Performance evaluation of quad-pol data compare to dual-pol SAR data for river ice classification

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ABSTRACT
Satellite SAR data are a unique source of information about river ice since the microwaves penetrate through clouds as well as snow and ice cover. The influence of the number of polarization channels on the nature and amount of information is, however, not yet fully investigated. The article intends to compare quad-pol and dual-pol data. The studied areas include two rivers with different types of ice cover – the Peace River in Canada and the Vistula River in Poland. We used RADARSAT-2 quad-pol Single Look Complex (SLC) data. The comparison methods include separability analysis (Hellinger distance, Bhattacharyya distance) and Wishart supervised classification. We found that dual-pol and quad-pol data provide equivalent information for homogeneous ice cover (overall classification accuracy above 80% for all polarization modes). Differences were observed in case of complex river ice cover with high diversity of ice types.

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Introduction

Ice phenomena are a natural element of the river regime in the temperate climate zone. The main reasons why they should be monitored are: flood protection, maintaining the patency of transportation routes and adjusting the operations of hydroelectric power plants. Satellite imagery make it possible to obtain information for long sections of rivers, including those located in areas inaccessible for ground-based observations. MODIS data are often used because of the possibility to acquire information on a daily basis (Chaouch et al., 2014; Cooley & Pavelsky, 2016; Kraatz, Khanbilvardi, & Romanov, 2016). However, the limitation for the use of MODIS data – and other data acquired in the visible range and near infrared ranges of electromagnetic radiation spectrum – is the occurrence of clouds. Microwave radiation overcomes this constrain as it penetrates through clouds. Also, microwaves pass through well frozen snow and ice cover. For these reasons SAR data are a unique and complementary source of information for the needs of ice cover monitoring.

The research conducted on river ice analysis with SAR data has taken several directions: study of the values of backscatter coefficients for different types of ice cover (Gherboudj, Bernier, & Leconte, 2010); automatic algorithms for ice types classification (Chu, Das, & Lindenschmidt, 2015; Chu & Lindenschmidt, 2016; Gauthier, Tremblay, Bernier, & Furgal, 2010; Mermoz, Allain, Bernier, Pottier, & Gherboudj, 2009); study of ice thickness (Kamiński, Alho, Colpaert, & Lotsari, 2017; Mermoz et al., 2014). However, few studies are found that examine how SAR data parameters – frequency, polarization and incidence angle – influence the possibility of detecting specific ice types. It should be stressed that recognizing the types of ice cover is largely dependent on these parameters. In this study we investigated an impact of a number of polarization channels.

Analysis of data in different polarization may reveal different information about the surface characteristics. Interpretation of the radar images requires understanding of how the vertical and horizontal polarizations differ in their interactions with the surface and what causes the depolarization of the scattered signal. The basic physical process responsible for the depolarization of the scattered signal is the multiple signal bouncing. It can be triggered by surface structure (so-called surface scattering) or the presence of numerous volume-scattering elements (so-called volume scattering). In the case of river ice, the surface scattering is influenced by the effective (calculated in relation to the wavelength) roughness and dielectric constant at the air-ice and ice-water interface (Mermoz et al., 2014). The higher
the effective roughness, the bigger depolarisation of the incident wave, which is observed in decrease in values of co-polarization channels (HH, VV) and increase in values of cross-channels (HV, VH). Volume scattering, which also effects in depolarization of the scattered signal, is caused by air bubbles and various impurities embedded in the ice cover (Mermoz et al., 2014).

Gherboudj et al. (2010) modelled the interaction of the radar signal with the different ice types formed on natural freshwater bodies. They showed that the difference of the co-polarization channels (VV and HH) can be used to distinguish between clear ice cover and columnar ice embedded with tubular air inclusions. For the range of incidence angle used by RADARSAT-2 the difference of co-polarization channels is higher for the clear ice than for the ice cover with the tubular air inclusions. Russell et al. (2009) received the best separation of water from ice for HH polarization while HV polarization showed a greater impact on the separation of individual classes of ice (consolidated ice, intact ice, frazil ice). The classification algorithm with two polarization channels (HH + HV) have provided better results for the classification of ice compared to a single polarization (Russell et al., 2009). Jasek, Gauthier, Poulin, and Bernier (2013) investigated the effect of the number of polarization channels using the IceMAP algorithm, which is based on the backscattering coefficients and the texture of the image. The combination of three polarizations (HH + HV + VV) provided a visual product that allowed accurate interpretation of the various ice types and processes, but given the overall accuracy of the five sets of data, the best classification results were obtained for the two polarization data HH + HV (Jasek et al., 2013).

The aim of this study is to compare the potential of the quad-pol and dual-pol data to recognize certain types of ice cover. As studied areas we chose sections of two rivers: Peace River in Canada and Vistula River in Poland (Figure 1). The selected rivers sections differ in terms of the water flow conditions and, in consequence, the formed ice cover. We generated dual-pol data from the original quad-pol RADARSAT-2 data as sub-sets. Our study involved analysis of separability using Hellinger distance and Bhattacharyya distance, and Wishart supervised classification.

Data

To compare the potential of the quad-pol and dual-pol data to recognize types of ice cover we used quad-pol RADARSAT-2 data (C-band) (Table 1) in the form of Single Look Complex (SLC) product. The SLC data retain the optimum resolution

![Figure 1. Study areas: (1) the Peace River (Canada) km 909 – km 919 with characteristic points: Vermilion Rapids (km 913) and Vermilion Falls (km 915.7); (2) the Vistula River (Poland) km 570 – km 670 with characteristic points: Kepa Oslicka (km 625–626) and Wloclawek dam (km 675). Base map source: ESRI.](image_url)
available for each mode as well as the phase and amplitude information of the original SAR data. We also used Landsat data, aerial photos, terrestrial photos and ground measurements (Table 2) to get information which types of ice cover occur in particular sections of the Peace River and the Vistula River. The formation of river ice depends on the flow conditions which are conditioned by the shape of the river bed and its bathymetry. For this reason, usually the same types of ice are formed in the same places every year, and so archival data are often used to know the distribution of ice types for a given section of the river.

In the case of the Peace River aerial surveys, satellite and ground observations, or field measurements are conducted regularly, but not over the entire length of the river and not simultaneously. The section considered in this study is very remote and inaccessible, and so it was not possible to perform field measurements in the dates of SAR data acquisition. However, the river characteristics and the ice processes in the section are very well known and confirmed by historical Landsat images and aerial photos published by Jasek et al. (2013).

The terrestrial photos and ground measurements were available for the Vistula River. During the last 20 years, the Department of Hydrology and Water Management at the Nicolaus Copernicus University in Toruń carried out measurements in about 100 cross-sections of the river bed, often in the same cross-sections in the interval from a few to a dozen of days during one winter. For precise measurements of ice cover, a special non-core sampler was used. The sampler enabled measurement of ice thickness and identification of ice cover layers characterized by different compactness. Therefore, this sampling method allows to precisely detect hanging frazil dams under fixed ice cover. During sampling, changes in the thickness of different ice cover layers can be recorded with a high precision of 5 cm. In a cross-section, measurements are made every 25–50 m.

In the winter 2013/14 fieldwork has been carried out on 4th February in three cross-sections (km 622, km 625, km 635) where different ice cover types were observed (Figure 3). After an ice cover formation, when there are no significant flow variations and the average daily air temperature remains negative, the ice cover changes very slowly from day to day. We verified and confirmed stability of the ice situation between the dates of the ground measurements and SAR data acquisition by analysing the daily reports from the Regional Water Management Board – the body of the national hydrological service responsible for the monitoring of water levels and ice cover on rivers.

### Areas of interest and characteristics of ice cover types

The study areas consists of sections of two rivers: Peace River in Canada and Vistula River in Poland (Figure 1). The ice cover on the Peace River is heterogeneous (high diversity of ice types), whereas the ice cover on the Vistula River is homogeneous (little diversity of ice types).

### Table 2. Additional satellite, aerial and ground data used to get information about the distribution of ice types on areas of interest.

| Data type             | Acquisition date | Covered area                                      |
|-----------------------|------------------|---------------------------------------------------|
| Landsat TM            | 09.11.1984       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 25.11.1984       | Peace River: whole area of interest (km 909–919)  |
| Landsat ETM+          | 19.11.1999       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 12.11.2002       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 27.11.2002       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 22.11.2003       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 18.11.2005       | Peace River: whole area of interest (km 909–919)  |
| Landsat TM            | 22.11.2005       | Peace River: whole area of interest (km 909–919)  |
| Aerial photos (from Jasek et al., 2013) | 30.11.2011 | Peace River: Vermilion Rapids (km 913), Vermilion Falls (km 915,7) |
| Terrestrial photos    | 04.02.2014       | Vistula River: three cross-sections (km 622, km 625, km 635) |
| Ground measurements   | 04.02.2014       | Vistula River: three cross-sections (km 622, km 625, km 635) |
**Peace River**

The Peace River (1923 km) originates in the Rocky Mountains and flows from South to North-East crossing two Canadian provinces: British Columbia and Alberta. The selected 10 km-long and 1.6 km-wide section of the river (km 909–919) is located in northern Alberta. Two characteristic points, Vermilion Rapids (km 913) and Vermilion Falls (km 915.7), are responsible for a large diversity of ice-cover types found on such a short stretch (Jasek et al., 2013). We chose this river section because it is within an area of interest for BC Hydro who operates a hydroelectric facility on this river. Due to its remote location the section is inaccessible for ground measurements of ice cover, which on the one hand confirms deep need to use satellite data application, but, on the other, limits possibility of collecting reference data.

Using archival Landsat data, aerial photos and expert knowledge, we selected five classes of ice in this river section: skim ice with three different degrees of compactness (SI, JSI, ASI), frazil pans (FR), consolidated ice (CI) (Figure 2). During the selected period of ice cover formation, open water (OW) was observed in areas of rapids and falls.

The skim ice (SI) is a thin and smooth layer of ice floating on the water. It forms in river stretch with low flow velocity. For the selected section of the Peace River such conditions occur above the rapids (km 913) (Jasek et al., 2013). For the selected period we observed on the SAR RGB images areas of skim ice that varied in pixel brightness, which was caused by the different compactness of skim ice fields. Therefore we distinguished three classes: skim ice (SI) – flowing ice fields (low compactness), juxtaposed skim ice (JSI) – ice fields stacked in a side riverbed (moderate compactness), and agglomerated skim ice (ASI) – ice fields that flowed with the river and were cumulated at the borders of stable ice cover (high compactness).

Frazil ice (FR) is the name for ice crystals of about a dozen millimetres that form around the air bubbles or particles suspended in the stream. They form in river stretch with the turbulent flow, where water is supercooled in the entire water column. Frazil ice is adhesive, so individual crystals merge into larger structures. These structures flow to the water surface, where they connect to each other creating characteristic discs of up to several centimetres, called frazil pans. On this 10 km section of the Peace River, frazil pans have been observed on the stretch between the rapids and the falls (km 913–915.7) (Jasek et al., 2013).

Consolidated ice (CI) was the last ice class selected for the Peace River. It was formed below the falls (km 915.7) by accumulation of ice that flowed with the river current. It is characterized by very diverse morphology and high thickness. The greater thickness of ice cover results in limitation of the flow cross-section, which leads to an increase in water...

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**Figure 2.** Examples of ice cover types observed on the Peace River: OW – open water, SI – skim ice, JSI – juxtaposed skim ice, ASI – agglomerated skim ice (higher surface roughness than juxtaposed skim ice – JSI), FR – frazil run, CI – consolidated ice. RADARSAT-2 image: backscattering coefficients, RGB colour composition: HH HV VV.
level. Thus, detection and determination of the extent of the consolidated ice cover is particularly important.

Figure 4 shows the mean values of the backscattering coefficients for each class of ice cover in the HH, HV, VV polarizations. For consolidated ice (CI) the mean value is at least 10 dB higher in each polarization compared to the mean value for the other classes. Therefore, it can be assumed that this class will be correctly distinguished from other forms of ice cover. In the case of open water (OW) and skim ice (SI), the mean values in each polarization differ by less than the standard deviation of the samples. This suggests that issues in distinguishing between these classes may occur.

**Vistula River**

The second study area was a 100 km-long reach of the Vistula River, which is the longest river (1047 km) in Poland. The river starts in the Carpathian Mountains and flows from South to North up to the Baltic Sea. The selected section is located in central Poland and contains a water reservoir, ended with a dam, and unregulated river upstream the reservoir. In this section, the width of the river bed varies from 500 to 1600 m. Presence of the Wloclawek dam results in slow water flow in the Wloclawek reservoir and, in consequence, in a homogeneity ice cover.

Based on the field observation and expert knowledge, we identified four classes of ice cover (Figure 5) for the selected section: smooth ice (SmI), contact zones between fields of smooth ice (CZ), two types of ice cover from mobile ice forms – juxtaposed (JI) and agglomerated (AI) with higher surface roughness than juxtaposed ice. Detection of agglomerated ice cover (AI) is particularly important from the point of view of flood protection. Smooth ice cover (SmI) is firstly formed along the river banks and then expands towards the middle of the river. For this reason in literature, this type of ice is also referred to as "border ice". A field of smooth ice can be torn off from the shore (e.g. due to rising water level) and moved along with the river current. The floating field stops at the boundary of the existing ice cover. As a result of collisions, contact zones between the fields (selected for this research as a separated class – CZ) have a greater roughness than the interior of the field. On the analysed section of the Vistula River, expansion of the smooth ice cover takes place from the dam in Wloclawek (km 675) upstream.

We divided ice cover from mobile ice forms (mainly different form of frazil ice) as juxtaposed ice (JI) and agglomerated ice (AI). The agglomerate ice (AI) refers to the ice cover with higher roughness and thicker hanging frazil ice layer than the juxtaposed ice (JI). Ice cover from mobile ice forms is formed in the river section above the Wloclawski reservoir, where the flow velocity is higher. In this

Figure 3. Location of ground measurements on the Vistula River taken on 4 February 2014, cross-section: km 622, km 625 and km 635.
river stretch, there are convenient conditions for the formation of frazil ice and forms of mobile ice of various sizes – frazil pans (with a diameter of dozen centimetres), frazil fields (up to a few meters in diameter). Forms of flowing mobile ice are stopped by the narrowing of the river channel, shallows,
infrastructure elements (e.g. bridge supports) or existing ice cover. This results in the accumulation of ice and the expansion of the ice cover upstream. The inflow of further forms of mobile ice exerts pressure on the ice cover. This leads to the compaction of the cover, which results in a rougher surface and greater thickness. For the analysed section of the Vistula River, one characteristic is the occurrence of the so-called hanging frazil dam, which forms when frazil ice accumulate under the existing ice cover. The hanging frazil dams reduce cross-sectional area, which results in an uncontrolled rise in water level. Therefore, in the context of the Vistula River, it is particularly important to detect the river sections of high compacted forms of mobile ice. Ice cover showing different levels of mobile ice compaction occurs around the Kępa Ośnicka island (km 625–626).

**Figure 6** shows the mean values of the backscattering coefficients for individual classes in polarizations HH, HV, VV. The difference between the mean values in each polarization between the classes is at least 5 dB and is approximately 5 times higher than the standard deviation for each set. Therefore, we can assume that the selected classes can be properly distinguished.

**Method**

**Polarimetry theory**

The relationship between electric components of the incident and scattering wave, $E_I$ and $E_S$, respectively, can be described by the following equation:

$$E_S = \frac{e^{-jkr}}{r} |S| E_I,$$

where $r$ represents the distance between a target and system antenna and $k$ is a wavenumber of the illuminating wave (Lee & Pottier, 2009; Touzi, Boerner, Lee, & Lueneburg, 2004; van Zyl, 2011). Matrix $S$ is named as the Sinclair matrix or scattering matrix. In the orthogonal basis, where $v$ and $h$ represents respectively vertical and horizontal polarization, for linear polarized quad-pol data the scattering matrix $S$ is as follow:

$$S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}.$$  

Each element of the scattering matrix is a complex number whose value is determined by target shape, size, orientation and permittivity as well as radar frequency, illuminating and scattering angels (Ulaby et al., 2014). In the monostatic backscattering case (e.g. RADARSAT-2), the reciprocity constrains the Sinclair scattering matrix to be symmetrical, that is, $S_{HV} = S_{VH}$. In case of coherent scattering complex Sinclair matrix is sufficient to describe a target. However, in case of non-coherent or partially coherent scattering – like in the most of microwave remote sensing applications – the covariance matrix is used to the complete target characterization (Lee & Pottier, 2009; Touzi et al., 2004).

Introducing the target vector $\Omega$ containing scattering matrix elements as:

![Image](https://via.placeholder.com/150)

**Figure 6.** Mean value and standard deviation of the backscattering coefficients for selected classes based on RADARSAT-2 data of 28.01.2014. Incidence angle: 46 degrees. Study area: the Vistula River. Classes: Sml – smooth ice. CZ – contact zones between fields of smooth ice. JI – juxtaposed ice mainly from frazil ice. Al – agglomerated ice (higher surface roughness than juxtaposed ice – JI).
\[ \Omega = [S_{HH}^2 S_{HV}]^T \]  

(3)

distance decreases, so the separability of two classes. Based on classification practice, it is assumed that two classes are separable if the value of Hellinger distance for these classes is at least 1.34 (95% of the saturation level).

As the results from Hellinger distance showed saturation for most of the observations we repeated the analysis with another frequently used measure of separability which does not show saturation – Bhattacharyya distance. The measure is closely related to Bhattacharyya coefficient \( \rho \) and is defined as:

\[ d_b(f,g) = -\ln \rho \]

Wishart supervised classification

In the literature, several approaches to river ice classification can be found. Many of them are based on analysis of the backscattering coefficient (Lindenschmidt, Van der Sanden, Demski, Droini, & Geldsetzer, 2011; Lindenschmidt, Das, & Sagin, 2014; Sobiech & Dierking, 2013) or the backscattering coefficient together with the images texture (Chu et al., 2015; Chu & Lindenschmidt, 2016; Gauthier et al., 2010; Jasek et al., 2013). While analysing quad-pol data different types of polarimetric decompositions can be applied, for example the Freeman-Durden decomposition was applied by Lindenschmidt, Das, and Chu (2017). It should be noticed, however, that most of the decompositions cannot be applied to dual-pol data. For this reason we decided to analyse data stored in a form of covariance matrix. The covariance matrix follows the complex Wishart distribution, which is well suited for classification application.

The complex Wishart classifier is based on the classical Bayesian approach to classification. For polarimetric SAR data, the similarity measure is derived from the probability density function of covariance matrix. Details on the Wishart supervised classification algorithm can be found in Canty (2014) and Lee and Pottier (2009). The training fields – used to train an algorithm – and test fields – used to assess classification accuracy – were selected independently from each other through visual interpretation of SAR data. While interpreting SAR data we used expert knowledge gained on the base of analysis of Landsat data and aerial photos – in case of the Peace River – or terrestrial photos and ground measurements – in case of the Vistula River. They were digitalized on RGB images separately for each data. The test fields represented 1% of the classified area.

We extracted the three dual-pol data from the source quad-pol data (Figure 7). This allowed us to keep constant the geometric imaging parameters which have impact on the value of the signal such as incidence angle and pixel size. We carried out supervised classification using the script described...
in Canty (2014) and made available by the author. In the original script version two thirds of pixels from training fields were used to train the algorithm and one third to assess the accuracy of classification. We modified the script in such way as to have all the pixels from the training fields used for training the algorithm. We performed the assessment of the accuracy of classification using other, independently selected test fields.

**Results**

**Separability**

Tables 3 and 4 show the Hellinger distance values for data sets for heterogeneous and homogeneous ice cover, respectively. These data represent trends that have been observed during analysis of all data for each area. Values lower than 1.34 indicate that the two classes are not separable.

In the case of the heterogeneous ice cover (Table 3) for quad-pol data, all pairs of classes are separable. For dual-pol HH + VV and VH + VV data values of the Hellinger distance for open water (OW) and skim ice (SI) were lower than the threshold value, which indicates a problem with separation. For dual-pol HH + HV data, however, the value of the Hellinger distance for water (OW) and initial ice (SI) was higher than the threshold value, so it can be assumed that HH + HV polarizations allows to separate these two classes. None of dual-pol data allows to distinguish between different degrees of frazil ice accumulation (JSI, ASI), or to separate frazil pans (FR) from skim ice cover with different degrees of accumulation.

In case of homogeneous ice cover (Table 4) for the quad-pol data we obtained the Hellinger distance value above the threshold (1.34) for all pair of classes.

For all dual-pol data we obtained the Hellinger distance values above the threshold for all pairs of classes except ice cover from mobile ice forms (JI) and contact zones between smooth ice fields (CZ). It means that none of dual-pol data allows to separate these two classes. It should be noted that the

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**Figure 7.** Scheme of processing adopted for comparing the results of classification of quad-pol data and dual-pol data (HH + HV, HH + VV, VH + VV).

**Table 3.** Hellinger distance for heterogeneous ice cover (study area: the Peace River). Data set: RADARSAT-2 registered on 01.02.2013. Polarization modes: quad-pol (HH-HV-VH-VV), dual-pol: HH-HV, HH-VV, VH-HH. Classes: OW – open water, SI – skim ice, JSI – juxtaposed skim ice, ASI – agglomerated skim ice, FR – frazil run, CI – consolidated ice. The values below the threshold value (1.34) are marked in red.

|          | OW  | SI  | ASI | JSI | FR  | CI  |
|----------|-----|-----|-----|-----|-----|-----|
| RADARSAT-2 01.12.2013 HH-HV-VH-VV |     |     |     |     |     |     |
| OW       | 0   | 1.35| 1.41| 1.41| 1.41| 1.41|
| SI       | 1.35| 0   | 1.41| 1.41| 1.41| 1.41|
| ASI      | 1.41| 1.41| 0   | 1.4 | 1.41| 1.41|
| JSI      | 1.41| 1.41| 1.4 | 0   | 1.37| 1.41|
| FR       | 1.41| 1.41| 1.41| 1.37| 0   | 1.41|
| CI       | 1.41| 1.41| 1.41| 1.41| 1.41| 0   |

|          | OW  | SI  | ASI | JSI | FR  | CI  |
|----------|-----|-----|-----|-----|-----|-----|
| RADARSAT-2 01.12.2013 HH-HV |     |     |     |     |     |     |
| OW       | 0   | 1.35| 1.41| 1.41| 1.31| 1.41|
| SI       | 1.35| 0   | 1.41| 1.41| 0.43| 1.41|
| ASI      | 1.41| 1.41| 0   | 1.22| 1.38| 1.41|
| JSI      | 1.4  | 1.37| 1.22| 0   | 1.11| 1.41|
| FR       | 1.31| 0.43| 1.38| 1.11| 0   | 1.41|
| CI       | 1.41| 1.41| 1.41| 1.41| 1.41| 0   |

|          | OW  | SI  | ASI | JSI | FR  | CI  |
|----------|-----|-----|-----|-----|-----|-----|
| RADARSAT-2 01.12.2013 HH-VV |     |     |     |     |     |     |
| OW       | 0   | 0.83| 1.41| 1.38| 1.37| 1.41|
| SI       | 0.83| 0   | 1.41| 1.41| 1.36| 1.41|
| ASI      | 1.41| 1.41| 0   | 0.87| 1.29| 1.41|
| JSI      | 1.41| 1.41| 0.87| 0   | 1.16| 1.41|
| FR       | 1.36| 1.36| 1.29| 1.16| 0   | 1.41|
| CI       | 1.41| 1.41| 1.41| 1.41| 1.41| 0   |

|          | OW  | SI  | ASI | JSI | FR  | CI  |
|----------|-----|-----|-----|-----|-----|-----|
| RADARSAT-2 01.12.2013 VH-VV |     |     |     |     |     |     |
| OW       | 0   | 0.51| 1.41| 1.38| 1.37| 1.41|
| SI       | 0.51| 0   | 1.41| 1.37| 1.34| 1.41|
| ASI      | 1.41| 1.41| 0   | 1.28| 1.30| 1.41|
| JSI      | 1.38| 1.37| 1.28| 0   | 0.54| 1.41|
| FR       | 1.37| 1.34| 1.30| 0.54| 0   | 1.41|
| CI       | 1.41| 1.41| 1.41| 1.41| 1.41| 0   |
Table 4. Hellinger distance for heterogeneous ice cover (study area: the Vistula River). Data set: RADARSAT-2 registered on 28.01.2014. Polarization modes: quad-pol (HH-HV-VH-VV), dual-pol: HH-HV, HH-VV, VH-HH. Classes: SmI – smooth ice, CZ – contact zones between fields of smooth ice, JI – juxtaposed ice mainly from frazil ice, AI – agglomerated ice. The values below the threshold value (1.34) are marked in red.

| Time       | POL       | Confidence Matrix | Variance Honda (ddm) |
|------------|-----------|-------------------|----------------------|
| 28.01.2014 | HH-HV-VH  | 0.71              | 0.72                 |
| 28.01.2014 | HH-HV     | 0.56              | 0.57                 |
| 28.01.2014 | VH-HH     | 0.49              | 0.51                 |
| 01.12.2013 | HH+HV     | 0.70              | 0.71                 |

Table 5. Bhattacharyya distance for heterogeneous ice cover (study area: the Peace River). Data set: RADARSAT-2 registered on 01.02.2013. Polarization modes: quad-pol, dual-pol: HH + HV, HH + VV, VH + HH. Classes: OW – open water, SI – skim ice, JSI – juxtaposed skim ice, ASI – agglomerated skim ice, FR – frazil run, CI – consolidated ice.

| Time       | POL       | Confidence Matrix | Variance Honda (ddm) |
|------------|-----------|-------------------|----------------------|
| 01.02.2013 | HH+HV     | 0.70              | 0.71                 |
| 01.02.2013 | HH+VV     | 0.60              | 0.61                 |
| 01.02.2013 | VH+VV     | 0.55              | 0.56                 |

Table 6. Bhattacharyya distance for homogeneous ice cover (study area: the Vistula River). Data set: RADARSAT-2 registered on 28.01.2014. Polarization modes: quad-pol, dual-pol: HH + HV, HH + VV, VH + HH. Classes: SmI – smooth ice, CZ – contact zones between fields of smooth ice, JI – juxtaposed ice mainly from frazil ice, AI – agglomerated ice.

| Time       | POL       | Confidence Matrix | Variance Honda (ddm) |
|------------|-----------|-------------------|----------------------|
| 28.01.2014 | HH+HV     | 0.70              | 0.71                 |
| 28.01.2014 | HH+VV     | 0.60              | 0.61                 |
| 28.01.2014 | VH+VV     | 0.55              | 0.56                 |

Agglomerated ice cover from mobile ice forms (AI), whose detection is the most important for flood protection, has received Hellinger values above the threshold for all class combinations. Therefore, we can assume that this class will be correctly detected on both quad-pol and dual-pol data (regardless of the polarization combination).

While analysing Bhattacharyya distance for both types of ice cover – heterogeneous and homogeneous – we obtained distance values for quad-pol data twice as large as in case of dual-pol data (Tables 5 and 6). These results confirm higher potential of quad-pol data for separation of various type of ice cover. However, having regard to analysis of Hellinger distance, the higher separation ability may be not necessary to distinguish the ice classes that have been selected for this study.

**Wishart supervised classification**

We received similar images of ice distribution as a result of classification quad-pol and dual-pol data. In particular, the boundaries of ice classes with the most varied morphology – consolidated ice in case of the Peace River (Figure 8) and agglomerated ice in case of the Vistula River (Figure 9) – were the same. The confusion matrices are provided in Table A1 (area of...
In the case of heterogeneous ice cover for all polarizations, we obtained an average accuracy of more than 65% (Figure 10). For two acquisition dates for HH + HV polarization lower values of accuracy were obtained, compared to other polarization modes. It is not clear to us if there is a reason behind it or if perhaps it is a random occurrence.

In the case of homogeneous ice cover the overall accuracy of classification exceeded 80% for all polarizations (Figure 11). It varies less between polarization modes than in the case of heterogeneous ice cover. We did not observe lower values of overall accuracy for data with HH + HV polarization as was the case with heterogeneous ice cover.

For the Peace River, the lowest values of omission and commission errors were received for the consolidate ice (on average 1% for both omission and commission errors). For the open water, a mean error of commission of 17% and a mean error of omission of 15% were obtained, while for the skim ice, respectively 19% and 22%. The confusion matrix analysis showed that the water areas were misclassified as skim ice and the skin

Table A1. Confusion matrices, area of study: the Peace River.

| Class | OW | SI | ASI | JSI | FR | CI |
|-------|----|----|-----|-----|----|----|
| OW    | 87%| 56%| 0%  | 0%  | 0% | 0% |
| SI    | 13%| 35%| 0%  | 0%  | 0% | 0% |
| ASI   | 0% | 0% | 99% | 38% | 0% | 7% |
| JSI   | 0% | 0% | 1%  | 62% | 4% | 0% |
| FR    | 0% | 9% | 0%  | 0%  | 96%| 0% |
| CI    | 0% | 0% | 0%  | 0%  | 0% | 93%|
| Sum   | 100%| 100%| 100%| 100%| 100%| 100%|

Table A1. (Continued).

| Class | OW | SI | ASI | JSI | FR | CI |
|-------|----|----|-----|-----|----|----|
| CI    | 0% | 0% | 1%  | 0%  | 0% | 100%|
| Sum   | 100%| 100%| 100%| 100%| 100%| 100%|

In the case of heterogeneous ice cover for all polarizations, we obtained an average accuracy of more than 65% (Figure 10). For two acquisition dates for HH + HV polarization lower values of accuracy were obtained, compared to other polarization modes. It is not clear to us if there is a reason behind it or if perhaps it is a random occurrence.

In the case of heterogeneous ice cover the overall accuracy of classification exceeded 80% for all polarizations (Figure 11). It varies less between polarization modes than in the case of heterogeneous ice cover. We did not observe lower values of overall accuracy for data with HH + HV polarization as was the case with heterogeneous ice cover.

For the Peace River, the lowest values of omission and commission errors were received for the consolidate ice (on average 1% for both omission and commission errors). For the open water, a mean error of commission of 17% and a mean error of omission of 15% were obtained, while for the skim ice, respectively 19% and 22%. The confusion matrix analysis showed that the water areas were misclassified as skim ice and the skin
ice were misclassified as water. Classes representing the ice cover of the combined ice fields of varying degree of condensation – juxtaposed skim ice (JSI) and agglomerated skim ice (ASI) mixed together. The mean errors of commission and omission were respectively 9% and 31% for the juxtaposed skim ice and 34% and 6% for the agglomerated skim ice. Frazil pans were misclassified as different forms of skim ice (SI, JSI, ASI). The average commission error for frazil pans was 17% and 26% for the omission error. We have not observed the misclassification between the frazil pans and the open water, as it was in the case of studies described in Weber, Hixon, and Hurley (2003) and in Gauthier et al. (2010).

For Vistula River, we obtained low mean values of commission and omission errors for the agglomerated ice (1% and 5%, respectively) and smooth ice (1% and 7%, respectively). A slightly higher average error of commission was obtained for juxtaposed ice (11%) with a low average error of omission (1%). Large mean errors of commission and omissions were obtained for the contact zone class – 38% and 24%,
Figure 8. Images after Wishart supervised classification of RADARSAT-2 quad-pol and dual-pol (HH + HV, HH + VV, VH + VV) data of 08.12.2013. Study area: the Peace River. Classes: OW – open water. SI – skim ice. JSI – juxtaposed skim ice. ASI – agglomerated skim ice. FR – frazil run. CI – consolidated ice.
Figure 9. Images after Wishart supervised classification of RADARSAT-2 quad-pol and dual-pol (HH + HV, HH + VV, VH + VV) data of 01.02.2014. Study area: the Vistula River. Classes: Sml – smooth ice. CZ – contact zones between fields of smooth ice. Ji – juxtaposed ice mainly form frazil ice. Al – agglomerated ice.
respectively. This class was misclassified with the juxta-
posed ice. In the case of the contact zone class, regard-
less of the polarization mode for data from any term, we did not obtain the errors of commission and omis-
sion lower than 10%.

Discussion

Classes with the most varied morphology – consoli-
dated ice (CI) on the Peace River and agglomerated ice (AI) on the Vistula River – are equally detected with quad-pol and dual-pol data (regardless of polariza-
tion channel combination). This has been confirmed at both stages of the assessment – separability analysis and supervised classification. For all polarization modes (quad-pol and three dual-pol) the Hellinger distance values for pairs of the consolidated ice (CI) and each of other classes were higher that the threshold above which classes separability is assumed. Also, when com-
paring the agglomerated ice (AI) with each of other classes selected for the Vistula River, the Hellinger dis-
tance values were above the separability threshold. Classified images, regardless of input polarization mode, showed the same boundaries for the consolidated ice (CI) on the Peace River and agglomerated ice (AI) on the Vistula River.

In the case of the Peace River, the primary problem was the distinction between open water and skim ice. Both classes had similar values of the backscattering coefficients. Separability analysis based on the covariance matrix, thus using more information than analysis of the value of the back-
scattering coefficients, also did not show distinction between these classes. For two sets of dual-pol data (HH + VV, VH + VV), the Hellinger distance values for class pair open water – skim ice were lower than the threshold value. For dual-pol HH + HV and quad-pol data the values were at the threshold limit. Moreover, we obtained the largest omission and commission errors (up to 30 % – 40%) in classification for these two classes. The problem in distinguishing between water and smooth ice was reported in Jasek et al. (2013). Additional information about snow laying on the ice from optical satellite data (when available) may solve this problem. Used in the first step of analy-
sis, optical data allow to distinguish ice covered with snow from open water. Then, types ice cover can be classified based on SAR data.
The class division for the Peace River was too detailed. Although we distinguished visually two forms of skim ice with moderate and high compactness (JSI and ASI), they have not been correctly separated in supervised classification, regardless of polarization mode. For further research, we propose the following broader definition of classes in the Vermilion Chutes section: open water, skim ice, frazil pans, consolidated ice cover.

For the Vistula River, it was impossible to distinguish contact zones between fields of smooth ice, regardless of the polarization mode of input data. However, detection of the contact zones was not as important as detection of other ice types. The other classes: smooth ice, juxtaposed and agglomerated ice cover that form from mobile ice were classified with very high accuracy both with quad-pol and all dual-pol data.

In this study we used supervised classification with an algorithm of maximum likelihood, which is widely used in remote sensing research. However, due to a requirement of training samples this classification method will not be appropriate for long-term monitoring. Especially, while using the maximum likelihood algorithm, which in its basic version assumes similar values of standard deviation for each class, the training samples have to be selected and verify by a user. Also training samples selected based on ground measurements have to be verify for their standard deviation values. For long-term monitoring unsupervised classification based on backscattering values or texture parameters may be apply as shown in Chu et al. (2015), Chu & Lindenschmidt (2016)), Gauthier et al. (2010) and Jasek et al. (2013).

A reason for the differences in accuracy of classification results between dates is not clear. One possibility is changes in data acquisition geometry. We used SAR data with a broad range of incidence angles (from 19° to 46°). As relative surface roughness changes with the incident angle, so does backscattering of different ice types. Further studies of the influence of the incidence angle on separation ice types are needed.

Conclusions

The quad-pol data did not improve significantly the accuracy of the river ice classifications in comparison with the classifications made with dual-pol data. The accuracy of all classifications for a given date was very similar. Further, the problem with misclassification between smooth ice and open water was not resolved with the quad-pol data. To improve the river ice classification, we propose to investigate impact of the radar frequency and to perform ice classification with multi-frequency SAR data.

As the results obtained for dual-pol and quad-pol data were comparable, we recommend application of Sentinel-1 data for river ice monitoring. There are very few studies (e.g. Łoś & Pawłowski, 2017) dedicated to this topic. The main Sentinel-1 acquisition mode over land – the Interferometric Wide (IW) swath mode – provides dual-pol data VV + VH with the 250 km swath. It gives a great opportunity to obtain information for long river sections. The nominal resolution of 5 m by 20 m (single look complex) allows, also after multi-looking or filtering, to preserve accuracy required for river ice monitoring in which the goal is to observe phenomena with dimensions of tens of meters. For areas in the temperate climate zone (like Poland or most of Canada), the Sentinel-1 A/Sentinel-1 B constellation provides data every 2 days which makes this data an ideal source of information for river ice monitoring systems.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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