 and 15 m tall that retain more than 3 million cubic meters of water (ICOLD). The GeoDAR database contains around 40% of the records also listed in the WDR (the WDR contains more than 58,000 dams); however, these records correspond to 90% of the total reservoir area, catchment area, and capacity and therefore represent the most complete dataset on the location of large dam reservoirs (Wang et al. 2022). A detailed technical characterization of the GeoDAR database can be found in Wang et al. (2022).

Data concerning the exact construction dates of dam reservoirs were obtained from the GRanD database (Lehner et al. 2011; Zenodo repository: <https://zenodo.org/record/6163413>), which contains both location data and construction dates for dam reservoirs. To determine areas of periodic ice cover on rivers, data on the average temperature of individual months for the 1970–2000 period were used, derived from the WorldClim version 2.1 database (Fick and Hijmans 2017). This database provides high-resolution climatic and meteorological data for land areas on a global scale. In this database, the average air temperatures of multi-year months were determined by interpolating measurement data from 20,268 climatological stations onto a grid. The detailed technical specification of the database can be found in Fick and Hijmans (2017). The data were acquired as a raster grid with a resolution of 2.5'. The methodology developed by Bennett and Prowse (2010) was used to determine the areas in which ice cover periodically occurs on rivers. It was assumed that the occurrence of ice cover on rivers corresponds to trends of the 0 °C isotherm, and in areas where the average temperature of the period was less than 0 °C, there is a possibility of ice cover formation. These assumptions are consistent with the state of current knowledge and practices of modeling ice phenomena on rivers (Bennett and Prowse 2010; Yang et al. 2020). Thus, using data extracted from the WorldClim database, areas were determined in which the average air temperature for the 1970–2000 multi-year period was below 0 °C (database repository: <https://www.worldclim.org/data/worldclim21.html>). This analysis was performed for three distinct periods: January, the Northern Hemisphere winter period (October to March), and the average

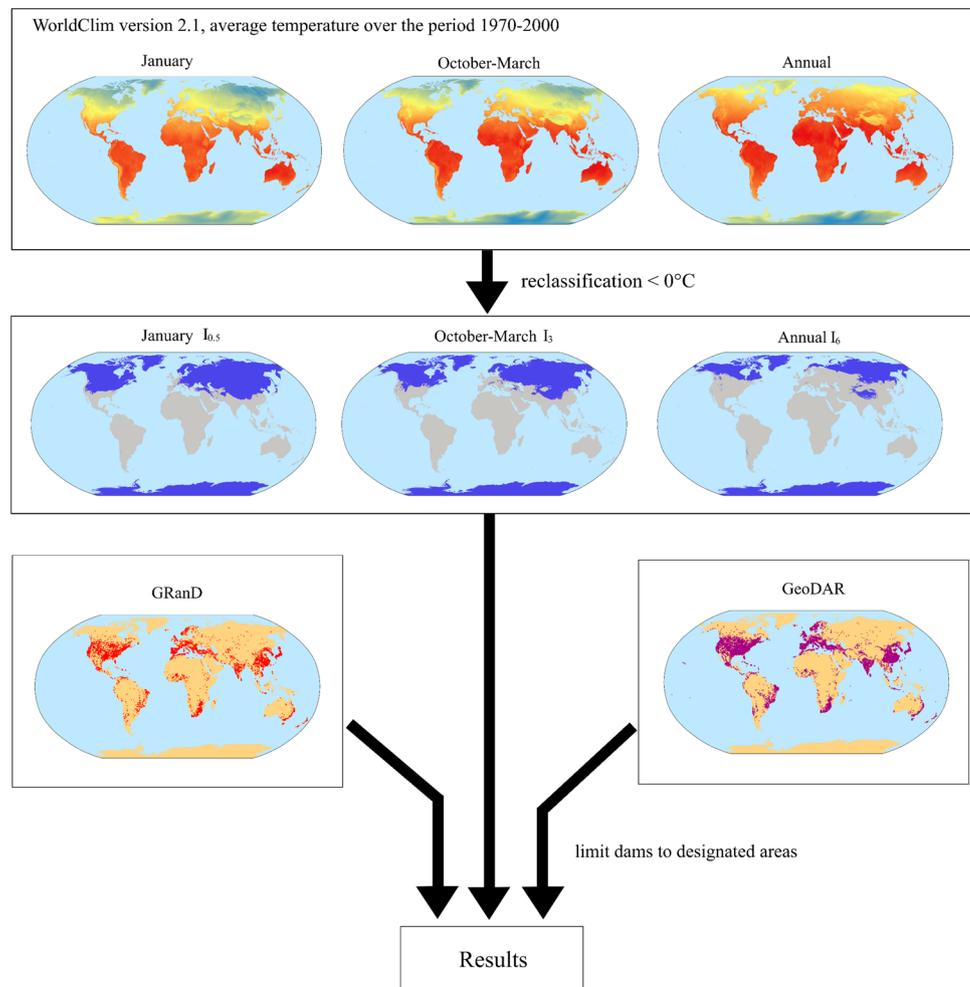
temperature for the entire year. Assuming an even temperature distribution during these periods, they can be assumed to correspond to 0.5-, 3- and 6-month periods, respectively, with temperatures below 0 °C. According to the nomenclature introduced by Bennett and Prowse (2010), the areas corresponding to these periods were assigned the designations $I_{0.5}$, I_3 , and I_6 , respectively. For each of these areas, the number of functioning dam reservoirs was determined based on the GeoDAR and GRanD databases (Fig. 2). Based on the obtained data, maps of the spatial distribution of reservoirs in the areas of ice cover occurrence were plotted, and statistics regarding their distribution were calculated. The resulting data allowed the spatial distribution of changes in river ice cover occurrence and the distribution of reservoirs to be compared. Additionally, as a specific example, 10-m near-infrared imagery from the Sentinel-2 L1C satellite was used to visualize the impact of the W.A.C. Bennet Dam and Williston Reservoir on ice cover occurrence on the Peace River.

The impact of climate change on river ice cover

The impact of climate change on ice cover occurrence on rivers worldwide is due to the natural relationship between heat fluxes and water temperature. The annual variation in air temperature is one of the primary factors affecting heat exchange conditions at the boundaries between water, ice, and the atmosphere, and consequently the heat balance of the water surface and ice (Shen 2010). Detailed descriptions of the physical processes leading to the thermal growth, persistence, and breakup of river ice can be found in the studies of Lal and Shen (1993), Prowse et al. (2007), Beltaos and Prowse (2008), Shen (2010), and Ashton (2011). Due to the interconnectedness of these environmental elements, the currently observed increase in global air temperature affects all riverine ice processes (Fox-Kemper et al. 2021; Shen 2016).

Over large areas of the northern part of North America (regional breakdown in the following description of air

Fig. 2 Analysis framework for the abundance and spatial distribution of dam reservoirs



temperature trends according to the Intergovernmental Panel on Climate Change (IPCC) atlas; Gutiérrez et al. 2021, accessed June 26, 2023), in the October to March period, a significant increase in mean air temperature ranging between 0.3 and 0.43 °C per decade was observed between 1980 and 2015, depending on the database used (Rohde et al. 2013; Harris et al. 2020; Gutiérrez et al. 2021; Morice et al. 2021; Thornton et al. 2021). Most of the available data suggest that the temperature increase over this period occurred more rapidly in the northeast part of North America compared to the northwestern part. Over the period 1980–2015, the trend was significantly weaker or statistically insignificant over central North America and along the west coast, including considerable parts of the Rocky Mountains. In the area of central, eastern, northern, and western Europe, in the October to March period, a significant increase in the mean air temperature ranging between 0.4 and 0.49 °C per decade was observed over the period 1980–2015, depending on the database used (Rohde et al. 2013; Harris et al. 2020; Gutiérrez et al. 2021; Morice et al. 2021; Cornes et al. 2018). The strongest trend was observed in the Fennoscandian Peninsula area. Within Asia, the strongest trend was observed in the Russian Arctic. Over the period 1980–2015, the increase in mean air temperature (October–March) ranged from 0.38 to 0.43 °C per decade depending on the database used. Significant trends were also recorded in central and eastern Asia and the Tibetan Plateau where the increase in mean air temperature over the same period was in the range of 0.27–0.39 °C depending on the database used (Rohde et al. 2013; Harris et al. 2020; Gutiérrez et al. 2021; Morice et al. 2021; Yatagai et al. 2023).

The relationship between variations in climatic parameters and the occurrence of ice cover on rivers has been studied extensively, particularly over the past 20 years. Magnuson et al. (2000) use data from a number of locations (rivers and lakes) to show that since 1850, ice breakup (on rivers and lakes) has been occurring later by about 0.6 days per decade, corresponding to an increase in mean air temperature of 0.12 °C per decade (Magnuson et al. 2000; Prowse and Bonsal 2004). Beltaos (2003) examined the Miramichi River in Canada and showed that the observed trend for earlier ice cover breakup is consistent with higher winter and early spring flows and increasing spring temperatures. Prowse et al. (2002), based on the analysis of the 0 °C spring isotherm, showed a significant relationship between its pattern and river ice cover breakup in Canada. Beltaos et al. (2006a, b) showed that mid-winter thaw plays an important role in ice regime changes, including the incidence of ice jams on the Peace River. In addition to local climate, large-scale climatic factors also influence river ice processes. Bieniek et al. (2011) showed that variations in the phases of the El Niño–Southern Oscillation (ENSO) influence ice breakup on Alaskan rivers. During the warm phase of

ENSO, there has been an increase in air temperature during spring in Alaska, causing an earlier breakup of the ice cover (Bieniek et al. 2011). Weyhenmeyer et al. (2011) showed that in the Northern Hemisphere, areas where the temperature only periodically drops below 0 °C are most susceptible to interannual changes in the timing of ice formation and disappearance. Significant results were presented by Lesack et al. (2014) showing that the observed earlier breakup of the Mackenzie River delta ice cover is attributable to increased air temperature during spring, but is not influenced by warmer winter and changes in river runoff, which may suggest a key role of spring temperature changes. The main characteristics of ice cover studied in the context of the effects of climate warming include its seasonal duration (usually described by the number of days with ice per year), the date of freeze-up, the date of breakup, and the thickness of the ice cover.

Ice timing trends

Freeze-up The term freeze-up generally refers to the formation of stable ice cover on the surface of a river (Shen 2016). The date of onset of freeze-up is related to the water reaching the freezing point, which depends on the heat flux at the water–air interface (Beltaos and Prowse 2008). Table 1 shows the results of studies on ice cover freeze-up trends on the world's rivers. The longest series of measurements dates to the first half of the nineteenth century (Rannie 1983; Magnuson et al. 2000; Ionita et al. 2018). Across North America, freeze-up trends are both temporally and spatially complex. On a local level, trends observed at individual water gauge stations indicate both later and earlier ice cover formation in the twentieth and twenty-first centuries. For example, trends indicating later freeze-up were observed in northwestern Canada (Yukon River), Atlantic coastal rivers in the state of Maine, USA, on the Red River in the province of Manitoba, Canada, and on the Canada's MacKenzie River, among others. In these areas, later ice cover formation was observed at rates between 0.61 and 3.2 days/decade (Rannie 1983; Magnuson et al. 2000; Dudley and Hodgkins 2002; Janowicz 2010). In contrast, earlier ice cover freeze-up trends have been recorded at stations across Canada, particularly on the west coast (Zhang et al. 2001). In the Athabasca River basin, earlier freeze-up of 0.5–5 days per decade has been reported (Rokaya et al. 2019).

Based on data from 41 water gauge stations across Canada for the period 1950–1998, Lacroix et al. (2005) noted 15 stations at which ice cover formed earlier and 22 stations at which formation occurred later. Taking the entire Canadian area into account, ice cover formation was estimated to occur on average 0.3 days later per decade (Lacroix et al. 2005). Spatial heterogeneity in freeze-up trends across North America was confirmed by modeling results (Park et al. 2016).

Table 1 Summary of trends in freeze-up timing. The table shows studies based on long measurement series (> 1 year)

Reference	Investigation period	Region	Main findings
Magnuson et al. (2000)	1846–1995	North America, Asia	Later freeze-up on the Mackenzie (0.61 days/decade), Red (1.32 days/decade), and Angara (0.85 days/decade) rivers
Rannie (1983)	1798–1981	North America, Canada	Later freeze-up on the Red River (1.2 days/decade)
Zhang et al. (2001)	1947–1996	North America, Canada	Later freeze-up across Canada
Burn and Elnur (2001)	1960–1997	North America, Canada	Mixed trends, earlier freeze-up at 14 out of 73 gauge stations
Lacroix et al. (2005)	1950–1998	North America, Canada	Mixed freeze-up trends (average 0.3 days/decade later)
Janowicz (2010)	1986–2009*	North America, East Canada	Later freeze-up, approximately 3.2 days/decade
Park et al. (2016)	1979–2009	North America, Asia, Arctic	Later freeze-up (average 1.6 days/decade in Eurasia and 1 day/decade in North America)
Rokaya et al. (2019)	1951–2014*	North America, West Canada	Earlier freeze-up at 12 out of 17 gauge stations, between –0.5 and –5.0 days/decade
Dudley and Hodgkins (2002)	1930–2000*	North America, Northeastern USA	Later freeze-up at 4 out of 5 gauge stations (average 2.8 days/decade)
Obyazov and Smakhtin (2014)	1958–2008	Asia, Southeast Russia	Later freeze-up, on 77% of gauge stations the freeze-up began 0.2–3.8 days/decade
Smith (2000)	1917–1994*	North Asia and North Europe	Mixed trends, earlier freeze-up at 3 out of 9 gauge stations (0.8–3.2 days/decade)
Punsalmaa et al. (2004)	1945–1999*	Asia, Mongolia	Later freeze-up, 2–30 days in study period
Jiang et al. (2008)	1968–2001	Asia, North China	Later freeze-up (4.2 and 5.7 days/decade)
Shiklomanov and Lammers (2014)	1955–2012	North Asia, North Europe	Later freeze-up (between 0.8 and 2.6 days/decade)
Newton and Mullan (2020)	1931–2005*	Northern Hemisphere	Later freeze-up, especially in the period 1991–2005 (0.7 days/decade on European rivers in period 1931–2005)
Gebre and Alfredsen (2011)	1920–1980*	Europe, Norway	Mixed trends, earlier freeze-up on 6 out of 11 gauge stations (one significant 3.3 days/decade), on 5 gauge stations later freeze-up (three significant, 0.9–11.1 days/decade)
Takács and Kern (2015)	1875–2006	Europe, Hungary	Later freeze-up, average 0.7 days/decade
Takács et al. (2018)	1774–2018*	Europe, Hungary	The later first appearance of ice (1.2–3 days/decade) and freeze-up (0.4–1.3 days/decade)
Ionita et al. (2018)	1837–2016	Europe, Romania	Since the 1950s, the ice cover has stopped forming
Marszelewski and Pawłowski (2019)	1956–2015	Europe, Poland	Later freeze-up, 0.8–2.7 days/decade
Podkowa et al. (2023)	2010–2020	North America, Asia, Arctic	Later freeze-up 2.2 days in the decade 2010–2020

Data marked with * indicate that multiple periods were used in the study. The table shows the longest one

Based on these results, later river ice cover formation was found to dominate in the northeastern part of North America in the 1979–2009 period, whereas earlier formation was found to dominate in the west of the continent, mainly in the Rocky Mountains. Based on this model, ice cover freeze-up in the Arctic area of North America during this period was estimated to occur on average 1 day later per decade (Park et al. 2016).

Across Eurasia, river freezing trends are likely to be less spatially variable: most of the area exhibits later ice

formation in the second half of the twentieth century and the twenty-first century. In Eastern and Central Asia, the freeze-up was later by 0.2–5.7 days per decade. Based on measurements from 67 measuring stations, ice cover formation occurred in the Transbaikalian area 1 day later per decade (Obyazov and Smakhtin 2014). The largest changes were observed on the Yellow River, where from the late 1960s to the start of the twenty-first century, freeze-up at two stations occurred later by 4.2 and 5.7 days per decade (Jiang et al. 2008). In northern Mongolia, from the mid-1950s to

the end of the twentieth century, ice cover formed later by 2 to 30 days (Punsalmaa et al. 2004). In the Eurasian Arctic, freeze-up studies focus mainly on the largest rivers flowing into the Arctic Ocean. Analyses based on measurement series from large Arctic rivers from 1917 to 1994 have shown mixed trends (Smith 2000). Earlier ice cover formation (from 0.8 to 3.2 days per decade) was observed on rivers of northwestern Eurasia (Onega, Varzuga, Mezen, and Yenisei), while later formation rates (0.5 and 0.6 days per decade) were observed on Siberia's Indigirka and Kolyma rivers (Smith 2000).

Shiklomanov and Lammers (2014) showed later ice cover freeze-up by 0.8–2.6 days per decade on four Arctic rivers (Ob, Lena, Jana, and Kolyma) during 1955–2012. In the European area, ice cover formation delays were recorded, among other areas, in the Danube and Oder (Central Europe) catchments and on parts of the Fennoscandian Peninsula rivers (Gebre and Alfredsen 2011; Takács and Kern 2015; Ionita et al. 2018; Marszelewski and Pawłowski 2019). In the lower reaches of the Drava River (northeastern Croatia), freeze-up occurred later by 0.4–3.3 days per decade during the period 1875–2014 (Takács and Kern 2015). In the lower reaches of the Danube River in the period 1837–2016, later ice formation of 2.8 days per decade was recorded; as a result, by the middle of the twentieth century, ice cover had stopped forming there, despite previously being present almost every year since the first half of the nineteenth century (Ionita et al. 2018). On the Oder River (Polish–German border) in the period 1956–2015, ice cover freeze-up occurred later by 0.8–2.7 days per decade (Marszelewski and Pawłowski 2019). Ambiguous results were obtained for rivers in the western part of the Fennoscandian Peninsula. Of the 11 measuring stations, five recorded later ice formation (two of which were statistically significant), whereas six recorded earlier ice formation (one of which was statistically significant; Gebre and Alfredsen 2011).

The researchers recorded both earlier (trends reaching almost 5 days/decade, Burn and Elnur 2001; Smith 2000; Gebre and Alfredsen 2011; Rokaya et al. 2019) and later ice cover formation (reaching 11.1 days/decade, Rannie 1983; Magnuson et al. 2000; Smith 2000; Burn and Elnur 2001; Dudley and Hodgkins 2002; Punsalmaa et al. 2004; Lacroix et al. 2005; Jiang et al. 2008; Janowicz 2010; Gebre and Alfredsen 2011; Obyazov and Smakhtin 2014; Shiklomanov and Lammers 2014; Takács and Kern 2015; Takács et al. 2018; Marszelewski and Pawłowski 2019; Podkowa et al. 2023). However, later ice cover formation was observed in the vast majority of the studied areas and, based on the works cited, it can be concluded that this is a dominant trend globally. Opposing trends were recorded, among others, in Asia and western part of North America (Athabasca River catchment). The largest trends for later ice cover formation were recorded in Norway on the Beiraelva River (11.1 days/

decade, Gebre and Alfredsen 2011) and in China on the Yellow River (5.7 days/decade, Jiang et al. 2008).

Breakup The ice cover breakup process is divided into two distinct modes: thermal breakup and mechanical breakup. Mechanical breakup is facilitated by low water levels during ice formation and high snow cover in the catchment resulting in high river water levels during breakup (Beltaos 2003). In contrast, thermal breakup is favored by low snowpack thicknesses or delayed snowmelt, which is associated with small river flow volume changes and a gradual increase in air temperature allowing gradual melting of the ice cover (Beltaos 2003; Cooley and Pavelsky 2016). Consequently, the main factor determining the type of ice cover breakup is the water level in the river. It has been shown that site-specific increases in river water level above the level at which the ice cover formed mark a transition from thermal to mechanical breakup (Beltaos 2003). Since the beginning of the twentieth century, earlier river ice cover breakup has been recorded on a global scale. The most important studies of river ice cover breakup trends are presented in Table 2. The longest series of measurements analyzing ice cover breakup trends date back to the eighteenth and early nineteenth centuries, but most works are limited to the twentieth and twenty-first centuries. Based on the results of the studies collected in the review, it was estimated that since the nineteenth century, ice cover breakup has occurred on average 1.2 days per decade earlier in the areas studied.

North American areas generally record earlier spring breakup of river ice cover, but the trends are spatially complex. In some areas, they are mixed, with delays in breakup also recorded at individual stations (Williams 1970; Rannie 1983; Magnuson et al. 2000; Zhang et al. 2001; Lacroix et al. 2005; Rham et al. 2008; Chen and She 2020). Earlier ice cover breakup occurs in central and western Canada (e.g., Nelson River Basin), and in the Arctic (Zhang et al. 2001; Lacroix et al. 2005; Chen and She 2020). This trend occurred in these areas during the twentieth century and intensified during the twenty-first century (Janowicz 2010). Trends indicating later breakup, or no trend, have been recorded mainly in the eastern part of the continent (Atlantic Canada) and locally in the west (e.g., Athabasca River basin; Zhang et al. 2001; Rokaya et al. 2019; Chen and She 2020).

These trends are partially confirmed by modeling results, which indicate that river ice cover breakup occurs as much as 6 days per decade earlier in central and northeastern Canada, but later in the Labrador Peninsula and the Rocky Mountains (Park et al. 2016). However, despite the observed spatial heterogeneity in these trends, at a North American scale, breakup occurs on average earlier by an estimated 0.7 days per decade in the Arctic and 1.6 days per decade in Canada, as indicated by studies based on in situ observations and modeling results (Lacroix et al. 2005; Park et al. 2016). In the Eurasian area, ice cover breakup trends tend to be

Table 2 Summary of trends in breakup timing. The table shows studies based on long measurement series (> 1 year)

Reference	Investigation period	Region	Main findings
Huntington et al. (2003)	1931–2001	North America, USA, Maine	Earlier breakup at one station, 2.1 days/decade
Dudley and Hodgkins (2002)	1938–2000*	North America, USA, Maine	Earlier breakup at four stations, 1.7–3.8 days/decade
Hodgkins et al. (2005)	1930s–2000*	North America, USA, New England	Earlier breakup at 14 out of 16 stations
Zhang et al. (2001)	1947–1996*	North America, Canada	Earlier breakup in all regions of Canada, except Atlantic Canada
Burn and Elnur (2001)	1960–1997	North America, Canada	Earlier breakup at 20 out of 73 stations
Rokaya et al. (2019)	1951–2014*	North America, Canada, Alberta	Mixed trends, later breakup at eight stations, but only one trend statistically significant
Janowicz (2010)	1896–2009*	North America, Northwest Canada	Earlier breakup at one station of 0.5 days/decade; the last two decades have seen an advancement of the breakup date
Williams (1970)	1840–1960*	North America, Canada, New Brunswick	Ice tended to clear from rivers about 10 to 15 days earlier in the 1950s than in the 1870s
Rannie (1983)	1798–1981	North America, Canada, Manitoba	Earlier breakup by about 10 days in the twentieth century compared to the nineteenth century
Lacroix et al. (2005)	1950–1998	North America, Canada	Earlier breakup, on average 1.6 days/decade at 45 stations
Chen and She (2020)	1950–2016	North America, Canada	Earlier breakup on five selected rivers, 0.34–1.56 days/decade on average
Goulding et al. (2009)	1974–2006*	North America, Canada	Earlier breakup at 10 out of 11 stations, 2.09 days/decade on average
Rham et al. (2008)	1970–2002	North America, Northwest Canada	Earlier breakup (1 day/decade on average) in upstream portions of the major tributaries of the Mackenzie River Basin
Sagarin and Micheli (2001)	1917–2000	North America, Alaska	Earlier breakup approximately 0.5 days/decade
Magnuson et al. (2000)	1845–1990s*	North America, Asia, Europe	Earlier breakup on the investigated rivers, 0.2–1.3 days/decade
Obyazov and Smakhtin (2014)	1958–2008	Asia, Russia, Transbaikal	Earlier breakup at 75% of 67 stations, 0.2–2.8 days/decade (on average 3 days earlier throughout the area)
Soldatova (1993)	1893–1985	Asia, Russia	Mixed trends; on some of the rivers surveyed earlier breakup 0.7–1 days/decade
Jiang et al. (2008)	1968–2001	Asia, North China	Earlier breakup at two stations (5.7 and 3.3 days/decade)
Punsalmaa et al. (2004)	1945–1999*	Asia, North Mongolia	Earlier breakup, 5–30 days in investigation period (different study periods)
Smith (2000)	1917–1994	Asia, Europe, Arctic Russia	Earlier breakup, 1.0–3.2 days/decade
Cooley and Pavelsky (2016)	2000–2014	Asia, North America	Earlier breakup (2.5–12.5 days/decade) on some river sections
Shiklomanov and Lammers (2014)	1955–2012	Asia, Europe	Earlier end of ice events, 0.7–0.9 days/decade
Gebre and Alfredsen (2011)	1912–1990s*	Europe, Norway	Mixed trends, on most rivers earlier breakup (one significant 0.9 days/decade), on four stations later (one significant at 1.5 days/decade)
Klavins et al. (2009)	1921–2000*	Europe, Estonia, Lithuania, Russia	Earlier breakup on most of the rivers studied
Frolova et al. (2011)	1900–2005	East Europe	Earlier breakup on most rivers, 0.2–2.4 days/decade

Table 2 (continued)

Reference	Investigation period	Region	Main findings
Kuusisto and Elo (2000)	1709–1998	North Europe, Finland	Earlier breakup on two rivers 0.4–0.5 days/decade
Helama et al. (2013)	1802–2002	North Europe, Sweden	Earlier breakup
Ionita et al. (2018)	1837–2016	Europe, Romania	Since the 1950s, the ice cover has stopped forming
Marszelewski and Pawłowski (2019)	1956–2015	Europe, Poland	Earlier breakup at two stations (4.2 and 0.8 days/decade), later at one station (4.5 days/decade)
Takács and Kern (2015)	1875–2006	Europe, Hungary	Earlier breakup on average 1.7 days/decade in the Drava River Basin
Takács et al. (2018)	1774–2018*	Europe, Hungary	Earlier breakup of the ice cover (0.7–1.3 days/decade) and ice-off (0.9–2.7 days/decade)
Sharma et al. (2016)	1693–2013	Europe, Finland	In the period 1693–1866, breakup earlier by 0.3 days/decade, while in the period 1867–2013, breakup earlier by 0.66 days/decade
Podkowa et al. (2023)	2010–2020	North America, Asia, Arctic	Earlier ice cover breakup by 0.6 days in the decade 2010–2020
Newton and Mullan (2020)	1931–2005	Northern Hemisphere	Earlier breakup in the Northern Hemisphere (average 0.23 days/decade)

Data marked with * indicate that multiple periods were used in the study. The table shows the longest one

less spatially variable. On most rivers in this area, earlier ice cover breakup at rates of up to several days per decade has been recorded (Magnuson et al. 2000; Cooley and Pavelsky 2016; Newton and Mullan 2020). In Asia, these trends occur in the Arctic, Transbaikal, northern Mongolia, and China (Smith 2000; Punsalma et al. 2004; Jiang et al. 2008; Shiklomanov and Lammers 2014). On Asia's large rivers (e.g., Lena, Ob, and Yenisei), trends have varied along the rivers longitudinal profiles since the beginning of the twenty-first century. On the Yenisei and the Lena, the magnitude of the trends increases upstream, whereas on the Ob, earlier ice cover breakup occurs only in the middle reaches of the river (Cooley and Pavelsky 2016). Within Europe, earlier ice cover breakup has been recorded on rivers of the Fenoscandian Peninsula, central Europe, and Eastern Europe (Klavins et al. 2009; Frolova et al. 2011; Gebre and Alfredsen 2011; Takács and Kern 2015; Sharma et al. 2016; Ionita et al. 2018; Marszelewski and Pawłowski 2019; Newton and Mullan 2020). These trends in most areas of Europe and Asia are confirmed by modeling results, which found that the breakup of ice cover on rivers of the Eurasian Arctic in the period 1979–2009 occurred 2.3 days earlier per decade (Park et al. 2016).

Earlier breakup of ice cover reaching up to 12.5 days/decade was recorded in the vast majority of the study areas. The largest shift was recorded in the period 2000–2014 for some sections of the Yenisey, Ob, and Lena rivers (Cooley and Pavelsky 2016). No changes were recorded only for the

Athabasca River catchment (Rokaya et al. 2019). On the basis of the cited works, it can be concluded that this is a global trend, as evidenced by the consistent direction of change towards earlier breakup in all the studied areas.

River ice duration

Due to changes in freeze-up and breakup dates, the ice cover duration on most of the world's rivers has decreased. This trend has been recorded since the beginning of the twentieth century and has intensified since the beginning of the twenty-first century (Magnusson et al. 2000; Newton and Mullan 2020). The trend in ice cover duration decline ranges from less than 1 day to as many as a 11.5 days per decade and varies spatially (Fig. 3; Jiang et al. 2008).

In North America, decreasing ice cover duration has been recorded in the northeastern part of the United States (New England) and the southern and southwestern parts of Canada, among others (Rannie 1983; Burn and Elnur 2001; Dudley and Hodgkins 2002; Hodgkins et al. 2005; Janowicz 2010). In some areas, the opposite trend (increased ice cover duration) was recorded; this occurred in the eastern part of Canada (Atlantic Canada) and the Athabasca River Basin (Zhang et al. 2001; Rokaya et al. 2019). Generally, a decrease in the duration of ice cover of approximately 1 to 11 days per decade has been recorded across Asia. The largest changes occurred on the Yellow River (Inner Mongolia), where in the period 1968–2001, ice cover duration

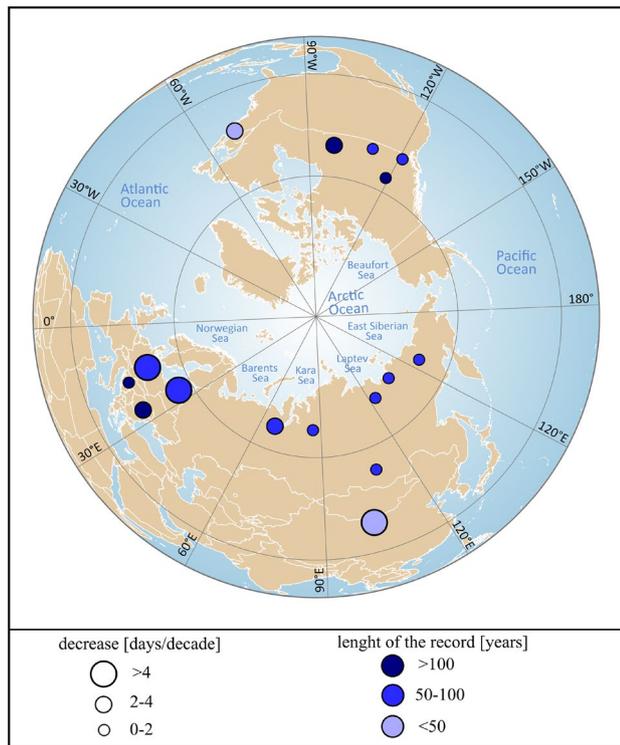


Fig. 3 Changes in the duration of ice cover determined by measurements from water gauge stations (source: Magnusson et al. 2000; Dudley and Hodgkins 2002; Jiang et al. 2008; Klavins et al. 2009; Obyazov and Smathkin 2014; Shiklomanov and Lammers 2014; Takács and Kern 2015; Ionita et al. 2018; Marszelewski and Pawłowski 2019; Chen and She 2020)

reductions of 38 and 25 days were recorded at two stations, equivalent to 11.5 and 7.6 days per decade, respectively (Jiang et al. 2008). In the Transbaikal area, an average ice cover duration decrease of 1.6 days per decade was recorded at 57 measurement stations in the period 1958–2007 (Obyazov and Smathkin 2014). Decreasing trends in the number of days with ice cover were also recorded in central and northern Siberia, reaching values of up to 7.4 days per decade at individual stations. In Western Siberia in the period 1955–2014, the average days with ice cover decreased by 7 days per decade (Shiklomanov and Lammers 2014; Vuglinsky 2017; Vuglinsky and Valatin 2018). Within Europe, a decrease in the number of days with ice cover was recorded in the Baltic region (2.8–6.3 days per decade), in addition to the Oder (average 4.6 days per decade), Danube (average 2.8–4.2 days per decade), and Drava (average 1.3 days per decade) river basins, among others (Klavins et al. 2009; Takács and Kern 2015; Takács et al. 2018; Ionita et al. 2018; Marszelewski and Pawłowski 2019). On many of the world's rivers, ice cover has stopped forming due to the rise of air temperatures in winter (Ionita et al. 2018). Based on satellite imagery analysis, Yang et al. (2020) compared the extent of

river ice in the decades 1984–1994 and 2008–2018. They showed that the monthly decline in river ice extent globally (for rivers greater than 90 m wide) varied from 0.3 to 4.3 percentage points depending on the month. They recorded the largest declines over the studied period around the Tibetan Plateau, in Eastern Europe, and Alaska.

In the vast majority of the studied areas, a decrease in the duration of ice cover is observed, exceeding as many as 10 days/decade in some areas. Based on the trends in the duration and ice cover freeze-up and breakup, it can be concluded that this effect occurs due to later ice cover formation and earlier breakup. The consistent direction of these changes observed in many different locations on different continents justifies a conclusion that the decrease in ice cover duration is a global trend.

River ice thickness and volume

Due to the difficulty of measuring ice thickness on rivers, relatively few studies have analyzed its variability over time. Within North America, decreasing ice thickness has been recorded on the Peace River and the Piscataquis River in Maine, USA, among others (Huntington et al. 2003; Beltaos and Bonsal 2021; Imrit et al. 2022). On the Piscataquis River in the period 1912–2001, the rate of decrease in average ice thickness was estimated at 2.6 cm per decade (Huntington et al. 2003). Imrit et al. (2022) recorded a decrease in ice thickness ranging 1.3 to 5.3 cm per decade on four out of the five rivers studied in North America. In Asia, ice thickness studies have been conducted for rivers in the Arctic, Transbaikal, and Mongolia. In northern Mongolia, a decrease in the maximum ice cover thickness of 5–25 cm per decade was recorded (Punsalma 2004). Declining trends were also recorded on most rivers in Siberia where in the period 1980–2014, they averaged 3.5 cm per decade in Western Siberia and 3.6 cm in eastern Siberia (Vuglinsky 2017; Vuglinsky and Valatin 2018). The decreasing trend in maximum thickness also occurred on large rivers flowing into the Arctic Ocean (Ob, Yenisei, Lena, Jana, and Kolyma); in the period 1955–2012, the thickness decreases on these rivers ranged from 2.3 to 12.6 cm per decade (Shiklomanov and Lammers 2014). The Transbaikal area also recorded a decrease in the maximum thickness of ice cover on most of the studied rivers. In this area, at 25% of the water gauge stations, the decrease in thickness ranged from 2 to 6 cm per decade; at another 25%, it was more than 6 cm per decade (Obyazov and Smakhtin 2013). For the Arctic area, the decrease in the maximum thickness of river ice cover was investigated based on modeling results (Park et al. 2016). The downward thickness trend was estimated at an average decrease of 3 cm per decade in the Eurasian Arctic and an average decrease of 5 cm per decade in the North American Arctic. As a result of changes in the thickness and area

occupied by the ice cover, the maximum volume of river ice is also changing. It is estimated to be periodically around 140 km³ globally (Brooks et al. 2013). Currently, there is a lack of research on temporal variations of river ice volume on a global scale, and available studies tend to focus on individual rivers. For example, Jiang et al. (2008) estimated that total annual ice volumes decreased by 40,000,000 m³ in the lower Yellow River between 1950 and 2001.

The impact of dam reservoir operations on river ice cover

The influence of dam reservoirs on the occurrence of river ice cover can be divided into indirect and direct effects. Indirectly, reservoirs influence river ice by modifying the conditions under which the ice cover freeze-up and breakup processes occur. This is due to the dams modifying the natural hydrological and thermal regimes of rivers, both on a daily and seasonal scale (Chien 1985; ICOLD 2022; Haghghi et al. 2014). The river ice freeze-up process depends directly on the river's hydraulic conditions, which are modified by flow changes caused by the operation of dam reservoirs (Beltaos 2003; Carr et al. 2014). The operation of the dam may cause turbulent flow and increase the velocity of water in the riverbed, resulting in impeded ice formation. Changes in flow also determine the dates of breakup: by decreasing or increasing the spring flow volume, dam reservoirs can accelerate or delay the occurrence of mechanical breakup of the ice cover (Gerard 1989; Shen 2003; Huokuna et al. 2022). Another important factor is the fact that mobile ice flowing from the upper parts of the catchment is caught by the dam, remains in the reservoir, and does not participate in the development of a stable ice cover below the dam (Starosolszky 1990). The reservoir's uptake of suspended material, which plays an important role in the occurrence of phase transformation in the water and the formation of the ice cover, may also affect the development of the ice cover (Takács and Kern 2015). Dam reservoirs can also affect ice processes in sections above the facility because they act as a barrier to mobile ice and, once the reservoir freezes, upstream ice development occurs through impeded (or completely stopped) ice outflow below the reservoir (Gerard 1989).

Reservoirs can also directly affect ice cover occurrence by altering the natural thermals of rivers (Maheu et al. 2016; Sukhbaatar et al. 2020). Reservoirs tend to reduce the annual amplitude of water temperature fluctuations by cooling the water flowing out of the reservoir in summer and warming it in winter (Lehmkuhl 1972; Ashton 1979; Preece and Jones 2002; Olden and Naiman 2010; Maheu et al. 2016; Jiang et al. 2018). This effect is caused by thermal stratification in the reservoirs and the release of bottom hypolimnion waters.

In the summer, water temperature in the reservoirs decreases with depth, while in the winter it increases up to 4 °C (at this temperature, water reaches its highest density). It occurs primarily in large dam reservoirs but also in medium-sized and small reservoirs in some instances (Soja and Wiejaczka 2014; Kędra and Wiejaczka 2016, 2018; Maheu et al. 2016; Wiejaczka and Wesoly 2017; Wiejaczka et al. 2018). This effect can influence the ice cover formation process by delaying the freezing point of water from being reached during ice formation seasons. In some cases, the water temperature can remain above zero throughout the entire winter period in the section below the dam so that ice cover will not form (Maheu et al. 2014; Huokuna et al. 2022). Similarly, this effect can influence the ice cover breakup process by accelerating spring thermal breakup and reducing the strength of the ice, resulting in greater susceptibility to mechanical breakup (Shen 2003; Cooley and Pavelsky 2016).

To date, the impact of reservoir operations on river ice cover has not been sufficiently studied. Most works focus on individual cases, and it is challenging to relate the results of these studies to the global scale of the phenomenon (Table 3). There are no publications in the literature that analyze the impact of dam reservoir operations based on a large number of cases that would allow for statistical analyzes. As a result, the average extent of the impact of dam reservoirs on the ice cover of rivers downstream of the dam and the number of river sections that are transformed by the reservoirs are unknown. It is also not entirely clear how the parameters of the dam and reservoir (e.g., dam height, reservoir volume, method of dam operation) influence the scale and extent of ice regime transformation of the rivers below.

Most of the research has focused on the impact of dam operations on the occurrence of ice cover on rivers in Europe and North America. Changes caused by the construction of the Włocławek Dam reduced the duration by 26% for ice phenomena and 47% for ice cover (Pawłowski 2015). On the Raba River (Hungary), construction of the reservoir resulted in an average annual decrease of 8 days in the number of days with ice cover (Takács et al. 2013). A change in the natural ice regime was also recorded on the Danube (Hungary); the sharp decrease in ice cover frequency recorded in sections of the river has been shown to relate to the operation of hydroelectric power plants and the supply of wastewater to the river (Starosolszky 1990). On the Daugava River (Latvia), the construction of hydropower plants has generally resulted in later formation and earlier breakup of the ice cover, resulting in decreased ice cover duration by up to several tens of days (Apsīte et al. 2016).

Transformation of the ice regime of rivers due to the operation of dam reservoirs has also been recorded in Asia. On China's Yellow River, the construction of dam reservoirs was shown to cause later freeze-up by an average of 14 days and earlier breakup by 21 days (Chang et al. 2016). The ice

Table 3 Summary of the impact of dam reservoirs on river ice cover. The table shows studies based on long measurement series (> 1 year)

Reference	Investigation period	Region	Findings
Starosolszky (1990)	1875–1986	Europe, Hungary	In the river below the reservoir, the number of days with ice cover decreased significantly
Takács et al. (2013)	1817–2004*	Europe, Hungary	After the construction of the reservoirs, there was a reduction in the duration of ice cover at the analyzed stations of 8 days. The frequency of ice phenomena decreased 5–7%
Takács and Kern (2015)	1875–2014	Europe, Hungary	During the studied period, the lower Drava River experienced an average reduction in ice cover duration of 1.4 days/decade (average across four stations). After the 1970s, this effect was partly due to anthropogenic interventions in the upper part of the river (i.e., construction of reservoirs and hydropower management)
Pawłowski (2015)	1882–2011	Europe, Poland	In the studied period, the ice cover duration decreased by 3.9 days/decade. In the period after the construction of the dam reservoir (1970–2011), the ice cover duration decreased by 47% compared to 1882–1907. Currently, the ice regime of the Vistula River is being transformed more by anthropogenic factors than climate change
Apsīte et al. (2016)	1919–2012*	Europe, Latvia	After the construction of the reservoirs, the ice cover duration at two gauging stations below was recorded to decrease by average values of 91 and 25 days. In general, freezing of the ice cover occurred later, while breakup occurred earlier
Chang et al. (2016)	1951–2010	Asia, China	As a result of the dam reservoirs, the duration of ice cover in the studied period was reduced by 33, 22, and 8 days at three stations (5.5, 3.6, and 1.3 days/decade). Freezing of the ice cover occurred later, while breakup occurred earlier. This impact was recorded at stations several hundred kilometers below the reservoir
Belolipetsky and Genova (1998)	1984–1985	Asia, Russia	As a result of the operation of the Krasnoyarsk Reservoir on the Yenisey River, ice cover does not form along a stretch of about 250 km downstream of the reservoir. It has been shown that the use of surface water intake from the reservoir can lower the river's water temperature in winter and significantly shorten the section where the ice cover does not form to 65–70 km
Maheu et al. (2014)	2012–2013	North America, Canada	Effects on the thermal and ice regimes of the river below were recorded at two of the four dams studied. Below these dams, ice cover did not form at distances of 1.7 and 2.5 km from the reservoir, and at distances of 4.3 and 7.1 km, there was a significant transformation of the ice regime
Maheu et al. (2016)	2012–2014	North America, Canada	The analysis showed that the two storage dams significantly influenced the conditions for the formation and maintenance of the ice cover over distances of 1.7 and 2.5 km. On these river sections during the winter, the water temperature remained above 0 °C, which suppressed ice cover formation
Jasek and Pryse-Phillips (2015)	1973–2011	North America, Canada	As a result of the operation of the Williston Dam Reservoir, no ice cover forms on the Peace River below the facility for a distance of 100–300 km, depending on hydrological and meteorological conditions. It is likely that this distance will increase as a result of climate change

Data marked with * indicate that multiple periods were used in the study. The table shows the longest one

regime transformation also occurs for reservoirs of different sizes and damming levels. Maheu et al. (2016) showed that small reservoirs in eastern Canada reduced the frequency of ice cover on rivers at distances up to 2.5 km downstream of the reservoir.

One of the best studied rivers in terms of dam reservoir effects on ice processes is the Peace River in Canada (Gerard and Karpuk 1979; Andres 1994, Andres et al. 2003; Andres 1996; Beltaos et al. 2006b; Andrishak and Hicks 2008a, b;

Beltaos et al. 2006a, b; She et al. 2012; Beltaos and Peters 2020; Emmer et al. 2021; Beltaos and Carter 2021). A large number of studies on the ice processes on this river are due to the occurrence of ice floods experienced by the Town of Peace River and other localities along the river's course (Emmer et al. 2021). Since 1968, the river has been regulated by the W.A.C. Bennett Dam and the resulting Williston Reservoir. A number of studies have shown that below the reservoir, ice cover does not form for several hundred

kilometers (100–300 km), and throughout the river, ice processes are transformed by the operation of the reservoir (She et al. 2012). In the case of the Peace River, research has also been conducted on the impact of future potential climate change on the river ice regime transformed by Williston Reservoir (Andrishak and Hicks 2005, 2008b). The results suggest that future climate change will result in an increase in the section below the reservoir where ice cover does not form (Andrishak and Hicks 2005; Andrishak and Hicks 2008a, b; Jasek and Pryse-Phillips 2015).

A significant number of studies on the impact of reservoirs on river ice cover arise from the practical need to transform river ice conditions through various engineering practices (for example, controlling river flow). The main practices used to transform river ice cover in the context of dam reservoirs are reducing flow during the ice cover formation period to control the ice cover formation process, maintaining stable flow during the steady ice cover period, and controlling flow during the ice cover breakup period. A detailed description of engineering control of river ice phenomena with examples can be found in the works of Ashton (1986), Jain et al. (1993), and Tuthill (1999). Studies of this type provide a close and detailed description of the effects of dam reservoirs on river ice cover, but are usually based on short periods from which it is difficult to infer long-term effects on the river ice conditions.

There are indications that dam reservoirs in some areas exert a much greater influence on disturbances in ice cover formation than is currently recognized. First, the rapid increase in the number of large dam reservoirs globally coincides with a period of intensification of the trends observed in river ice cover. According to ICOLD data, from the 1950s to the beginning of the twenty-first century, around 50,000 large dam reservoirs were constructed globally (Fig. 4a). Although there is a lack of precise data concerning the growth of this value in areas with ice cover, an analysis based on the GRanD database confirms this trend (Fig. 4b; Lehner et al. 2011). ICOLD estimates that more than 58,000 large dam reservoirs had been constructed by 2022. An analysis based on the GeoDAR database showed that 8090 dam reservoirs are currently located in areas with periodic ice cover. Given the characteristics of this database, this value represents a significant underestimation. This is because this database contains only 40% of the results also listed in the World Register of Dams (Wang et al. 2022). Because the observed ice cover frequency decline has intensified in many areas since the mid-twentieth century, dam reservoirs can be assumed to be partially responsible for this effect. The significant importance of dam reservoirs in transforming the ice regime of rivers is also implied by their spatial distribution (Fig. 4d). As the analysis in this study showed (Fig. 4d), in the zone where ice cover formation conditions last for less than three months on average, most reservoirs are situated

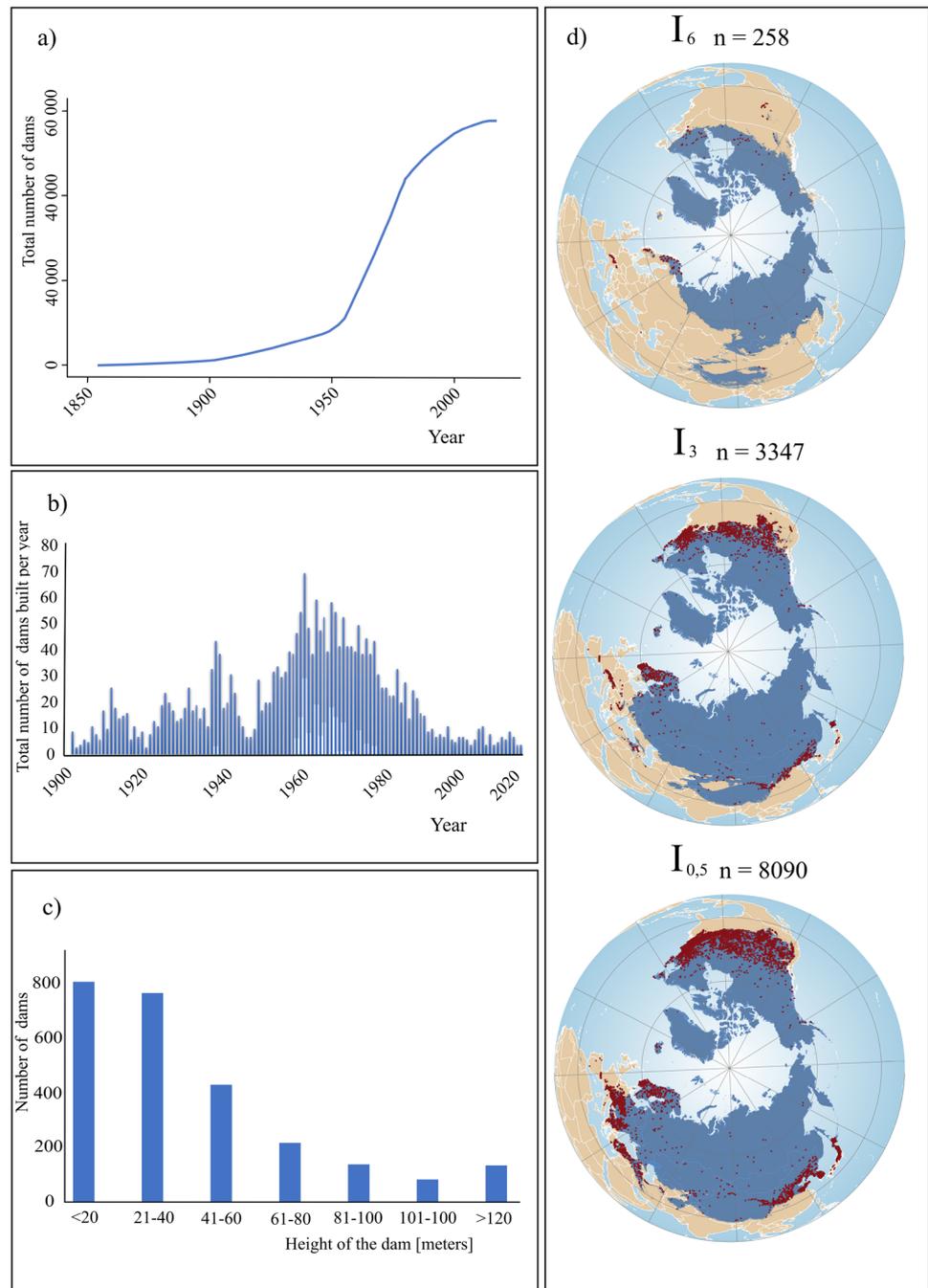
on rivers where ice cover forms periodically (7832 reservoirs according to the GeoDAR database). Additionally, these areas are where the most dynamic changes are observed in freeze-up and breakup dates and the duration of river ice cover. A comparison of the obtained spatial distribution of dams and the data presented by Yang et al. (2020) on the global decline in river ice extent in the period 1984–2018 indicates that areas with the greatest declines in ice area typically correspond to areas with numerous dams. These areas include Eastern Europe, Central Asia (around the Tibetan Plateau), and the central part of North America. The potential role of dam reservoirs in ice cover formation can also be inferred indirectly from studies of reservoir impacts on river thermals. A study of 112 dam reservoirs on four continents showed that 88% of them warm the downstream river by 1.5–5 °C (Ahmad et al. 2021). The analysis showed that about 70% of dams in areas where ice events periodically occur are below 50 m in height: this is significant because the warming effect is recorded for both large and small reservoirs (Maheu et al. 2016; Wiejaczka et al. 2018).

The extent of the impact of dam reservoirs on ice cover formation disturbance is not well estimated. Most studies indicate that its influence ranges from a few kilometers to tens of kilometers, but some studies suggest that its effects can reach distances up to several hundred kilometers (Lehmkuhl 1972; Andrishak and Hicks 2008a, b; Maheu et al. 2016; Chang et al. 2016). The significant role of dam reservoirs on ice formation is also evidenced by examples of the impact of dam removal. It has been shown that dam demolition can result in increased ice supply and increase the frequency and thickness of ice jams downstream (White and Moore 2002; Tuthill et al. 2007; Carr et al. 2011). This may also result in increased ice thickness due to an increase in mobile ice accumulation (White 2001).

Remote sensing in monitoring the impact of climate change and dam operations on river ice cover

Satellite remote sensing can be a particularly useful tool for analyzing the impact of dam reservoirs and climate change on river ice cover. This is due to the complex way in which these factors affect the temporal and spatial variability in ice cover characteristics. There is also the advantage of being able to analyze ice on rivers where there are no water gauge stations. Remote sensing techniques allow for the monitoring of changes in the extent of ice cover (and its parameters) over significant stretches of rivers, helping capture temporal trends more accurately. Remote sensing data are most commonly used to distinguish the spatial distribution of class types such as water, thermal ice, consolidated ice, and frazil ice (Mermoz et al. 2009; Duguay et al. 2015).

Fig. 4 **a** Summary of the number of large dam reservoirs worldwide according to ICOLD (2015); **b** number of large dam reservoirs formed in periodic ice cover areas by year; **c** number of reservoirs with different dam heights in periodic ice cover areas; and **d** spatial distribution and number of reservoirs in ice cover areas for more than 6 months (I_6), 3 months (I_3), and 0.5 months ($I_{0.5}$)



Multispectral and radar (SAR) instruments are most commonly used to study spatial distribution of ice phenomena (Duguay et al. 2015). Both satellite- and airborne-derived imagery are used.

Ice cover detection from SAR data is possible due to the effect that ice cover has on the backscattering coefficient of the beam transmitted by the satellite. One of the greatest advantages of radar satellites is that they can monitor the presence of ice cover regardless of weather conditions and time of day. To study the characteristics of ice cover, the

most commonly used imagery is that acquired by Radarsat-1, Radarsat-2, TerraSAR-X, and Sentinel-1 satellites. A considerable amount of research based on SAR data has been conducted on the ice cover of large rivers in northern and northwestern North America, such as, among others, Athabasca, Peace, and Slave (Leconte and Klassen 1991; Weber et al. 2003; Tracy and Steven 2003; Gauthier et al. 2006; Drouin et al. 2007; Van der Sanden et al. 2009; Mermoz et al. 2009; Unterschultz et al. 2009; Gauthier et al. 2010; Lindenschmidt et al. 2010; Van der Sanden and

Drouin 2011; Jasek et al. 2013; Mermoz et al. 2013; Lindenschmidt and Chun 2014; Floyd et al. 2014; Das et al. 2015; Lindenschmidt and Li 2018; Li and Lindenschmidt 2018). Within Europe, river ice studies based on SAR data have been conducted on the Danube, Tisza, Nemunas, and Vistula rivers (Łoś and Pawłowski 2017; Stonevicius et al. 2022; val Leeuwen et al. 2022). Within Asia, similar studies have been conducted, among others, for rivers of the Tibetan Plateau and large rivers of Northern Asia (Melentyev et al. 2005; Sobiech and Dierking 2013; Zhang et al. 2022). Most river ice studies based on SAR data focus on monitoring and mapping the extent of different ice cover types over very short periods of time (usually based on single selected days) and their characteristics (mainly thickness). Relatively few works attempt to reconstruct the phenology of river ice phenomena over a long period of time and juxtapose the results with climatological parameters. Several authors attempted to monitor ice phenomena based on SAR data on river sections below large dam reservoirs (Weber et al. 2003; Gauthier et al. 2006; Jasek et al. 2013; Das et al. 2015; Lindenschmidt and Li 2018), but in most of such studies, the analyses were based on images from single days, during selected winter seasons.

When analyzing the phenology of ice phenomena, satellite optical imagery (mostly multispectral) was used much more frequently. Data acquired by Landsat, Terra, Aqua, and Sentinel-2 satellites were most commonly used to analyze the phenology of river ice phenomena. River ice studies based on this type of data have been conducted for rivers in North America, Europe, and Asia (Chaouch et al. 2014; Sakai et al. 2015; Cooley and Pavelsky 2016; Brown et al. 2018; Beaton et al. 2019; Li et al. 2021, 2023). Using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, Cooley and Pavelsky (2016) presented a temporal spatial distribution of ice cover breakup trends using large Arctic rivers as an example. They showed that there was a significant trend for earlier ice cover breakup in significant sections of the rivers studied during the period 2000–2014. Brown et al. (2018) used Landsat constellation satellite data and found a significant lag (1–2.1 days per decade) in the dates of ice cover formation in 40% of the study sites in Alaska during the years 1972–2016. Li et al. (2020) utilized Landsat imagery to show that river ice area decreased by an average of 0.26 km² each year during the period 1999–2018 (Babao River, Tibetan Plateau). Of particular importance in recognizing the impact of climate change on river ice cover is the study by Yang et al. (2020). They analyzed more than 400,000 images from the Landsat satellite constellation over the period 1984–2018. They showed that globally, for all rivers wider than 90 m, the extent of ice cover is decreasing, with an average decrease in ice cover duration of 6.10 ± 0.08 days per 1 °C increase in global mean air temperature. During the study period, they observed the

most considerable changes in Alaska, Central Europe, and around the Tibetan Plateau. The impact of dam reservoirs on river ice cover was also analyzed using multispectral data. Vyshnevskiy (2020) analyzed the impact of the Kiev hydroelectric power plant on the thermal and ice regime of the Dnieper River. He showed that, as a result of climate change and the operation of the hydropower plant, the ice regime of the Dnieper at Kiev has become unstable. However, the paper did not conclude how much of the observed changes were due to the operation of the dam and how much to climate change, and the work was limited to selected periods after the construction of the reservoir.

Other types of remote sensing data (panchromatic, altimetry, passive microwave) are also used in river ice cover studies. An example is the research conducted by Podkova et al. (2023) on the ice cover of large Arctic rivers. On the basis of data acquired from the Soil Moisture and Ocean Salinity (SMOS) satellite constellation, they showed that in the years 2010–2020, ice formation in the studied rivers occurred on average 2.2 days later and breakup occurred on average 0.6 earlier, resulting in a 3.4-day decrease in ice duration over this period.

Discussion

Based on the literature review presented above, it can be concluded that the factors controlling the ice processes on Earth's rivers are currently relatively poorly understood. Despite the crucial role played by river ice cover in the natural environment and on human activity, few studies have investigated this aspect compared to other elements of the Earth's cryosphere (Jeffries et al. 2012). This problem was highlighted by Morsem and Hicks (2005) who emphasized that the scientific community's interest in river ice cover research has gradually increased. Although several significant papers have been published in this area since the publication of their article in 2003, the scientific community's awareness of river ice research nonetheless seemingly remains too low. This is evidenced by the fact that river ice topics were not addressed in the cryosphere chapter (chapter 9) of the first part of the IPCC (Physical Science Basis, Fox-Kemper et al. 2021; Caretta et al. 2022), even though its role in global greenhouse gas exchange between rivers and the atmosphere has been demonstrated (Raymond et al. 2013). Of the two factors that affect ice cover analyzed in this study, the impact of climate change is far better recognized.

The studies presented in this paper provide evidence that increasing global air temperatures represent a major factor that has influenced changes in river ice regimes since the first half of the twentieth century. This is evidenced by the relationship between the observed temporal–spatial patterns

of changes in river ice phenology and thickness and their link to climate warming (Beltaos and Prowse 2008). An example of this is larger decrease in ice cover duration in the northeastern part of North America as compared to the northwestern part, probably related to the stronger increasing trend in winter mean air temperature there over the period 1980–2015 (Park et al. 2016; Gutiérrez et al. 2021). The key role of the climate factor is indicated by the more consistent and stronger trend in ice cover breakup than in freeze-up observed in most of the studied areas. This pattern is most likely due to the greater role of non-climatic factors in the ice cover formation process, such as the shape of the riverbed, and the strong relationship between ice breakup and the 0 °C isotherm (Lacroix et al. 2005; Bennett and Prowse 2010; Thellman et al. 2021). Consequently, ice cover duration on rivers decreases due to increasing air temperature, primarily due to earlier breakup rather than later freeze-up. Yang et al. (2020) estimated that globally, the seasonal duration of ice cover shortens by an average of 6.1 ± 0.08 days for every 1 °C increase in global air temperature. Changes in river ice cover parameters are consistent with observed trends in changes in other elements of the terrestrial cryosphere. During the period 1981–2018, a global decrease in snowpack mass was observed, estimated at 5 Gt per year (Mudryk et al. 2020; Fox-Kemper et al. 2021). Changes in the area and mass of snow cover are directly related to the occurrence of ice cover by changing river flow conditions. Increases in spring air temperatures, precipitation, and intensification of the hydrological cycle at high latitudes can lead to earlier snowmelt occurrence and the formation of surges that initiate earlier mechanical breakup of river ice cover (Prowse et al. 2007; Brown and Mote 2009; Déry et al. 2009; Prowse et al. 2010; Rawlins et al. 2010; Cooley and Pavel-sky 2016). Increasing air temperatures in temperate climate zones result in multiple freeze-ups and breakups during a single season; this effect has been recorded in areas in which there was stable ice cover for several months annually in the nineteenth century. In extreme cases, there is a complete cessation of ice cover formation, which is often strongly correlated with increases in the average winter air temperature (Ionita et al. 2018). An issue that is not fully recognized is the impact of climate change on the occurrence of ice cover on small mountain and upland rivers because the vast majority of studies investigate large and medium lowland rivers, for which long measurement series are available. The spatial distribution of trends in ice cover characteristics is also insufficiently characterized. Most studies use data from measuring stations, which can be analyzed point-wise and reflect local environmental conditions. However, interpolating measured parameters across broader areas is subject to considerable uncertainty.

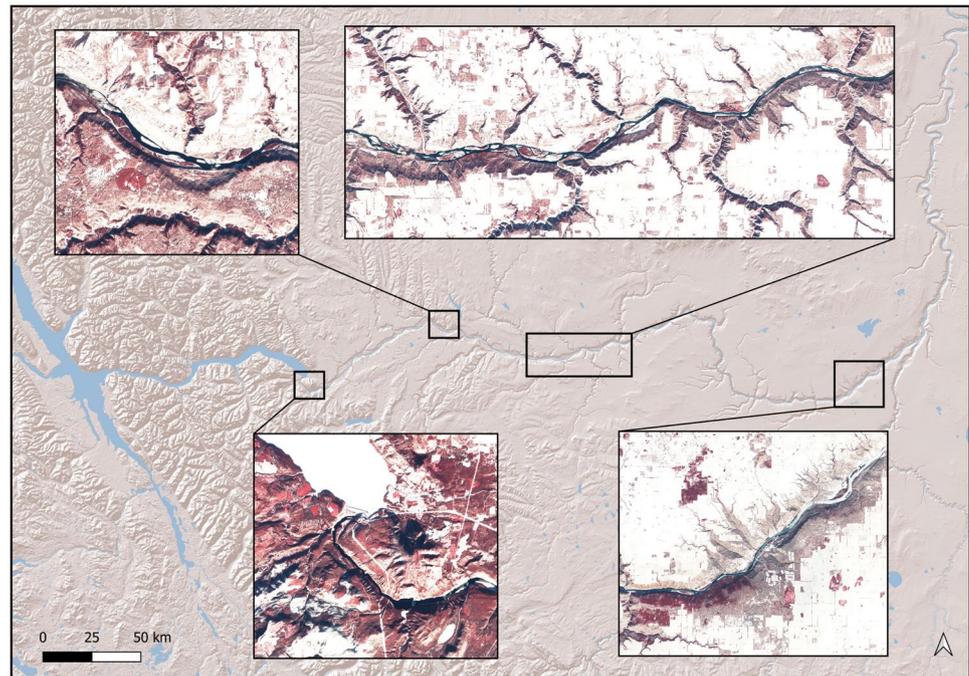
The impact of dam reservoirs on the occurrence of river ice cover is currently not sufficiently recognized due to the

small number of studies based on long measurement series, the lack of methods to separate the impact of climate change and dam reservoirs, and the small number of studies based on satellite remote sensing methods. The research results presented in this review suggest that at the local scale, dam reservoirs can fundamentally affect river ice in sections up to several tens of kilometers downstream. Some studies also suggest the influence of dam reservoirs at a regional scale. For example, a study of the Longyangxia and Liujiaxia reservoirs on the Yellow River in China showed that they influenced the occurrence of ice cover more than 1000 km below the reservoir (Chang et al. 2016). One of the main problems in assessing the impact of dam reservoirs on river ice cover is the difficulty involved in decoupling their influence from that of increasing air temperatures. The presence of dam reservoirs along a certain stretch of river amplifies trends resulting from climatic variability, making it impossible to assess their impacts quantitatively and qualitatively. Chang et al. (2016) presented a method for separating the impact of reservoirs and climate change, but it has significant limitations, and applying it to other examples may be challenging. The current lack of studies based on remote sensing data also represents a key problem. Most studies are based on data from water gauge stations, making it much more difficult to assess the extent of reservoir impacts. In addition, some of the studies investigating the impact of climate change on ice conditions fail to consider the possible impacts of dam reservoirs. In some cases, authors analyze the relationship between air temperature variability and ice phenomena but disregard the fact that some of the measurement stations selected for analysis are located below large dam reservoirs, which may have a significant impact. This approach may lead to inaccurate assessment of the relationship between air temperature variability and the occurrence of ice phenomena and, thus, erroneous conclusions.

Currently, there is a lack of systematic studies in the literature on the impact of dam reservoirs on ice cover occurrence based on satellite remote sensing data. This results in poor recognition of the temporal and spatial distribution of trends in ice cover parameters below dam reservoirs and the extent of their influence. This is a significant problem given that satellite observations confirm the important role of some large reservoirs on river ice cover. An example is the impact of the operation of Williston Reservoir on ice cover occurrence on the Peace River (Fig. 5).

During the period presented (February 8–12, 2017), there was no ice cover on the river below the reservoir for 360 km even though all its tributaries and the reservoir were covered with ice. This is most likely the result of deliberate flow control by the W.A.C. Bennet dam aimed at reducing the likelihood of ice jamming downstream, thereby transforming the river's water thermals (Weber et al. 2003; Rokaya et al. 2017). Due to the potential scale of impacts from this

Fig. 5 Occurrence of ice cover on the Peace River below Williston Reservoir from February 8–12, 2017. Source: Map tiles by Stamen Design, under CC BY 4.0. Data by OpenStreet-Map, under ODbL



reservoir type, they cannot be fully assessed based on data from water gauge stations. To accurately recognize this effect and statistically analyze the magnitude and extent of reservoir impacts on river ice cover, it is essential to conduct studies based on remote sensing data in areas of river ice cover for multiple reservoirs and different climatic zones.

Conclusions

This paper presents a review of studies on the impacts of climate change and the operation of dam reservoirs on river ice cover occurrence. Data on average air temperature and the distribution of dam reservoirs were also analyzed to estimate the number of reservoirs in areas where ice cover periodically occurs. The results obtained from the review and data analysis can be summarized as follows:

1. Trends in the dates of freeze-up are not clear. Most studies indicate later freeze-up in the twentieth and twenty-first centuries, but contradictory trends of earlier formation have been recorded in some areas. This is most likely due to the significant role of non-climatic factors in the river ice cover freeze-up process (Thellman et al. 2021). Based on the collected studies, it was estimated that the freezing of the river ice cover occurred a few to several days later on the surveyed rivers in the twentieth and twenty-first centuries.
2. Ice cover breakup in the vast majority of the studied areas occurs earlier. This is most likely due to the sig-

nificant relationship between the breakup process and the 0 °C isotherm (Bennet and Prowse 2010). Based on the research collected, it was estimated that breakup occurred a few to several days earlier in the study areas in the twentieth and twenty-first centuries.

3. As a result of changes occurring in the freeze-up and breakup of river ice cover, the ice cover duration has decreased by up to several days per decade. Earlier breakup is more responsible for this effect than later freeze-up. A decrease in ice cover thickness was also observed in most of the study areas.
4. The breakup and freeze-up trends are typically less spatially differentiated in Eurasia than in North America, as shown by the results of measurements from water gauge stations and model studies.
5. Studies of individual reservoirs indicate that their impact on ice cover at the local scale is significant, and their range of influence can reach several hundred kilometers. The role of reservoirs in the occurrence of ice cover on regional and global scales is not recognized, but the rationale presented here suggests that this role may be significant, especially in central North America, Europe, and East Asia.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The author declares that he has no known competing financial interests or personal relationships that could influence the work presented in this article.

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