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APPLICATION OF SATELLITE SENTINEL-1 RADAR IMAGES FOR DESCRIPTION OF ICE PHENOMENA ON DĘBE RESERVOIR

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ABSTRACT

Winter conditions of low air temperature cause development of ice phenomena at rivers and reservoirs, creating often problems in their exploitation. There is a need to continuously monitor the spatial extension of ice phenomena and their different forms. Local water authority (RZGW Warszawa) prepares for rivers under their administration a daily reports on ice conditions in winter. Ice reports are prepared from visual inspection of the RZGW personnel visiting selected sections of the river course. This is specially problematic in holidays and weekends when usually data from observations are missing. In this study it is tested application of microwave remote sensing data from Sentinel-1 platform to observe the development and recession of the ice cover at the Dębe reservoir in winter 2017. Satellite Sentinel-1 radar images are distributed by the European Space Agency (ESA) on the open access policy. These are two satellites A and B which every 2 days collect images in SAR active remote sensing technique. Dębe reservoir was created in 1963 by closing by the barrage Narew river below its confluence with Bug river. Maximum water head is 7.1 m, and average 6.8 m. Area of the reservoir is 30.3 km^2 average discharge of Bug river at Wyszków gauge is 162 $m^3 \cdot s^{-1}$, and Narew river at Zambski Kościelne gauge 139 $m^3 \cdot s^{-1}$. Retention time of water in the reservoir is 3–4 days. Comparison of the average water temperature at gauge Zambski Kościelne and Wyszków from the winter half-year of the period 1963–1981 shows the increase of water temperature by 0.5–1 C after the year 1972 when Ostrołęka power station was put in to operation. This difference in the temperature between Narew and Bug rivers is reflected by the ice conditions at the end of winter season. Sentinel-1 SAR instrument emits electromagnetic wavelength of 6 cm (C band), and are use two polarizations VH and VV. Using SNAP program geometric correction and color composite was created for selected images at the beginning and end of ice cover at Dębe reservoir on Narew river, covering period January 5-March 6, 2017. It has been found that interpretation of the Sentinel-1 images is most problematic if we want to detect boundary between open calm water and new fast ice. The flow of pancake ice on January 5, 2017 had been recorded and the pattern of ice distribution compared to flow lines calculated by the hydrodynamic CCHE2D model. Result of the hydrodynamic modeling shows circulation pattern in the widest part of the reservoir where are also the most favorable conditions for lake type of ice cover formation. End of ice cover is represented by the image of February 26, 2017 which shows the Narew river free from ice due to higher temperature of the water. Relatively simple visual interpretation of the Sentinel-1 VH and VV images can by used in the study of ice phenomena on major rivers and lakes.

Keywords: SAR Sentinel-1, Dębe reservoir, Narew, Bug, ice phenomena

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INTRODUCTION

In a climatic conditions of Poland characteristic feature is the lowering of the air temperature below 0ºC freezing point of water, which cause with some delay formation of ice phenomena at rivers, lakes and artificial reservoirs. Conditions at which starts formation of ice on water bodies can be described as static or dynamic. Ice cover formed at static conditions controlled by the air and water temperature is characteristic for a water bodies with low velocities of water flow and can be found at lakes, artificial reservoirs, shallow and sheltered parts of river channel. Dynamical conditions of ice formation depend on water velocity, amount of ice transported downstream by the river flow and action of wind. Ice cover formed in dynamical conditions is made from mobile forms of ice, transformed to cover of different level of compactness. Ice cover formation at the river has certain sequence from initial forms, through full coverage, to deterioration. Initial form of river ice are: border ice, frazil slush, pancake ice. Ice flowing down the river can be stopped by some obstacle forming ice jam. The obstacle in case of the artificial reservoir can be an edge of fast ice which usually forms faster in a lacustrine part of the reservoir. Obstacle for flow of the pancake ice produce conditions for build up of ice jam. If the frazil ice or pancake ice meet an edge of the fast ice, they can be submerged with the water and accumulate below the ice cover creating hanging dam. The final stage is deterioration of the ice cover and transport of ice floes. Formation of continuous ice cover from the dynamic mobile ice is the main process acting at rivers in dynamic conditions. Ice cover build up from the mobile ice usually reduce hydraulic conveyance by lowering of the river cross section area and increasing resistance for flow expressed by higher roughness coefficient.

Updated monitoring of ice phenomena on rivers is important for flood safety and proper operation of hydrotechnical structures. Observation of ice conditions at rivers and reservoirs is performed from the very beginning of hydrological measurements. In the program of observations performed by trained personnel at the hydrological gauges typical measurements included water stage, water temperature and thickness of ice. Advent of telemetric gauging stations has changed program of measurements. New technology makes possible real time measurements of water stage and temperature with a time step of 15 min. Telemetric posts do not provide information on ice thickness and type of ice phenomena. Monitoring of ice phenomena is organized by collecting field reports from personnel of Regional Water Management Authorities (RZGW). Observations in the field are collected and published by RZGW – Operation Centers of Flood Protection in the form of ice reports. Water Authority RZGW in Warsaw publish in winter ice reports from sections of Vistula, Bug and Narew rivers. As an example (see: Fig. 1) it is shown a subsection of such a report covering January 5–18, 2017. The ice report shows distribution in a longitudinal profile following ice phenomena: open water, frazil slush, border ice, complete ice cover, ice jam, ice floes with the border ice.

A new source of ice phenomena at inland waters are radar satellite images from Sentinel-1 platform which is operated by Copernicus program of European Space Agency (ESA). The main advantage is frequent time of recording and policy of free access. Sentinel-1 belongs to microwave type of remote sensing which means that is independed from weather conditions and time of the day.

Application of radar satellite images for the detection of ice on sea surface is used operationally at Arctic. Another successful application in oceanography is detection of oil spills at the sea. There are not many examples of studies on using radar satellite images for detection for ice at inland waters. Canada with their numerous rivers in the Arctic is good example of application radar satellite images from the Radarsat program. In Poland there are also some examples of use of radar satellite images for recognition of ice phenomena at Włocławek reservoir on Vistula river (Pawłowski et al., 2015, Łoś, 2017, Łoś and Pawłowski, 2017).

This study shows potential of application of Sentinel-1 radar satelite images for recognition of ice phenomena at Dębe reservoir on the Narew river. Dębe reservoir has been put to operation on 1963 it was a first reservoir in Poland located at the major lowland river. Maximum water head at the barrage is 7.1 m, average 6.8 m. Reservoir located below the confluence of Narew and Bug rivers has an area of 30.3 km^2 and its basin is protected by the side dams. The water level in the reservoir has to be maintained at constant level on average at ordinate 79.02 m a.s.l. During normal condi-

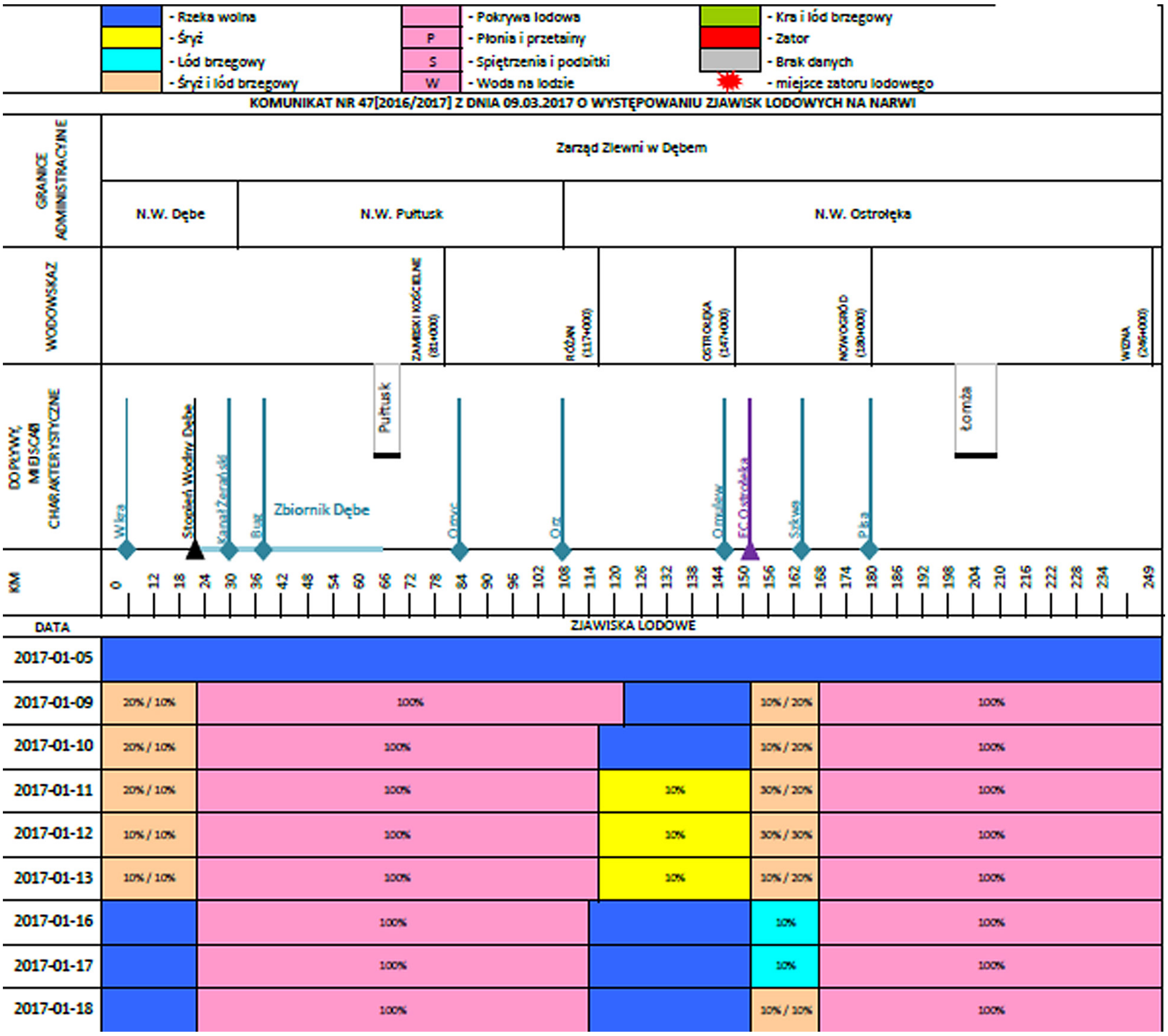

Fig. 1. Example of ice report on Narew river from January 5–18, 2017 published by Operational Center for Flood Protection at Water Authority RZGW in Warsaw

tions the water level fluctuates by not more than 0.5 m around average ordinate which correspond to the useful volume of the reservoir of 15.7×10^6 m^3. The total volume of the reservoir is 94.3×10^6 m^3 it has a length of about 30 km, average depth 3 around 3 m and length of the coast line 100 km (Dojlido and Gromiec, 2003). An average (1951–2010) discharge of the Bug river at Wyszków gauge was 162 m$^3 \cdot$ s^{-1} and of Narew river at Zambski Kościelne 139 m$^3 \cdot$ s^{-1}. The time of water turnover in the reservoir is short and it takes only 3–4 days. The characteristic feature of the Dębe reservoir is the relief of its bottom which reflects the pattern of original river courses and floodplains. In the most southern part of the reservoir there is a main basin (between Zegrze and Nieporęt) and secondary basin (near Białobrzegi). The deepest part of the reservoir are located in the old Narew river channel near Zegrze Północne and around the Zegrze Południowe where in the 70s there was intensive dragging works related to gravel exploitation.

The hydrological conditions at the reservoir have been studied using two-dimensional hydrodynamic model CCHE2D developed at University of Mississippi in U.S.A. Details of the model specification and simulations are described by Magnuszewski (2014). The average velocities in the verticals are calculated for a boundary conditions of long term (years 1951––2010) average discharge of Bug and Narew rivers. The results of modeling show considerable difference in the velocities of Narew and mouth of Bug river. This difference is reflected also by the different conditions of ice cover formation in the reservoir and on the Bug river. Ice forming at the reservoir with a low velocities of flow represent static ice typical for lakes, while ice on the Bug river represent dynamic conditions of ice jam made of pancake ice.

In understanding process of ice cover formation and disappearance it is important to analyze the water temperature measurements done at Bug river at Wyszków gauge and Narew river at Zambski Kościelne gauge. Fig. 2 shows the average water temperature in a winter half-year (months XI–V) of the period 1963–1982 measured at both posts. The water temperature starts to be different at Narew river after year 1972 when a large conventional power station in Ostrołęka town was put in to operation. Power station thermal water release increased the temperature of water at Narew river by approximately 0.5 C.

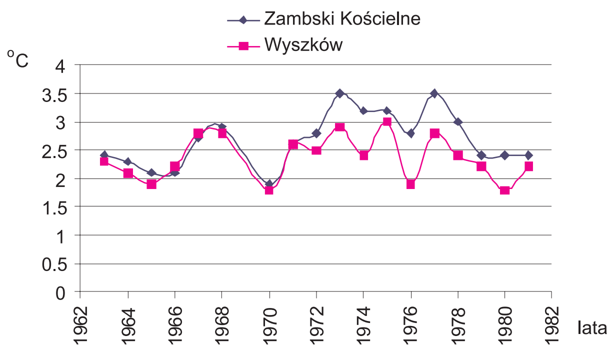

Fig. 2. Water temperature of Bug (Wyszków gauge) and Narew (Zambski Kościelne gauge) rivers in winter half-years of 1963–1981 after Hydrological Yearbooks by IMGW

SATELLITE RADAR REMOTE SENSING DATA PROCESSING AND INTERPRETATION

In satellite Sentinel-1 there is used active remote sensing system of Synthetic Aperture Radar (SAR). Located at moving platform of satellite side looking antenna sends signals in the form of pulses of radio waves, and records returning signals reflected from the ground objects. Signal processing of recorded radar echoes combines the signals send at multiple antenna positions. This process called synthetic antenna aperture makes possible to obtain high-resolution images.

In this work it has been used SAR images recorded by the two satellites of Sentinel-1 mission, described by letters A and B. Sentinel-1 A has been launched on April 3, 2014, while Sentinel-1 B on April 25, 2016. Both satellites use SAR system working in the C-band which correspond to radio wave frequency of 5.405 GHz.

Data recorded by the satellite are processed to number of products. In this work it has been used *Interferometric Wide Swath Mo*de (IW) data, geometrically corrected and registered to UTM coordinates as *Ground Range Detected Geo-referenced Product* (GRD). Spatial resolution of the image is 5 m x 20 m, while width of imaging is 250 km. The viewing angle of SAR antenna in reference to Earth Surface is 25^{o}. Altitude of Sentinel-1 satellite is 698 km, and in case of Poland revisit time is 2 days on average. Sentinel-1 A passage time over Dębe reservoir is around 16.00, while Sentinel-1 B around 04.00.

In GDR product there are two monochromatic images available of polarization VH and VV. Channel VH records signal send in vertical polarization and returned in horizontal polarization. Channel VV sends and receives signals in vertical polarizations. Images are written in a compressed archive together with coordinates of ground control points used to image registration and geometric correction. Size of file containing single compressed archive is 903 MB.

Data is provided on the free access mode from European system of Earth observation Copernicus, for registered user at address https://scihub.esa.int/. In the Open Hub page there is a tool for selection of interesting us terrain, satellite platform, time of image acquisition and type of product processing. For processing of Sentinel-1 images ESA has developed free software called SNAP. This program makes possible creation of subsections from the whole image od Sentinel-1. In this work subsections have been extracted covering Dębe reservoir and lower reaches of Narew and Bug rivers between coordinates 53.024–52.264 N, 20.650–21.544 E.

Scenes in GRD product are recorded pixel by pixel in the direction of satellite flight on the ascending or descending orbit. To process such a image it is necessary to geometrically correct orientation of the image to proper UTM coordinates. After geometric correction it has been obtained two channels in grey scale proportional to amplitude called Amplitude_VH and Amplitude_VV.

Radar image is obtained by sending from antenna pulse of electromagnetic radiation which returns as an „echo" reflected from ground objects. The distance between antenna and ground object is measured from the difference in time between sending pulse and receiving returning radiation. Electromagnetic wave which hits boundary between air and object is partly reflected and partly absorbed by the object. Returning signal is compared with send pulse and ratio is expressed in dB scale as σ–*backscatter*. The radar image pixel brightness is proportional to *backscatter,* better reflection of the electromagentic radiation means brighter pixel recorded in amplitude channels. Backscatter depends on couple of parameters such as:

- wave frequency, wave polarization,
- imaging configuration (incident and scattering angles), object geometrical structure, object dielectrical properties.

There are three types of radar wave reflection from the object which correspond to pixel brightness at the image:

- surface scattering is observed when pulse by the antenna is reflected from smooth surface of water or ice and the small portion of the electromagnetic energy returns back to the antenna – pixel at the image is darkest,
- volume scattering occurs when send pulse returns to antenna many times reflected from complex surfaces of soil or vegetation – pixels are gray,
- double bounce reflection from the objects made of rectangular surfaces like buildings, bridges – pixels are brightest.

The easiest method of radar images interpretation recorded as Amplitude_VH and Amplitude_VV images is the analysis of the pixels brightness. Amplitude_VH image shows very uniform level of pixels brightness even if it depicts the ice cover made of mobile ice. Much better differentiation of the pixel brightness is in the Amplitude_VV images Examples are shown at Fig. 3 and 4 representing subsection of Sentinel-1 image recorded on February 14, 2017 and covering mouth of Bug river at Dębe reservoir. Higher differentiation of pixels brightness in Amplitude_VV image stems from the fact that mobile ice at the contact with border ice create vertical surfaces giving strong double bounce reflection similar to radar reflector effect. At the mouth of Bug river it is visible as a bright stroke at contact line where ice floes and pancake ice collide with the static border ice (see: Fig. 4). This part of the Bug river has been dredged in the period 2015–2018 to increase depth of the channel and improve the conditions for free flow of ice.

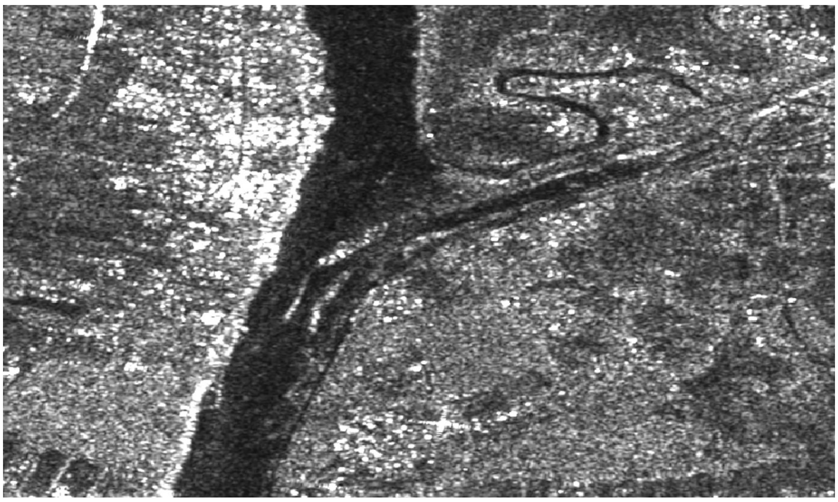

Fig. 3. Mouth of the Bug river to Dębe reservoir shown at Amplitude_VV image recorded by Sentinel-1 satellite on February 14, 2017

Monochromatic images in VH and VV polarization contain useful information but their interpretation in grey scale of clors is limited. To improve that process it is possible to create color composite in RGB (Red, Green, Blue) space. To create such a composition we need additional image, which can be obtained by performing algebraic operations on VH and VV images. Another option is conversion of source images to new one calculated using logarithmic function. In this work color composition has been created using following sources: Red – Aplitude_VH, Green – Amplitude_VV, Blue – log10(Amplitude_VV). In such a composition pixels representing lowest backscatter values are shown as dark blue, while pixels representing maximum backscater with the highest brightness are displayed in color close to white (see: Fig. 5).

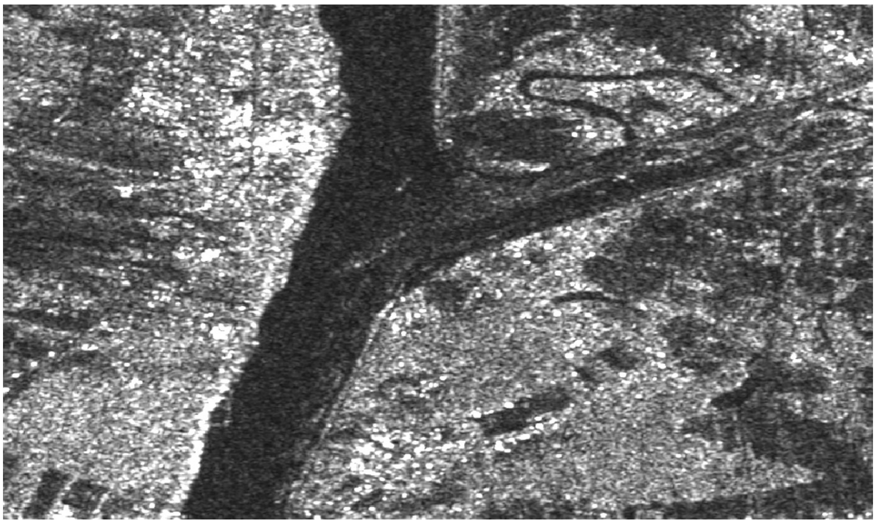

Fig. 4. Mouth of the Bug river to Dębe reservoir shown at Amplitude_VH image recorded by Sentinel-1 satellite on February 14, 2017

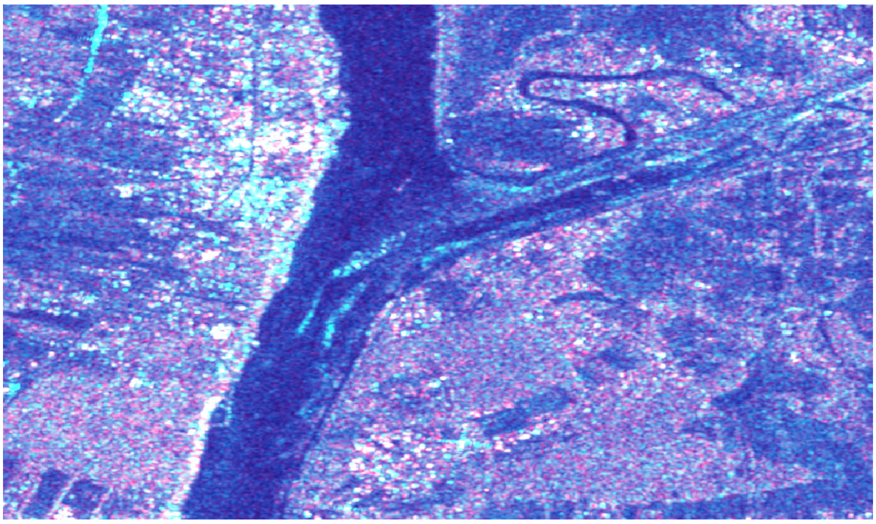

Fig. 5. Mouth of the Bug river to Dębe reservoir shown at color composite image recorded by Sentinel-1 satellite on February 14, 2017 where: R- Amplitude_VH, G- Amplitude_VV, B –log10(Amplitude_VV) – at Bug river it is visible contact between mobile ice and static ice and white field of ice jam upstream

DĘBE RESERVOIR AND ICE PHENOMENA ON SENTINEL-1 IMAGES

Initial phase of pancake ice flow to the reservoir from Bug river can be observed at Sentinel-1 image recorded on January 5, 2017. The stream of ice was driven by the NW wind with the velocity 5 m · s^{-1} (see: Fig. 6). The storage volume of the reservoir was 95.57 × 10^6 m^3, ordinate of water surface 79.19 m a.s.l. water inflow to the reservoir 401 m^3 · s^{-1}.

Computer hydrodynamic model CCHE2D was used to simulate the flow conditions during the time of image recording. The pattern of flow lines (see: Fig. 7) shows that water from the Bug river does not mix with

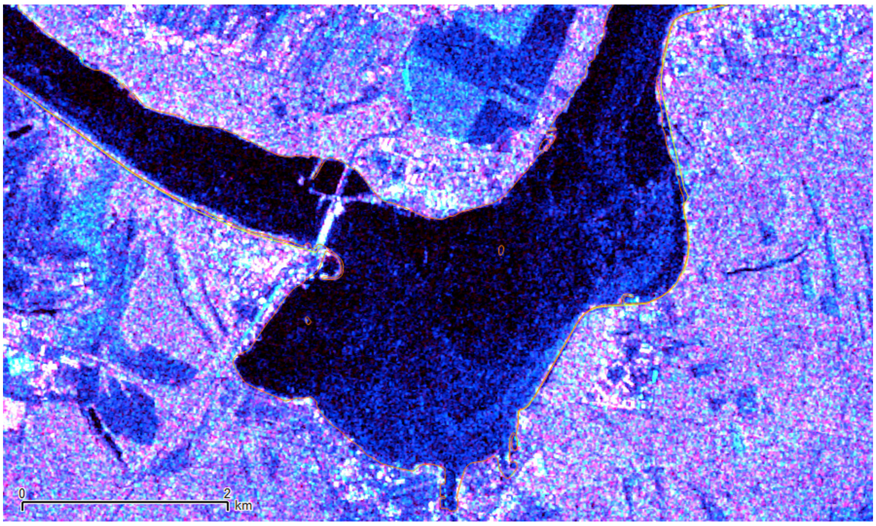

Fig. 6. Sentinel-1 image recorded on January 5, 2017 shows flow of pancake ice from Bug river to Dębe reservoir exposed to NW wind velocity 5 m · s^{-1}

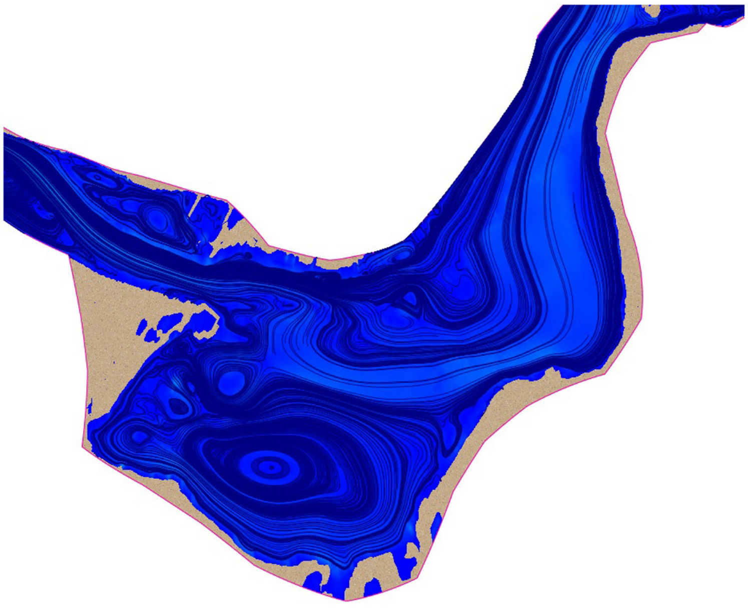

Fig. 7. Flow lines at Dębe reservoir on January 5, 2017 calculated by CCHE2D model with the influence of wind NW 5 m · s^{-1}

the Narew river, it flows parallel to the left bank and bends in the main body of the reservoir. In the widest part of the reservoir there is closed circulation structure which due to low flow velocities promotes formation of the fast ice developing in static conditions.

On January 9, 2017 whole reservoir has been covered by the continuous ice cover. This has been confirmed by the ice report published by Operational Center for Flood Protection at Water Authority RZGW in Warsaw (see: Fig. 1). Sentinel-1 image shows continuous ice cover at Dębe reservoir with still visible embedded structure of pancake ice flow. The volume of the water stored in the reservoir has been lower to 90.95 × 10^6 m^3 at water level ordinate 79.05 m a.s.l., and water inflow of 483 $m^3 \cdot s^{-1}$. The lowering of the water surface in the reservoir has created tension in the ice cover and formation of cracks visible at the Sentinel-1 image as a thin white lines (see: Fig. 8).

Important for reservoir exploitation is phase of ice cover disappearance. Fig. 9 shows ice cover at Dębe reservoir recorded by Sentinel-1 satellite on February 26, 2017. Characteristic is dark path of Narew river

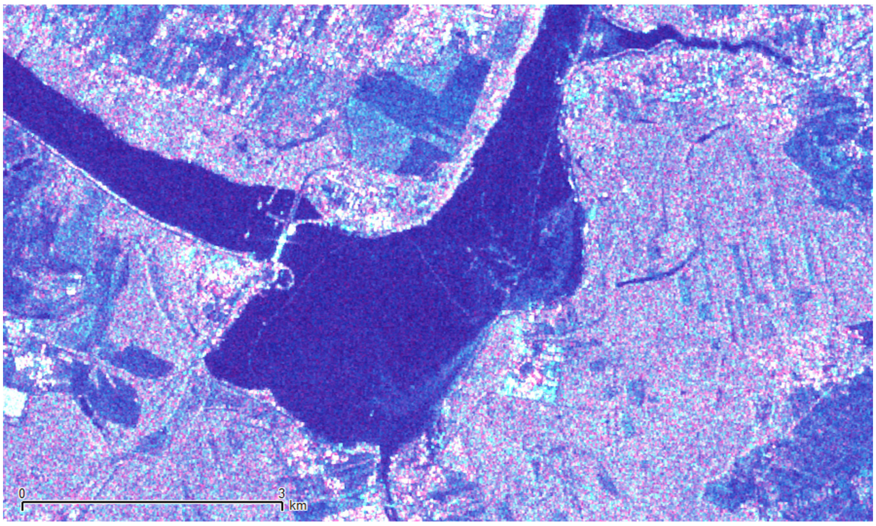

Fig. 8. Color composite from Sentinel-1 images recorded on January 9, 2017 shows continuous ice cover at Dębe reservoir with still visible embedded structure of pancake ice flow and lines of ice fractures

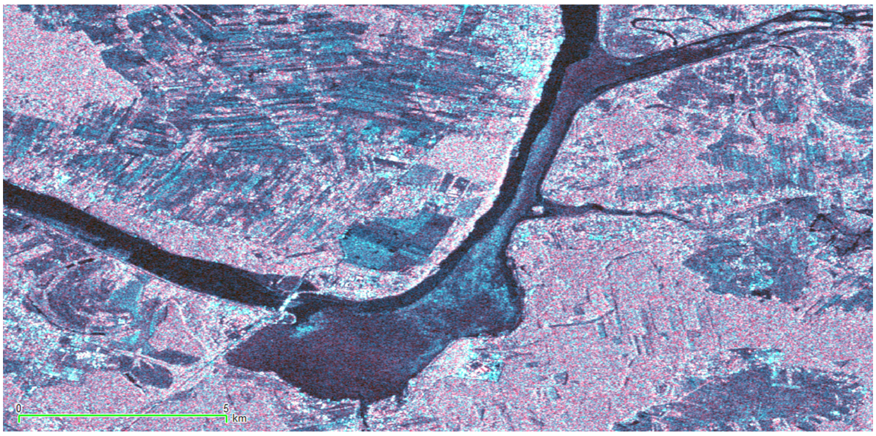

Fig. 9. Sentinel-1 image recorded on February 26, 2017 shows free from ice surface of Dębe reservoir along old thalweg of the Narew river

flow free from ice which can be explained by higher temperature of this river's water. Image shows also at the edge of the open water strong volume backscatter of the melting ice containing number of air bubbles in its structure. This property helps to find during interpretation a difference between melting ice and open still water. Continuous decaying ice cover is visible at main body of the reservoir and also at the mouth of the Bug river. Such a situation in ice cover disappearance at reservoir is favorable for easier outflow of ice from Bug river. This wide belt of open water flowing down the old Narew river thalweg makes unnecessary work of ice-breaking ships. On the other hand long time of ice cover duration at the main body of the reservoir is favorable for ice-boats and other winter sports.

DISCUSSION AND CONCLUSIONS

Radar satellite images from Sentinel-1 mission are very useful for detection of ice cover at major rivers and reservoirs. Data in the GRD product are available in a operational mode few hours after recording, relatively easy is also their processing in open source SNAP software. Frequency of recording every 2 days makes possible to use the images for preparation of ice reports and detection of ice jams, as well as observation of ice cover developmental and disappearance.

In work of Pawłowski et al. (2015) there has been used Radarsat-2 images with 4 channels of different polarization. According to unsupervised classification it was possible to detect following classes of ice cover: smooth ice without hanging dams, ice cover build from loose mobile ice forms, ice cover build from compacted mobile ice forms (ice jams). In this study it has been confirmed that the most visible form of ice cover (reflected by backscatter and pixel brightness) is the ice jam made of mobile forms of pancake ice and ice floes. In case of Dębe reservoir such an ice jams form at the edge of static ice cover developing faster at the main body of the reservoir. Strong difference in backscatter exists also between open water and melting ice at the phase of continuous ice cover disappearance. Using color composite image created from GRD product there has been encountered a problem of differentiation between still open water and the fast ice. Both surfaces have a very similar surface scattering and physical properties so at the image they are represented by very low brightness pixels in all amplitude and polarization channels. In visual interpretation the useful feature for the continuous fast ice at the reservoir can be an ice cracks caused by the changes in reservoir volume and level of water.

To improve the interpretation of Sentinel-1 images of different ice cover phenomena it is important to have a good understanding of hydrodynamics of the reservoir and water temperature of the inflowing rivers. The pattern of ice flows at the initial phase of ice cover development at the reservoir is controlled also by the wind force and direction. So it is useful to have a notion about meteorological conditions at the time of satellite image recording.

Sentinel-1 sattelite SAR images have a very large potential as a source of information about difficult to observe at the ground ice phenomena developing at major rivers and large reservoirs. These data can be used operationally by RZGW – Operation Centers of Flood Protection for creation of ice reports. Information on ice phenomena development at inland waters can improve our knowledge about hydrology and channel processes.

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ZASTOSOWANIE OBRAZÓW RADAROWYCH Z SATELITY SENTINEL 1 DO OCENY ZJAWISK LODOWYCH – NA PRZYKŁADZIE JEZIORA ZEGRZYŃSKIEGO

ABSTRAKT

Obrazy radarowe z satelity Sentinel-1 są udostępniane bezpłatnie przez Europejską Komisję Kosmiczną (ESA). Jest to para satelitów A i B, które z częstością co 2 dni rejestrują powierzchnie Ziemi w systemie teledetekcji aktywnej – radarowej. Wysyłany impuls promieniowania elektromagnetycznego w zakresie fal o długości 6 cm (pasmo C-SAR) wraca do anteny satelity i jest rejestrowany z uwzględnieniem dwóch składowych polaryzacji. Obrazy Sentinel-1 są przetwarzane za pomocą programu SNAP, który umożliwia korekcję geometryczną, radiacyjną i wykonywanie przetworzeń polegających na zastosowaniu operatorów matematycznych. Na przykładzie okresu zimy 9 I 2017–2 III 2017 wykonano porównanie zasięgu i form zjawisk lodowych na Jeziorze Zegrzyńskim i dolnych odcinkach Bugu i Narwi. Wynik analizy wskazuje, że w obrazach radarowych dobrze odwzorowuje się lód rzeczny, natomiast gładki lód jeziorny jest trudny do interpretacji. Obrazy radarowe Sentinel-1 w zakresie produktów Interferometric Wide i polaryzacji VV+VH mogą być wykorzystane do oceny przebiegu i zasięgu zjawisk lodowych.

Słowa kluczowe: satelita Sentinel-1, obrazy radarowe, zjawiska lodowe, rzeka Narew, teledetekcja