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The Cryosphere
Discussions

Assessment of the impact of dam reservoirs on river ice cover - an example from the Carpathians (central Europe)

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Abstract. This paper presents a method for determining the impact of dam reservoirs on the ice cover of rivers below their locations based on a long measurement period (1950–2020) and synthetic-aperture radar (SAR) data. Two rivers and two sets of dam reservoirs located in the Carpathian Mountains (central Europe) were selected for this study. In order to estimate the influence of their reservoirs, a logistic regression model was built to describe the relationship between the course of air temperature and the occurrence of ice cover (i.e., total ice cover and border ice) at water gauge cross sections above and below the reservoirs. The influence of reservoirs was then defined as the differences between the values predicted from air temperature and those observed at the water gauge cross sections. Additionally, the extent of the impact of the reservoirs was estimated based on SAR data (Sentinel-1) by identifying river sections below the reservoirs on which total ice cover did not form despite the persistence of very low air temperatures. This study demonstrates that dam reservoirs are an important factor in transforming the ice regime of rivers. We found that decreases in the incidence of ice cover as a result of their operation could exceed 80% in the sections immediately below their location, and that this reduction decreased as the distance from the reservoir increases. According to SAR data, it was estimated that total ice cover did not form in sections 26–60 kilometers below the reservoirs, despite the presence of favorable thermal conditions. Based on the research results presented here, it is reasonable to assume that the rapid increase in the number of dam reservoirs worldwide in the second half of the 20th century is an important factor transforming the ice regime of rivers. This study also demonstrates that the logistic regression model and SAR data are useful tools for assessing the impact of dam reservoirs on river ice cover.

Keywords

Dam reservoirs, river ice cover, logistic regression, synthetic aperture radar (SAR), Carpathians

1. Introduction

Over the course of the 20th and 21st centuries, human impact on the natural environment has increased significantly. The transformation of the environment and its effects, previously occurring on a local scale, have now begun to be observed on a regional and global scale. The rapid increase in the impact of human activity since the 1950s has affected both biotic and abiotic aspects of the environment and has been dubbed the Great Acceleration (Lewis and Maslin, 2015). The section of the environment undergoing the most significant change is the terrestrial part of the Earth's cryosphere. This is mainly because of climate change and a significant increase in air temperature, particularly in cold areas (Fox-Kemper et al., 2021). Since the second half of the 20th century, there has been a decline in the extent and mass of ice sheets, mountain glaciers, and snow cover, as well as notable melting of permafrost (Fox -Kemper et al., 2021). Significant changes have also been observed in the river ice phenomena, which due to their periodic nature and the relatively small volume of river ice, are particularly sensitive to climatic variability and human influence (Newton and Mullan, 2021).

An anthropogenic element of the geographic environment that can significantly affect the ice regime of rivers are dam reservoirs. Such structures change the conditions for the course of ice processes in rivers, mainly through alterations in the flow volume and change in the thermodynamics of rivers below their location in winter (e.g., Starosolszky, 1990; Takács et al., 2013; Maheu et al., 2014; Takács and Kern, 2015; Pawłowski, 2015; Apsîte et al., 2016; Chang et al., 2016). As a result of dam reservoir operation, an ice regime can be transformed over sections of several to even several hundred kilometers, sometimes causing the complete disappearance of ice phenomena (Maheu et al., 2014; Pawłowski, 2015; Chang et al., 2016). Pawłowski (2015) showed that the construction of the Wloclawek dam reservoir on the Vistula River (Poland, Central Europe) resulted in a 26% reduction in the duration of ice cover and a 47% reduction in all ice phenomena below its location. Chang et al. (2016) showed that the construction of the Longyangxia and Liujiaxia reservoirs on the Yellow River (northern China) resulted in a reduction in the ice cover duration of the river by 8–33 days and a reduction in the thickness of the ice cover by 16–25 cm. This effect has also been noted in small rivers with small and medium-sized reservoirs. For example, Maheu et al. (2014) showed that the operation of small dam reservoirs in eastern Canada resulted in change in the thermal regime of rivers and the disappearance of ice phenomena in rivers over a distance of 0.3–2.5 km.

Despite the significant role of dam reservoirs in transforming the ice regimes of rivers, the problem is relatively poorly recognized in many ways. Most studies focus on assessing the impact of individual reservoirs, neglecting the regional and global aspects of this issue. It has been estimated that there are more than 8,000 dam reservoirs in ice regime areas, most of which are located in central and northern Europe, eastern Asia and the central section of North America (Fukś, 2023). The main difficulty in assessing the impact of dam reservoirs on river ice cover comes in distinguishing whether changes are due to operational or climatic factors. So far, in order to study their impact, ice phenomena have been compared during periods with similar thermal conditions (usually determined by the average air temperature of winter) before and after the construction of reservoirs (e.g., Takács et al., 2013; Pawłowski, 2015; Chang et al., 2016). This approach makes it possible to assess the impact of reservoirs only on the basis of selected single years in which the relevant thermal conditions occurred. However, in order to accurately characterize the role of reservoirs in transforming the ice regime of rivers, it is necessary to conduct accurate, quantitative assessment of their impact on river ice cover for long periods. Another issue is the small number of studies based on remote sensing data (including radar) for relatively small mountain rivers, where the course of ice processes is poorly understood (Thellman et al. 2021). This results in poor understanding of the extent of the influence of dam reservoirs on river ice cover (especially small mountain rivers), making it difficult to estimate their role on a regional or global scale.

The main objective of this study is to determine the impact of Carpathian dam reservoirs on the ice cover of rivers below their locations based on long observation series and radar (SAR) imaging. Specific objectives include: (1) develop and present a method to quantitatively assess the impact of dam reservoirs on the duration of ice cover based on measurement data from water gauge cross sections; (2) estimate the extent of their impact based on satellite radar imagery (SAR) and assess the feasibility of using Sentinel-1 satellite radar data to determine the extent of reservoirs' impact on the ice cover of this type of river. The essential hypothesis tested here is that dam reservoirs, at local and regional scales, have a greater impact on transformations in the occurrence of river ice cover than climate change.

2 Study area, data, and methods

2.1 Study area

The study was based on two sets of dam reservoirs located in the Outer Western Carpathians (Solina-Myczkowce) and the Central Western Carpathians (Dunajec- Sromowce Wyżne) in central Europe (Fig. 1). These reservoirs are located on two second-order mountain rivers whose sources are in the higher reaches of the Carpathians: the Dunajec and the San rivers. The flow of the Dunajec at its mouth averages over 84 $m^{3}\cdot s^{-1}$ with a catchment area of 6735 km^2, while that of the San averages 134 $m^{3}\cdot s^{-1}$ with a catchment area of 16,824 km^2 (Punzet, 1991). The width of the rivers in the sections below the dams varies from 30 m to more than 100 m. The basic characteristics of both sets of reservoirs are shown in Table 1.

Table 1: Characteristics of the studied reservoirs.

Reservoir	River	Year of completion	Total capacity [milion m^3]	Type of dam	Damming height [m]	Average inflow during the winter [$m^{3}\cdot s^{-1}$]	Average outflow during the winter [$m^{3}\cdot s^{-1}$]
Czorsztyn	Dunajec	1997	231,9	ground dam	52	20,6	20,4
Sromowce Wyżne	Dunajec	1994	7,42	ground dam	10		
Solina	San	1968	473,0	concrete dam	58	24,1	24,6
Myczkowce	San	1961	10,0	ground dam	15		

Source of data: Hennig et al. 1991; Bajorek et al. 2003

The two reservoir complexes studied in here consist of a main reservoir and an equalization reservoir. The Czorsztyn and Solina reservoirs are intended mainly for electricity production, and play a role in flood control, while the Sromowce and Myczkowce reservoirs serve as equalizing reservoirs for daily flow fluctuations caused by the operation of hydroelectric power plants. Both reservoirs significantly affect the thermal regime of the rivers below their locations. It has previously been shown that the operation of the hydroelectric power plant at the Solina reservoir significantly transforms the thermal regime of the Myczkowce reservoir, and consequently of the river below it, warming it in winter by about 2 °C (Lewinska and Lewinski, 1972). In the case of the Czorsztyn-Sromowce reservoir complex, studies have shown that they warm the temperature of the Dunajec waters below the reservoir by 1-2°C (Wiejaczka et al. 2015, Kędra and Wiejaczka, 2017). In addition, a disturbance between the air and water temperatures of the river below the reservoirs caused by their operation has also been found (Kędra and Wiejaczka, 2016). Both sets of reservoirs also experience a transformation of river flow volume due to the operation of hydropower plants and equalization reservoirs, with respect to natural conditions.

The main reasons for selecting these sites for this study were the good availability of hydrological and meteorological data, as well as the location and characteristics of these reservoirs. These reservoirs represent facilities typical of mountainous areas in terms of the size of the dam and the flow of the rivers on which they are located. This allows the results obtained to be related to other similar facilities and rivers. Additionally, the literature lacks a sufficient number of studies regarding ice phenomena in relatively small mountain rivers (Thellman et al. 2021).

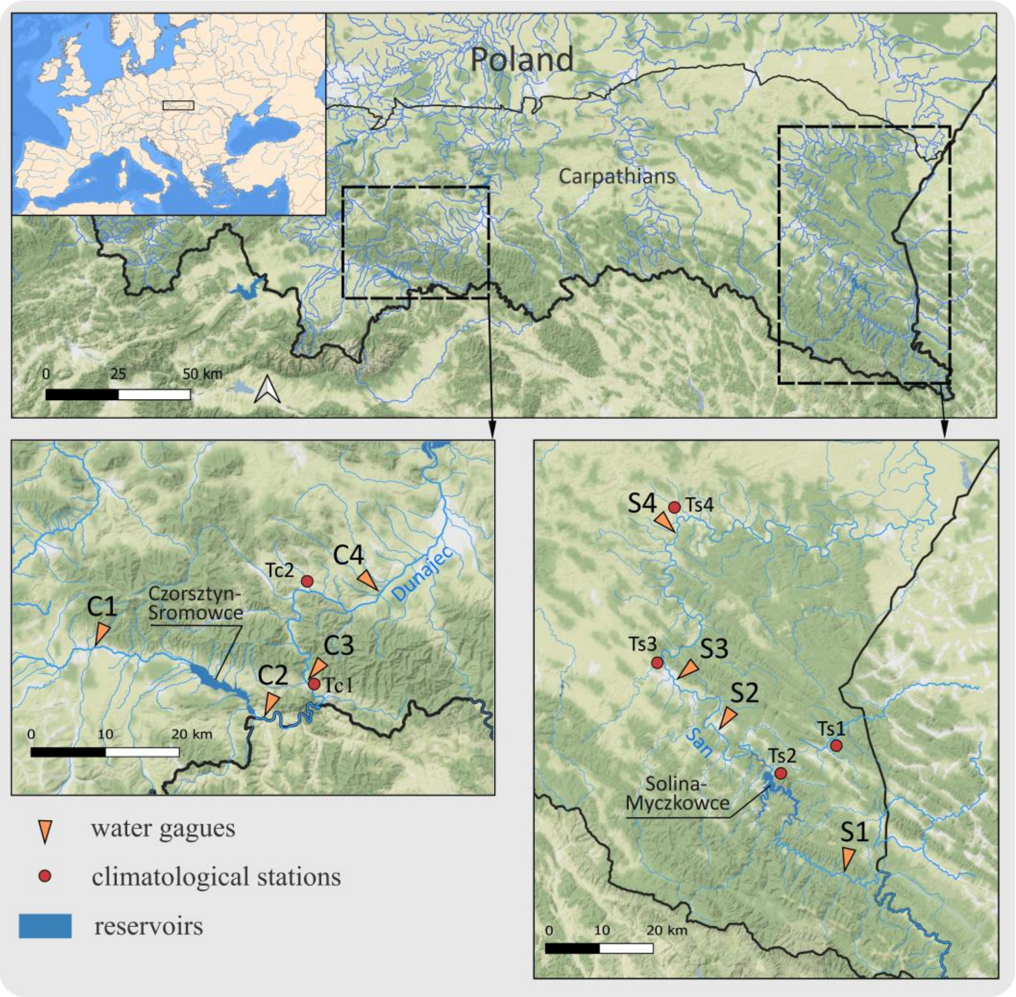

Figure 1: Study area and location of measurement stations used in the study.
Source: Map tiles by Stamen Design, under CC BY 4.0. Data by OpenStreetMap, under ODbL

2.2 Data and methods

In order to estimate the impact of dam reservoirs on river ice cover, data on the daily occurrence of ice cover over the period 1950–2020 were obtained at eight water gauge cross sections (four for each reservoir complex studied) (Figure 1). The occurrence of ice cover at a water gauge cross-section was defined as any occurrence of total ice cover (water surface completely covered by ice) or border ice (partial coverage of the water surface by ice). In both cases, one cross–section was located above the reservoir (C1, S1), while the others were located below the reservoir location, at distances ranging from several to tens of kilometers from the reservoir (C2: 1.8 km, C3: 22 km, C4: 52 km, S2: 11.7 km, S3: 33 km, S4: 80.5 km). Data on the occurrence of ice phenomena each day of the winter periods (November to March) in the 1950–1980 period were obtained from hydrological yearbooks published by the Polish State Hydrological and Meteorological Institute. These yearbooks were issued only in printed form, so for this study they were digitized by manually transcribing data on daily ice cover occurrence. Data on the occurrence of ice cover in the 1981–2020 period were obtained from the online public database of the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB, https://danepubliczne.imgw.pl/). Data on the course of average daily air temperature at climatological stations were also obtained from the IMGW-PIB public database. For the Solina-Myczkowce reservoir complex, climatological data were obtained from four stations (Ts1, Ts2, Ts3, Ts4), while for the Czorsztyn-Sromowce reservoir complex they were obtained from two (Tc1, Tc2). The acquired data on the occurrence of ice cover were subjected to statistical analysis involving a comparison of the duration of ice cover before and after the formation of the reservoirs at stations above and below its location, as well as a comparison of the two studied rivers. Data from periods for which there were no observations, or in which observations were incomplete, were excluded from the statistical analysis.

In order to separate the effects of climate change and reservoir operations on the ice cover of the studied rivers, a logistic regression method was used to model the relationship between air temperature and ice cover occurrence. Logistic regression is a method that allows the classification of a dichotomous explanatory variable based on one or more explanatory variables. The method was first proposed by Cox (1957) and is widely used in classification and prediction in natural science research. Previously, it has been used in studies of river ice phenomena (Yang et al. 2020, Wu et al. 2021), the delineation of flood-prone areas (Lee and Kim, 2021) or of areas susceptible to landslides (Ayalew and Yamagishi, 2005), among other applications, but has not been used in natural studies of the effects of dam reservoirs. Logistic regression analysis is based on the concept of odds ratios (OR) that represent the ratio of the probability (p) that an event will occur and the probability that the event will not occur, and which is expressed by equation (1).

$$OR = \frac{p}{1-p} \tag{1}$$

In order to carry out a binary classification of the dependent variable on the basis of the continuous independent variable, a logit transformation was applied by logarithmizing the odds ratio, as expressed by equation (2):

$$Logit(OR) = \log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 \qquad (2)$$

where x_1 is the explanatory variable and β_0 and β_1 are regression coefficients that are estimated using the maximum likelihood method. The probability of ice cover occurrence on a given day (p) is calculated using equation (3) and classification is done by applying a threshold value of probability that separates the occurrence of ice cover from its absence:

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1)}} \qquad (3)$$

where x_1 is the average air temperature of the 14 days prior to each day. The average air temperature of the 14 days prior to each modelled day was selected based on preliminary tests involving predicting the occurrence of ice cover based on the average of a different number of days prior to the modelled day.

The first stage of analysis required coding of the data from the water gauge stations, with a value of 1 assigned to each day in which ice cover occurred and a value of 0 assigned if it did not for the period from November to March over the entire study period (sometimes the period was shorter than 70 years due to data gaps). Each record was assigned an average air temperature from 14 days before the modeled day determined from measurements from the nearest climatological station. In some cases, data from several nearby stations were used simultaneously due to gaps in measurement data. Based on the acquired database, a logistic regression model of the relationship between the course of the average air temperature from 14 days before the modeled day and the occurrence of ice cover in the period before the dam reservoirs were built for each water gauge station. For the water gauges on the Dunajec River (C1, C2, C3, C4), data from the period 01.11.1957-31.03.1990 were used as the set for learning the model, while for the San River, data from the period 01.11.1956-31.03.1967 (S1) or 14.01.1951-31.03.1967 (S2, S3, S4) were used, depending on the station. The data for building the model was divided into a training set and a test set in the ratio of 70% to 30%. Model learning and hyperparameter optimizations (C - Inverse of regularization strength) were carried out based on the training set. Stratified cross-validation was used to avoid over-fitting the model on the training set, and the quality of the resulting models was determined by the prediction accuracy and the value of the area under the ROC curve (receiver operating characteristic curve) on the test set (ROC-AUC value). Based on the obtained models, for each adopted winter period, the probability of ice cover occurrence at the tested cross sections was calculated based on the average air temperature, from which it was determined whether ice cover could occur on a given day. Then, the ice cover occurrence data calculated from the model based on the course of the average air temperature was compared with actual observations of ice cover at all stations. In this study, it was assumed that the difference between the number of days with ice cover predicted by the model and the number of days with ice observed at the stations was due to the operation of dam reservoirs. In order to validate these results, the results of modeling and observations from stations above and below the reservoir were compared. All calculations were carried out using Python and the Scikit-learn library.

The period of January to February 2017 was chosen to determine the spatial extent of the impact of dam reservoirs on river ice cover based on remote sensing data. This choice was due to the persistence of very low air temperatures at measuring stations in the study areas during this period. Many stations recorded the lowest average January temperature since 2006 (–7.3°C) at this point, and occasionally, the air temperature reached as low as –20°C. It was found that such air temperature resulted in the persistence of ice cover on the studied rivers before the construction of dam reservoirs. Moreover, during this period, ice cover was observed at the water gauge cross sections above the two reservoirs from the beginning of December to the end of February. This study assumed that the lack of ice cover below dam reservoirs on the studied rivers during this period was due to dam operation.

In order to characterize the influence of the studied reservoirs on the occurrence of ice cover, the extent of river sections below the reservoirs where ice cover did not form on selected days was determined. The occurrence of ice cover was determined on the basis of radar (SAR) images acquired by Sentinel-1 satellites. In the first stage, the area of rivers (water surface) below the studied reservoirs was determined by manually creating polygons on the basis of aerial photos and cloudless Sentinel-2 satellite images. River areas in the vicinity of hydraulic structures (bridges), narrow river sections (< 30 m in width) and areas close to the banks (about 10 meters from the shore) were excluded from the analysis, which made it possible to exclude pixels partially covering areas other than the water surface. Then, for the designated polygons, Sentinel-1 SAR IW GRD imagery was acquired from five different days, for both studied rivers (02.01, 09.01, 14.01, 26.01, and 14.02.2017 for the Dunajec River and the Czorsztyn-Sromowce reservoir complex, and 09.01, 16.01, 21.01, 28.01 and 14.02.2017 for the San River and the Solina-Myczkowce reservoir complex). Data from descending orbits in VV and VH polarization were used. This study used imagery provided by Google Earth Engine, in which orbit metadata were updated, border noise was removed, thermal noise was removed, radiometric calibration values were applied, and terrain correction was performed. After preprocessing, the data had a spatial resolution of 10 meters. In order to classify the acquired images (water/ice), thresholds of the backscattering coefficient that separated the occurrence of ice cover from water were determined for both studied rivers. This determination of the presence of ice cover was made possible by the marked contrast between the two classes (ice/water) due to the significant effect of ice cover presence on the backscattering coefficient of the microwave radiation beam (Stonevicius et al., 2022; Palomaki and Sproles, 2022). Consolidated ice tends to have significantly higher backscattering values than water, mainly due to the roughness of its surface. For this purpose, the value of the backscattering coefficient was used for designated sections of rivers completely covered by ice (January 14 for the Dunajec River and January 9 for the San River). These sections were determined on the basis of cloudless images from the Sentinel-2 satellite. The thresholds of the values separating the two classes were calculated separately for the two studied rivers according to equation (4):

$$\tau_{\sigma} = \sigma - s \tag{4}$$

where σ is the average backscatter from selected sections of ice-covered rivers, and s is the average standard deviation of σ (Sobiech and Dierking 2013). For the Dunajec River, the thresholds were set at –19.24 dB for VH polarization and –10.16 dB for VV polarization, while for the San River they were set at –21.16 for VH polarization and –11.55 for VV polarization. The results were validated by comparing the classification results of Sentinel-1 radar imagery with optical imagery acquired by Sentinel-2 satellite for the Dunajec area acquired on February 14, 2017.

1. **Results**

For both studied rivers, the highest average annual number of days with ice cover during the study period occurred at cross sections located above the dam reservoirs: 65 days at point C1 (Dunajec) and 75 days at point S1 (San, Fig. 2).

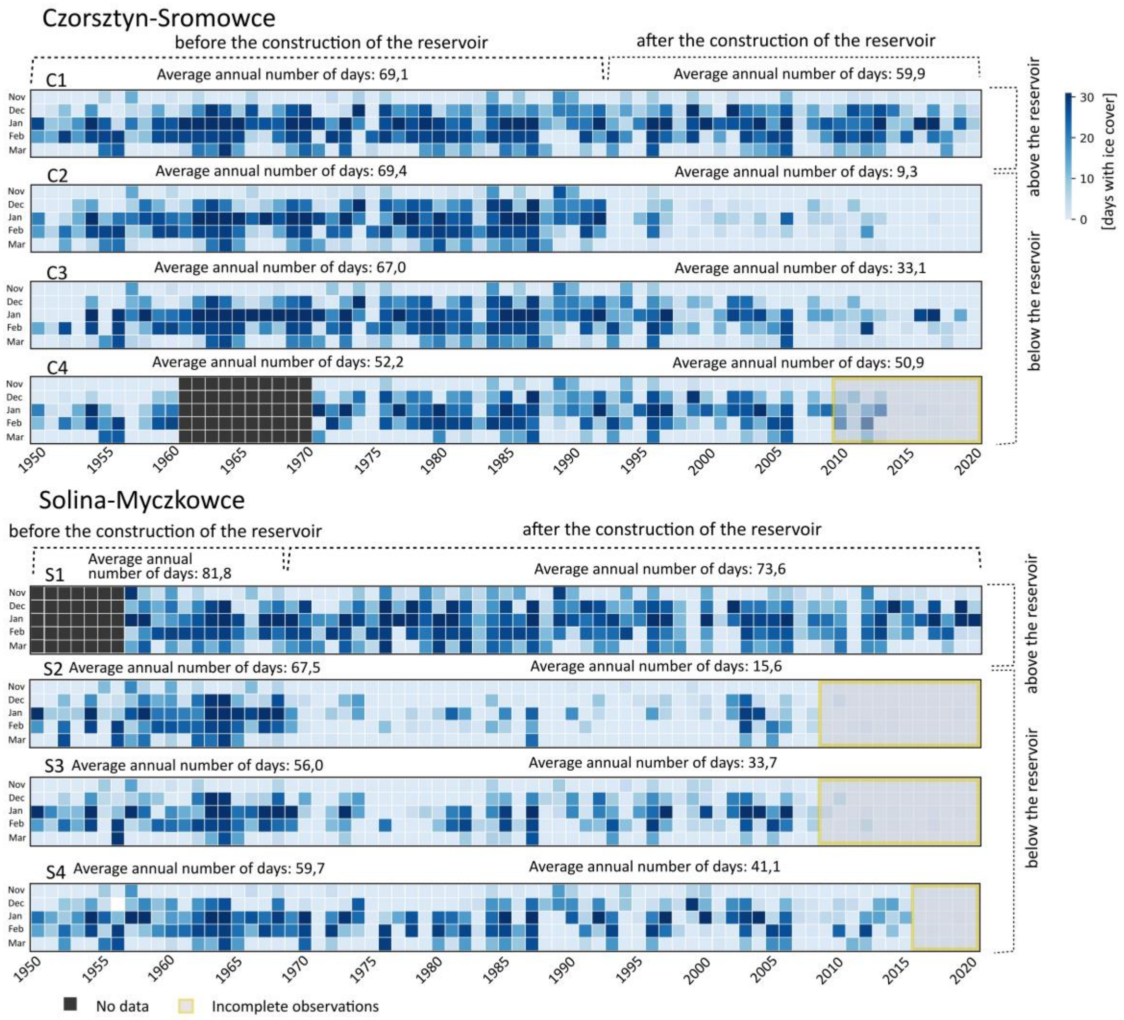

Figure 2: Observed number of days with ice cover in each month at water gauge stations.

At cross-sections below the reservoirs, the average annual number of days with ice cover ranged from 45–53 days for the Czorsztyn-Sromowce reservoir complex (C2, C3, C4) and from 32–46 days for the Solina-Myczkowce reservoir complex (S2, S3, S4). In all studied cross sections, a decrease in the frequency of ice cover was observed after the reservoirs were put into operation (Fig. 2).

In the case of the Dunajec River, the decrease in frequency varied along the river's longitudinal profile. At the cross-section located above the reservoir (C1), a 13.3% decrease in the number of days with ice cover was observed in the post-reservoir period (1993–2020) compared to the earlier period (1950–1992). At cross-sections located below the reservoir, the greatest decrease in the frequency of ice cover occurred at point C2 (86.2%) and decreased with increasing distance from the reservoir at cross-sections C3 and C4 (50.6% and 2.7%, respectively). For the San River, at the cross-section located above the reservoir (S1), a 10% decrease in the number of days with ice cover was observed in the period after its construction (1969–2020) compared to the earlier period (1950–1968). At cross sections below the reservoir (S2, S3, S4), the decrease in frequency was 77% , 39.8% and 31.2%, respectively. In the period before the construction of the reservoirs on the two rivers under study, the annual ice pattern followed a similar trend, despite the fact that they are approximately 140 kilometers apart. For example, the Pearson correlation coefficient of the annual number of days in the 1950–1968 period between stations C2 and S2 was 0.76 and was 0.86 between stations C3 and S3. In the period after the construction of the Solina-Myczkowce reservoir complex (1969–2009), the correlation dropped to 0.04 and 0.47, respectively.

The predictive ability of the logistic regression models was relatively high. The accuracy of correctly classifying days in the test set into two groups (days with ice cover/days without ice cover) based on the average air temperature of the 14 days before the modeled day ranged from 80–87%. The developed models had very good predictive ability, as evidenced by the high values of the area under the ROC curve ranging from 0.89–0.94 (Fig. 3).

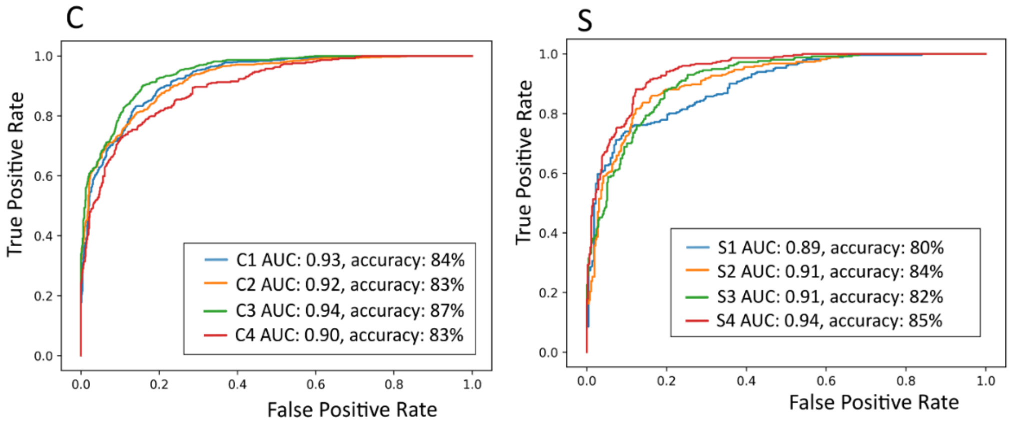

Figure 3: ROC curve, AUC values and prediction accuracy.

In the case of the Dunajec River, there is a noticeable difference in the values observed and predicted by the model below and above the Czorsztyn-Sromowce Wyżne reservoir complex (Fig. 4). At the C1 water gauge cross-section, the number of days with ice cover observed and predicted from air temperature before and after the reservoir was very similar (Fig. 4). At this location in the 1957–1992 period, the annual average observed number of days with ice cover was 73.1 days, while the number predicted by the model was 72.3 days.

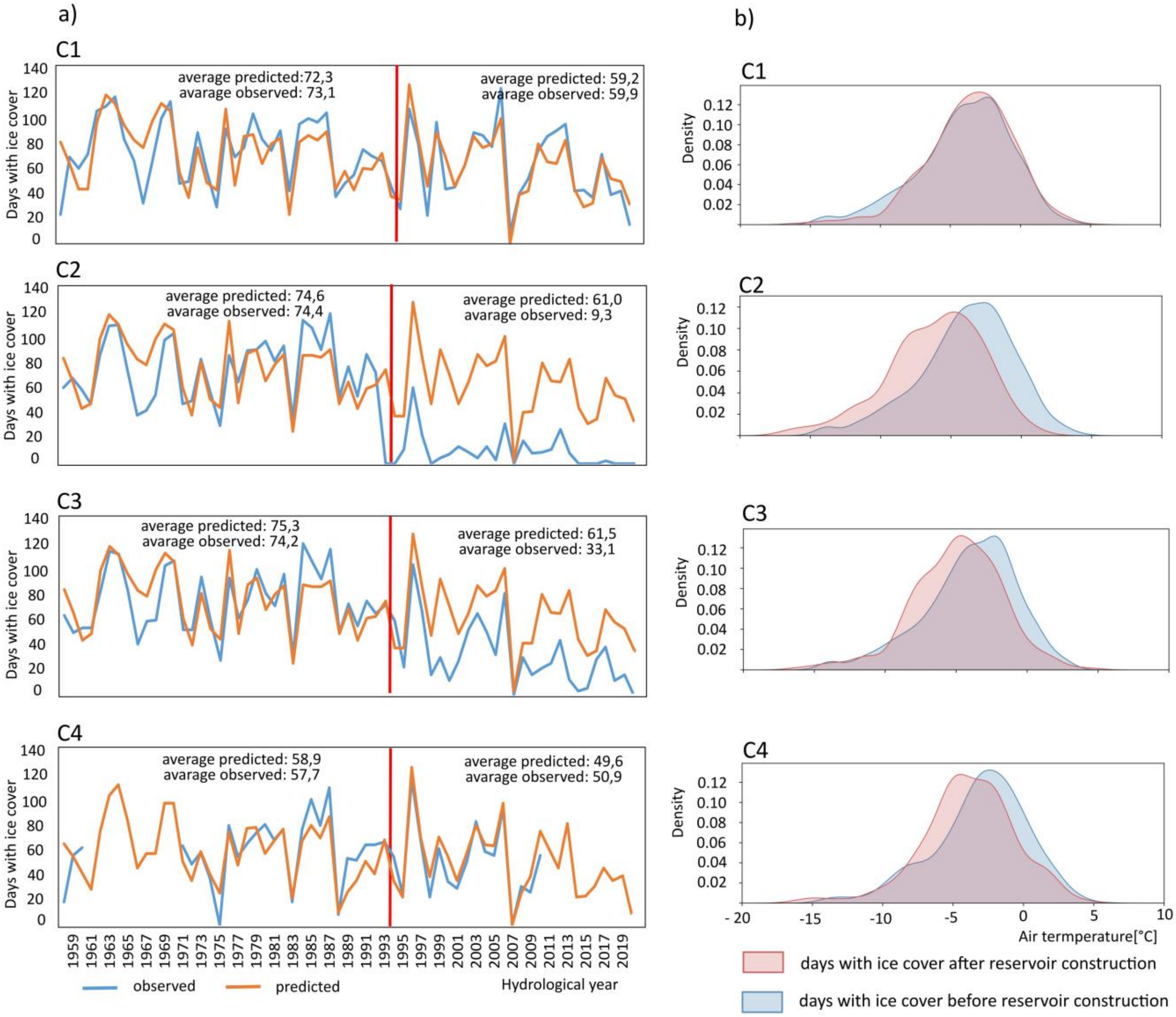

Figure 4: Comparison of modeling results based on air temperature with observations of ice cover for the Dunajec River and the Czorsztyn-Sromowce reservoir complex (a) and the density of the distribution of days with ice cover at temperatures before and after the construction of the dam reservoir (b). The red line indicates the year the dam was built.

In the post-reservoir period (1993–2020), these values were 59.9 and 59.2 days, respectively. At point C2, located directly below the reservoir, there was a significant discrepancy between the observed and predicted values based on air temperature in the post-reservoir period. In the 1957–1992 period, the average annual totals observed and predicted by the model were very similar: 74.4 and 74.6, respectively. In the period after the construction of the reservoir (1993–2020), the observed average annual number of days with ice cover was 9.3, while the number of days predicted by the model was 61.

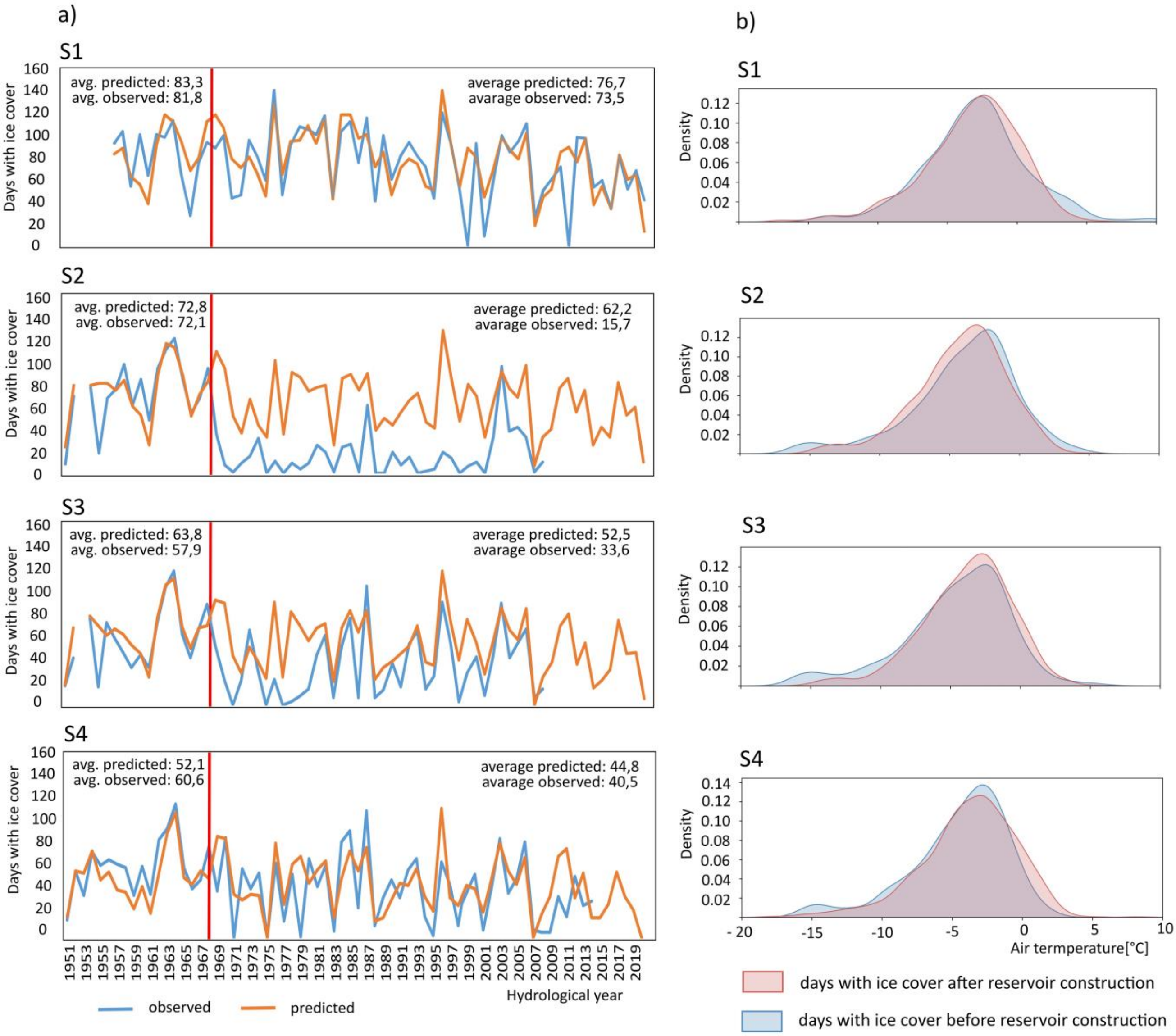

Figure 5: Comparison of modeling results based on air temperature with observations of ice cover for the San River and the Solina-Myczkowce reservoir complex (a) and the density of the distribution of days with ice cover at temperatures before and after the construction of the dam reservoir (b). The red line indicates the year the dam was built.

At point C3, after the construction of the reservoir, the difference between the observed and predicted average number of days with ice cover was less than at point C2, but still notable (half as much). At point C4 in the period after the construction of the reservoir, values were more similar to each other; the observed number of days was 50.1 while the predicted number of days was 47.5. In the cross sections located below the reservoir (C2, C3, C4), there was a significant shift in the distribution of the number of days with ice cover in the average air temperature in the period after the construction of the reservoir compared to the earlier period. This effect was not observed at point C1.

Similar results were obtained regarding the Solina-Myczkowce reservoir system (Fig. 5). In the cross-section located above the reservoir (S1), the temperature-based prediction and the observed average number of days with ice cover were similar both before (1950–1968) and after (1969–2020) the reservoir was built. For cross-section S2, located directly below the reservoir, a significant discrepancy was found in the observed and model-predicted average number of days with ice cover after the reservoir's construction. The average observed number of days with ice cover before the reservoir's construction was 72.1, while the number predicted by the model was 72.8. After the reservoir's construction, the observed average number of days dropped to 15.7 while the predicted number of days was 62.2. A similar trend was observed for cross-section C3. The annual average observed number of days with ice cover in the period after the reservoir's formation was 33.6, while that predicted by the model based on temperature was 52.5. At water gauge cross-section S4, the model-predicted and observed number of days with ice cover were very similar both before (predicted = 52.1; observed = 60.6) and after the reservoir was built (predicted = 44.8; observed = 40.5). In the case of the San River, a slight shift in the distribution of the number of days with ice cover in the mean air temperature was observed only at cross-section S2 located directly below the Solina reservoir.

It is worth noting that the accuracy of the prediction of ice cover occurrence by the developed models. Although the prediction accuracy determined from the test set varied in the 80–87% range, the multi-year averages of observed and predicted values at stations above the reservoirs were very close to each other (59.2/59.9 in cross-section C1 and 76.7/73.5 in cross-section S1 in the period after the construction of the reservoirs). The high agreement of these data suggests a higher accuracy than was determined from the test sets. This is most likely due to the dichotomous nature of the errors made by the model. The overall error includes predictions of the occurrence of ice cover when in reality there was none, and predictions of the absence of ice cover when in fact there was. Most likely, the existence of both types of errors in similar proportions resulted in high agreement over the long term (> 40 years).

The results of analysis of Sentinel-1 (SAR) data showed that, during the study period (January-February 2017), total ice cover did not form in a section of about 60 kilometers below the Czorsztyn-Sromowce reservoir complex and 26 kilometers below the Solina-Myczkowce reservoir complex (Fig. 6).

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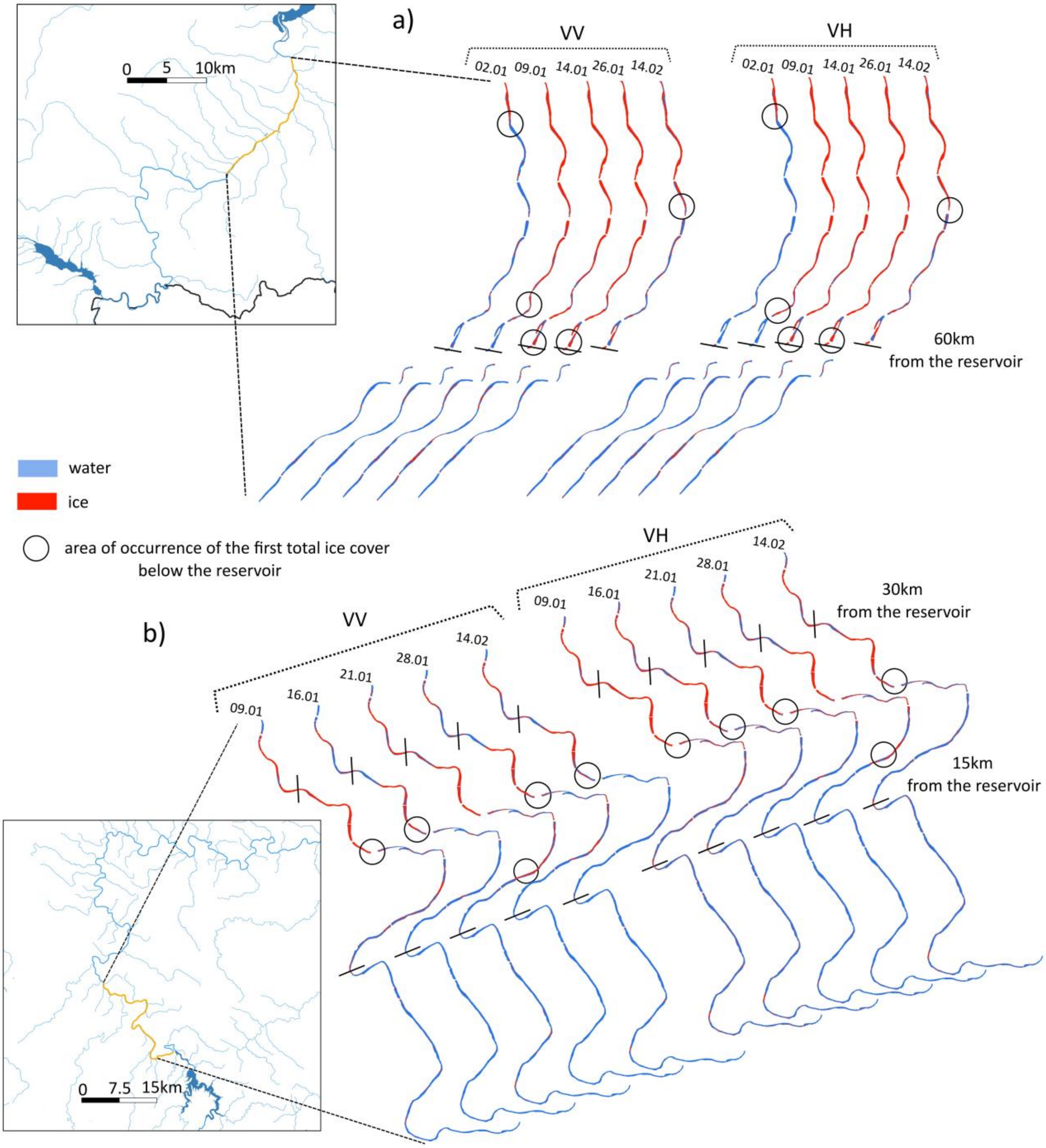

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291 **Figure 6**: The extent of ice cover on the Dunajec (a) and San rivers (b).

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The greatest icing events occurred in the second half of February, which was associated with the persistence of very low air temperatures (close to –10°C). On both studied rivers, three sections could be distinguished in terms of ice phenomena. Directly below the reservoir, a section was observed where the ice cover did not form completely. In the case of the Czorsztyn-Sromowce reservoir complex it reached about 40–50 kilometers below the reservoir, while in the case of the Solina-Myczkowce reservoir complex, it extended about 10 kilometers below the reservoir. Further away was a section where border ice occasionally formed, but the ice cover did not form completely, and the amount of border ice increased as the distance from the reservoir increased. The third section was characterized by the occurrence of total ice cover on most sections of the studied rivers (>60 kilometers in the case of the Czorsztyn-Sromowce reservoir complex and >26 kilometers below the Solina-Myczkowce reservoir complex).

Visual analysis of the classification results of SAR imagery, backscatter coefficient distribution maps, and optical imagery showed that the determination of the area where ice cover was not present below the reservoir was relatively accurate. River sections without ice cover were characterized by a predominance of pixels classified as water, while sections with ice cover were characterized by a predominance of pixels classified as ice (Fig. 7). The largest classification errors were recorded in narrow and shallow sections of the surveyed rivers without ice cover, where there was an increase in the backscatter coefficient unrelated to the presence of ice cover. This resulted in misclassification of pixels from this area as ice. Misclassification of pixels was also recorded in transition sections between open water and total ice cover where border ice was present, especially in narrow river sections.

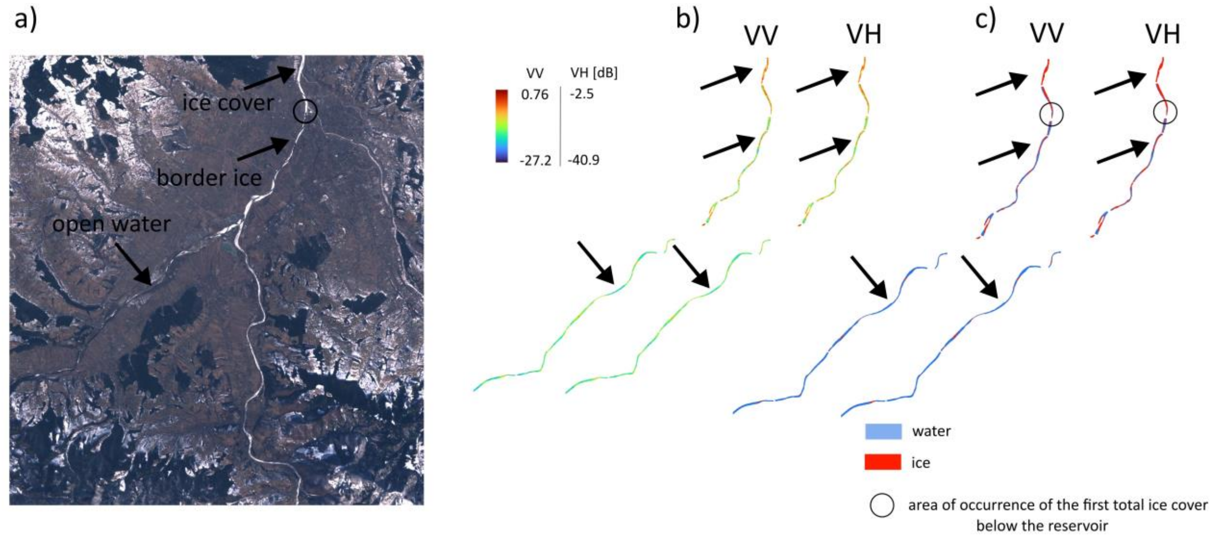

Figure 7: Comparison of Sentinel-1 backscatter coefficient (b), classification results (c) and Sentinel-2 data (a) acquired on February 14, 2017 for the Dunajec River.

Source: own elaboration based on data obtained from Copernicus Sentinel Data (https://scihub.copernicus.eu/). Copernicus Sentinel data (2017), processed by ESA.

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4. Discussion

This study demonstrates that the operation of the analyzed dam reservoirs was an important element in transforming the ice regime of the rivers below their locations. On the basis of observational data and modeling results, we found that the greatest transformations occurred at cross sections located closest to the facilities (C2, S2), and their influence decreased with increasing distance from the reservoir. This effect may be interpreted as a gradual decrease in the influence of the reservoir and restoration of the natural course of thermal and ice processes in rivers. The use of a classification method based on logistic regression allowed us to estimate that, in the case of the Czorsztyn-Sromowce reservoir complex, at cross-section C2 (1.8 km below the dam) in the period 1992–2020, the operation of the reservoir reduced the duration of ice cover by 84% on average, while at point C3 (22 km below the dam), reservoir operation reduced ice cover by 46%. Similarly, in the case of the Solina-Myczkowce reservoir complex, the operation of the reservoir reduced the duration of ice cover by about 75% at point S2 (11.7 kilometers below the dam), and by 36% at point S3 (33 kilometers below the dam). These results suggest that in the stretch of rivers about 20-40 kilometers below the reservoirs, the influence of the reservoirs was the main factor (it transformed the ice regime more than climatic variability) determining the observed disappearance of ice cover and the course of ice processes. This is supported by the much smaller magnitude of the decrease in the frequency of ice cover at cross sections above the reservoirs (10% and 13.3% after the construction of the reservoirs compared to the earlier period), where the decrease was mainly due to climatic conditions.

A visual comparison of the classification results of radar imagery (Sentinel-1) with optical data (Sentinel-2) showed that it was possible to determine, with relative accuracy, the extent to which there was no ice cover below dam reservoirs on mountain rivers with similar characteristics to those analyzed in this study. Based on the threshold of the backscattering coefficient to two classes (water/ice) on rivers similar to those studied here (width of 20–100 meters), it was possible to determine the approximate extent of the river section below the reservoir on which the total ice cover did not form. The range of influence of the studied reservoirs on the occurrence of river ice cover on the basis of SAR data was determined to be 26 kilometers for the Solina-Myczkowce reservoir complex, and 60 for the Czorsztyn-Sromowce reservoir complex. An analysis of the river network in the catchments of the studied rivers showed that the smaller extent of the influence of the Solina-Myczkowce reservoir complex was most likely due to the mixing of the waters of the San with two relatively large tributaries in close proximity to the reservoir, the Hoczewka and Oslawa (average winter flow at the mouth of 2.8 m^3/s^{-1} and 8.6 m^3/s^{-1}, respectively). The mixing of these waters with those of the San River (average winter outflow from the reservoir 24.6 m^3/s^{-1}) may lead to a drop in water temperature and the appearance of ice phenomena. This is also evidenced by the lack of a clear shift in the number of days with ice cover in the average air temperature at cross sections below the reservoir. By comparison, for the Dunajec River, total ice cover appeared during the analyzed period about 60 kilometers below the reservoir in the vicinity of a tributary of the Poprad River, one of the larger tributaries of the river.

Similar results have been previously obtained for other dam reservoirs located in mountainous areas, including in the Carpathian Mountains. Cyberska (1972, 1975) analyzed the influence of a complex of dam reservoirs (dam height of 32.5 meters) on the thermals and occurrence of ice phenomena on the Dunajec River (Poland). Cyberska estimated that in the period after the reservoir's construction, the 12–65 km downstream area of the reservoir saw an average 65% reduction in the duration of ice cover. These values are slightly higher than those obtained in this study, especially for cross sections located far from the reservoir, which may be due to the fact that they were estimated based on the comparison of periods before and after the reservoir's construction without accounting for the possible influence of changing climatic conditions. An estimate based on a similar methodology made by Wiejaczka (2009) showed that, on the Ropa River, at a cross-section located 16 km downstream of the dam, after the construction of the dam reservoir (dam height of 34 meters), there was a 35% decrease in the frequency of ice cover (total and border ice). Chang et al. (2016) compared periods with similar thermal conditions (before and after reservoir construction) and analyzed the impact of large (dams 178 and 147 meters high) dam reservoirs on ice phenomena on the Yellow River. They found that their operation reduced the duration of ice phenomena at downstream stations by 33, 22, and 8 days, which is less than the value estimated in this study. However, these results are particularly significant given that the gauging stations are located more than 800 kilometers below the reservoirs. An important role in the transformation of the ice regime was also demonstrated in the case of the Williston Reservoir in Canada on the Peace River (dam height 186 meters). As a result of that operation, total ice cover did not form for 100–300 kilometers downstream of the dam (Jasek and Pryse-Phillips 2015). This is far higher than the value estimated in this study, which may be due to the different sizes of these rivers and reservoirs. Similar results were obtained for the Krasnoyarsk reservoir (Belolipetsky and Genova 1998); downstream of the dam (124 meters), the ice cover also did not form for 100–300 kilometers, depending on hydrometeorological conditions. Transformations of the river ice regime have been observed for both large reservoirs (dams higher than 15 meters) and small ones. For example, Maheu (2016) analyzed the impact of small dam reservoirs (dams 7–13 meters high) on thermals and water ice in eastern Canada. Using two examples, he showed that the operation of these facilities significantly raised water temperatures and reduced ice formation in sections up to 2.5 kilometers downstream.

Similar effects on river ice cover have also been reported for lowland reservoirs, which have different characteristics (usually less depth) due to terrain. Takács et al. (2013) analyzed the occurrence of ice cover above and below small dams (< 10 meters) in the Raba River basin (Westen Transdanubia, Hungary). They based their study on selected periods with similar thermal conditions before and after the construction of the reservoirs, showing that, after their construction, the relative frequency of ice cover below their location decreased by up to 10%, and that anthropogenic factors were crucial in transforming the ice regime of rivers. The significantly smaller impact of these reservoirs than the values estimated in this study can be explained by their smaller size. Pawłowski (2015) showed that the construction of the Wloclawek reservoir on the Vistula River (Poland) resulted in a 47% reduction in the duration of ice cover downstream of its location and a 26% reduction in the duration of all ice events, leading to a significant transformation of the river's ice regime. Here, to demonstrate the impact of reservoirs, periods with similar average air temperatures before and after the reservoirs were selected. These values were smaller than those obtained in this work, which is likely due to the fact that the Wloclawek reservoir has a damming level that is five-fold lower (11 meters). Apsîte et al. (2016) analyzed the impact of the operation of three dam reservoirs (dam heights of 18–40 meters) on the phenology of ice phenomena on the Daugava River (Latvia), showing that, at a station 6 kilometers below the reservoir after its construction, there was a reduction in the duration of ice cover by 91 days. This is a greater decrease in the frequency of ice cover than estimated in this study, but it was not determined how much of this effect was due to the construction of the reservoir in relation to climate change.

An important issue in analyzing the impact of dam reservoir operations on the ice regime of rivers lies in distinguishing their impact from that of air temperature variability, which is fundamental to the course of river ice processes and is the main determinant of the currently observed shortening of the duration of ice events on rivers (Magnuson et al., 2000; Yang et al., 2020; Newton and Mullan 2020). In the studies cited above, the impact of reservoirs was analyzed by comparing thermally similar periods before and after their formation. Typically, periods have been selected based on average winter temperatures. However, approach appears to be an oversimplification due to the averaging of extreme values over entire periods. Furthermore, this method limits analysis to selected periods only. The method presented in this work made it possible to demonstrate the impact of reservoirs on river ice cover over the entire period after their creation, regardless of climatic variability.

The results obtained here and in other studies indicate that dam reservoirs crucially transform the ice regime of river areas downstream of their locations. This effect occurs for both large and deep reservoirs and relatively shallow and small reservoirs. The main reasons for the transformation of the ice regime of rivers by dam reservoirs may include the transformation of river thermals, changes in volume and flow dynamics due to their operation, and reduction in the supply of mobile ice from higher parts of the catchment. A certain role may also be played by a dam's capture of some suspended material, the presence of which, in the water, contributes to the occurrence of phase transformation of water and the formation of a slick (Takács and Kern; 2015). Of particular importance in the case of the studied rivers may be the transformation of their thermals; Kędra and Wiejaczka (2016, 2017) and Wiejaczka et al. (2015) previously showed that the Czorsztyn-Sromowce reservoir system had a significant impact on the course of the Dunajec River water temperature (Fig. 8), as well as the synchronization of air and water temperatures in the river.

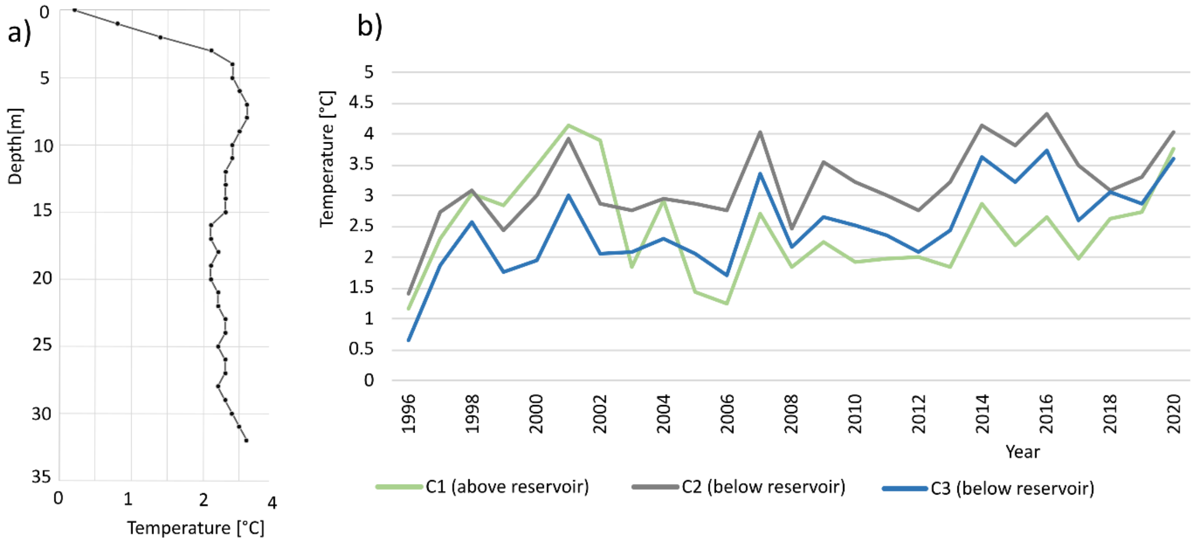

Figure 8: Vertical profile of water temperature in Czorsztyn Reservoir (a) and average water temperature of the winter periods in river at stations above and below the reservoir (b). Vertical profile temperature measurements were developed based on the work of Wiejaczka et al. (2015). The measurements were conducted on February 15, 2013. The average water temperature of the river was obtained from the database of the Polish Institute of Meteorology and Water Management.

During winter, dam reservoirs warm the river below by releasing warmer bottom hypolimnion waters (Soja and Wiejaczka, 2014). As a result, during cold winters, the water in the river below the reservoir reaches as much as 2 °C, limiting the possibility of ice cover development.

Despite the relatively high predictive ability of the presented logistic regression models and the high agreement between modeling results and observations at stations above the reservoirs, extreme caution should be exercised when analyzing the impact of dam reservoirs using the presented method because of limitations that arise from both the nature of the data and the river ice processes themselves. First of all, the presented method does not take into account other possible factors affecting river ice phenomena; these mainly may include regulation of rivers affecting the conditions of ice formation, all kinds of thermal pollutants emitted into rivers, discharges of municipal and industrial wastewater that can increase the content of dissolved substances and thus lower the freezing point, and the occurrence of natural changes in the hydrological and morphological characteristics of rivers and their channels. An important problem is also the significant sensitivity of the model to input data on the occurrence of river ice cover; due to its characteristics (large variation of parameters in the longitudinal profile of rivers, non-linear nature of development and disappearance, significant sensitivity to hydrological and meteorological conditions), this is difficult to describe and classify into a rigid framework, which can translate into modeling results.

The method presented in this paper and the results obtained here may be of significant importance in the study of the ice regime of rivers at local, regional, and global scales. This is due to the significant increase in the number of dam reservoirs in ice cover areas since the beginning of the second half of the 20th century (Fukś; 2023). It has been estimated that there are more than 8,000 such facilities, most of which are located in areas where ice cover on average lasts a relatively short time, from 15 days to 3 months (Fukś, 2023). In Europe, most of the reservoirs in areas where river ice is present are located in the central region and on the Fennoscandian peninsula (Fig. 9). In areas of ice cover, a particularly large number of reservoirs are also located in central North America and central and eastern Asia (Fukś; 2023). Moreover, these are areas where a significant reduction in the duration of river ice cover has been observed over the past 40 years (Yang et al., 2020). Based on the studies presented here, it is reasonable to assume that the increase in the number of dam reservoirs is responsible for part of this effect.

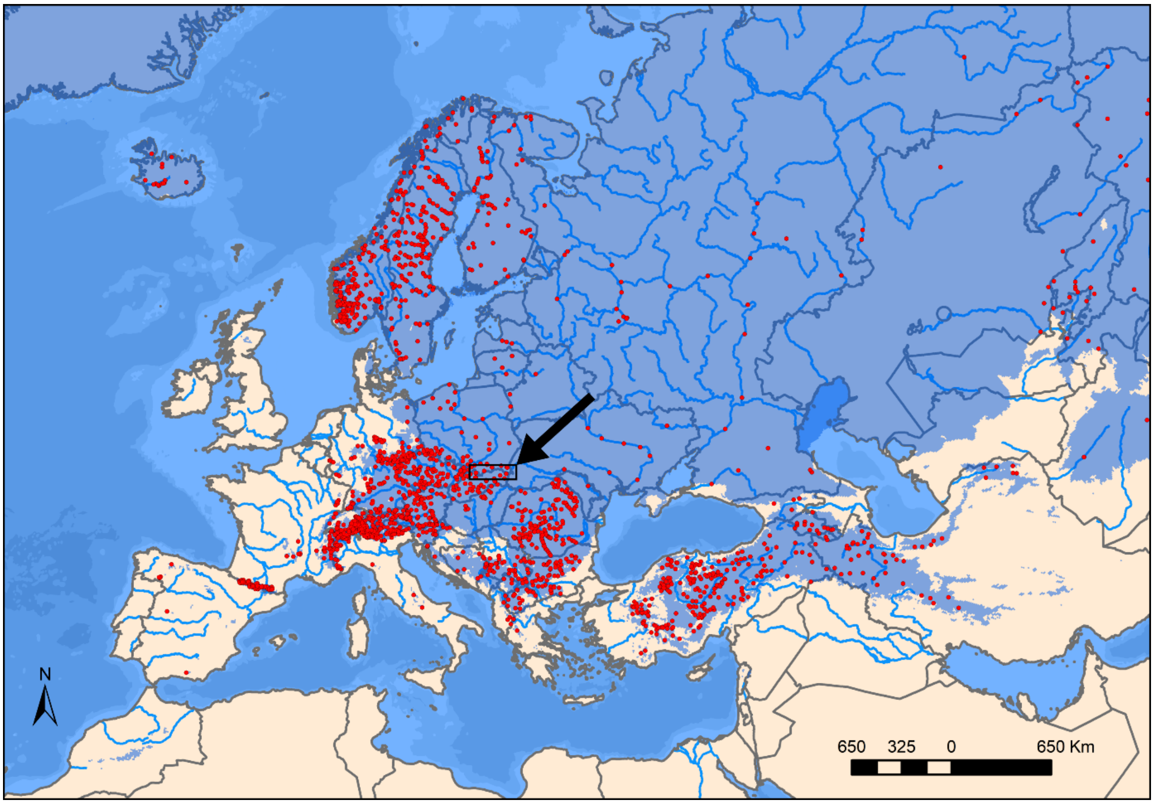

Figure 9: Location of dam reservoirs (red dots) in areas of river ice cover in Europe (highlighted in blue). The area of this research is marked with an arrow. Compiled from Fukś, 2023.

5. Conclusions

Using two reservoirs located in the Carpathian region as an example, this study presents a method for estimating the impact of dam reservoirs on river ice cover based on measurement data from water gauge cross sections and a logistic regression model. An estimation of the extent of the impact of dam reservoirs based on SAR data acquired by Sentinel-1 was also made here, and this method's use for determining the extent of dam impact was evaluated. The conclusions of the study can be summarized as follows:

1. At the local scale (single river), dam reservoirs have a greater impact on the observed decrease in the occurrence of ice cover of the rivers studied than does climate change. The results presented here suggest that, in areas with a large number of reservoirs, these reservoirs may play an important role at the regional scale. This is evidenced by the modeling results and their comparison to the variability of ice cover occurrence in cross-sections not influenced by a dam reservoir (C1, S1). The decrease in the incidence of ice cover due to the operation of dam reservoirs could exceed 80% in the sections of rivers immediately below dam locations, with this effect decreasing with increasing distance from the reservoir. Based on this

study, it can be assumed that the increase in the number of dam reservoirs is an important factor in the currently observed shortening of the duration of river ice cover.

2. The range of river sections below the studied reservoirs on which total ice cover does not form was estimated at 60 and 26 kilometers from the reservoir dam location. Based on the results presented in this study and a review of the literature, it can be concluded that the extent of dams' impact varies greatly. This is most likely due to a number of environmental conditions in which the river and reservoir are located, as well as the technical features of the dam and reservoir.
3. Logistic regression models are a useful tool for studying the impact of dam reservoirs on river ice cover. This is evidenced by the high predictive ability of the created models, the relatively high accuracy determined on the basis of test sets, and the very high agreement of the modeling results with observations at cross sections above the reservoirs. After appropriate adaptation, the logistic regression model and the presented procedure can be used to study the impact of dam reservoirs on other elements of the natural environment.
4. In relatively narrow (20–100 meters) mountain rivers, SAR data is a useful tool for determining the sections below dam reservoirs in which ice cover does not form. Despite the many errors inherent in the classification of SAR imagery, it is possible to estimate how far below the reservoirs there is ice cover, which permits study of the extent of their influence. The usefulness of this type of data is evidenced by the validation of results based on optical imaging of the Sentinel-2 satellite.

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Declaration of Competing Interest

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

Data availability

Data on the daily occurrence of ice cover on the studied rivers and daily air temperature were obtained from the repository of the Polish Institute of Meteorology and Water Management (IMGW-PIB, https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/) and hydrological yearbooks of surface waters of the Polish Institute of Meteorology and Water Management from 1949-1980. Sentinel-1 data was obtained from the Earth Engine Data Catalog (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S1_GRD).

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