Mapping of Spatio-Temporal Changes of Surface Water Using Sentinel-1 SAR Images

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Abstract. Exploration of surface water bodies and their spatial definition has great importance in water resources management and helps understand hydrological processes in the country. Fast, regular, and effective ways of mapping watercourses and their surroundings through remote sensing methods are crucial tools for capturing change and predicting hazards. The last decades have brought new data products, open-source software, and evaluation procedures that allow low-cost mapping of surface water objects. A widespread and sought-after option for this type of mapping is the use of SAR (Synthetic Aperture Radar) image products. Just through SAR technology that it is possible to identify changes in water in a relatively short time and at the same time under any meteorological conditions thanks to backscattered microwave radiation. This paper presents the possibilities of using SAR technology and its data for long-term temporal mapping of meteorological-hydrological changes in surface water using satellite images of Sentinel-1 product level GRD. As regards surface water extraction, this process is performing by segmenting the threshold values according to the Otsu principle. The water surfaces are then interpreted into the form of water masks of objects by the binarization of the final image. These values are subsequently compared with the supervised classification RFC (Random Forest Classifier) method results. Suitable processing and evaluation procedures conclude that the more suitable polarization configuration for mapping water bodies is VV (vertical-vertical) polarization. As for speckle filter tools to eliminate radar noise, the most suitable option seems to be using a Lee filter. To achieve more accurate results of the extracted water bodies, it is then appropriate to implement quantitative statistical indicators of accuracy and their numerical interpretation of the reliability of results. This paper aims to demonstrate the advantages of using satellite SAR images for spatiotemporal mapping of surface water in the landscape to observe hydrological processes due to inundation, ecological and meteorological changes, and anthropogenic activity.

1. Introduction
Mapping of surface water bodies such as rivers, lakes, and reservoirs has great importance for understanding the hydrological and geomorphological processes in the country. Timely and accurate information on sudden spatial changes in surface water can help manage floods, ensuring the protection of agricultural land, protected areas, and residential areas. With the advent of Earth remote sensing techniques, the possibilities for observing these changes are much more widespread, thanks to real-time observations and at regular temporal intervals.
Satellite remote sensing is an effective source of information to detect surface water over large areas and document their evolution in time [1]. It is possible to say that the information about surface water from satellite images can also be helpful in the analysis of water sources and evaluation of their properties. The analysis of spatial extent and temporal pattern of flood inundation from remotely sensed imagery is of critical importance to flood mitigation and management [2]. Water body extraction has become a very important part of remote sensing science since water monitoring plays an important role in water resource management [3].

For mapping water areas and their extraction, the use of SAR images has seemed to be a suitable tool for several years. Over the past years airborne and space borne synthetic aperture radar (SAR) systems have increasingly been used for mapping and monitoring of hydrological parameters [4]. Remote sensing technology is also effectively used to monitor geohazards and the development of human-made changes in the country [5]. Smooth open water surfaces act as specular reflectors and are therefore characterized by low SAR backscatter values [6]. For this reason, these areas are clearly and distinctly distinguishable from places without the presence of water, due to the higher values of SAR backscattered radiation. The assumption established for using SAR data relies on the fact that radar remote sensing is sensitive to the water content of soil due to the increase in the dielectric constant with the increase of the soil water content [7]. The surface reflectivity measured by radar imagery (also known as the radar backscatter coefficient $\sigma^0$) is a function of the radar system parameters (such as the frequency, polarization, incident angle) and the surface parameters (such as the topography, roughness, dielectric properties of the medium, moisture) [8]. SAR-based techniques for the detection of temporarily flooded vegetation include simple approaches, such as manual thresholding [9][10], automatic thresholding [11][12], clustering algorithms [13], distance-based classification methods [14], and rule-based classification [15]. When processing a large amount of data, especially for time series analysis, it is productive to use tools that can process them quickly and effectively [16].

This paper aims to identify the extent of changes in surface water bodies based on SAR images of Sentinel-1 in the semi-annual temporal interval. As part of obtaining the most suitable water extraction method, individual filtration tools for radar noise elimination are compared. This paper also includes a comparison of the results of both SAR polarization configurations. Method of supervised image classification called Random Forest Classifier is chosen to refine and compare the results of the manual segmentation of the threshold values.

2. Study area, materials, and methods

2.1. Study area

The Bodrog River is one of the sourceless rivers in eastern Slovakia, specifically in the East Slovakian lowlands (Figure 1). This river arises by the confluence of two rivers Ondava and Latorica, and the beginning of the Bodrog River is near the municipalities of Zemplín and Svätá Mária with approximate WGS84 geographic coordinates 48.454512 ° N and 21.819570 ° E. The mouth of the river is tributary to the river Tisza, near the town of Tokaj in Hungary. In terms of comparing the length of the stream, Bodrog is the eighth longest river in Slovakia.

The Bodrog River is also one of the rivers with the maximal possible culmination of the water level in Slovakia (the difference can reach up to 7 meters). The Bodrog river basin precipitation may characterize as a relatively differentiative throughout the year. The largest annual rainfall total of approximately 1000 mm / year is in the Vihorlat Mountains and the surrounding, specifically mountainous areas near the Slovakian-Ukrainian border. The paradox is that a few kilometers south, some areas of the East Slovakian lowland are among the areas with the lowest total annual precipitation with an approximate value of 550 mm/year.
Regarding the climatic-meteorological conditions of the Bodrog basin, at the end of 2017, high precipitation totals of up to 38.0 mm were in December. These values were also due to the melting of the snow cover due to abnormal outdoor temperatures in the third December decade. Based on these precipitation and climatic conditions, the following peak water levels $H_{\max}$ were measured the next day with declaration 3rd degree of flood activity in selected water meter stations. A similar situation was at the beginning of February 2018, when precipitation rain activity gradually turned into rain with snow. The subsequent rise in temperatures above 0°C increased the water levels of the rivers in the Bodrog basin. High values of culminating flow $Q_{\max}$ persisted in the following days, especially in the lower part of the Bodrog basin. An important month in terms of hydrological conditions in the Bodrog basin was also April 2018. In this month, the culminating flows in selected water meter stations were at the level of the first degree of flood activity. Due to the hydrological situation in the upper Bodrog basin and the Ukrainian part of the basin, three days later was declared the 2nd degree of flood activity in the water station Streda nad Bodrogom. (Table 1)

**Table 1.** Table of culminating water levels and flows with the determination of N-year and degrees of flood activity in selected water meter stations for temporal interval 11/2017 – 04/2018

| Flow station name  | River name | Date       | Hour   | $H_{\max}$ (cm) | $Q_{\max}$ (m$^3$/s) | N-year | Flood stage |
|--------------------|------------|------------|--------|-----------------|-----------------------|--------|-------------|
| Ižkovce            | Laborec    | 17.12.2017 | 07:45  | 780             | 520                   | 2      | 2.          |
| Veľké Kapušany     | Latorica   | 18.12.2017 | 16:45  | 784             | 340                   | 5-10   | 3.          |
| Streda and Bodrogom| Bodrog     | 19.12.2017 | 07:15  | 868             | 650                   | 2      | 3.          |
| Streda and Bodrogom| Bodrog     | 07.04.2018 | 15:00  | 759             | 438                   | < 1    | 2.          |

2.2. Satellite data

For temporal evaluation of hydrological activity, Sentinel-1A satellite images were used for this purpose. The Sentinel-1 mission is a constellation of two polar-orbiting satellites (Sentinel-1A and Sentinel-1B), which operate day and night, sensing with a C-band synthetic aperture radar instrument operating at a centre frequency of 5.405 GHz, allowing the acquisition of imagery regardless of weather and illumination conditions [17]. Acquisition of Sentinel-1 products was from the Data Search Vertex ASF (Alaska Satellite Facility) portal at the address search.asf.alaska.edu and the Copernicus Open Access Hub at the link scihub.copernicus.eu. For this study, Ground Range Detected (GRD) product level data obtained in the Interferometric Wide Swath (IW) scanning mode were used, with polarization configuration type VH a VV, and spatial resolution 10m x 10m/pixel. (Table 2)
Table 2. Table of used temporal satellite images SAR Sentinel-1 with their parameter

| Acquisition date | Satellite     | Absolute orbit | Orbit type   |
|------------------|--------------|----------------|--------------|
| 23. November 2017| Sentinel-1B  | 8404           | Descending   |
| 19. December 2017| Sentinel-1A  | 19774          | Ascending    |
| 12. January 2018 | Sentinel-1A  | 20124          | Ascending    |
| 11. February 2018| Sentinel-1B  | 9578           | Ascending    |
| 19. March 2018   | Sentinel-1B  | 10103          | Ascending    |
| 12. April 2018   | Sentinel-1B  | 10453          | Ascending    |

2.3. Methodology

The acquired SAR images were preprocessed using ESA’s open-source Sentinel-1 Toolbox [18]. The data processing process consists of thermal noise removal, radiometric calibration, radar noise filtering, and Doppler terrain correction based on the SRTM (Shuttle Radar Topography Mission) digital elevation model. For interpretation of results was used the segmentation of threshold values based on the Otsu method. The supervised classification method Random Forest Classifier is used to refine the results. The essence of this type of classification is the classification of individual pixels into classes based on vector patterns created by the user. For an obviously and more complete idea of the process steps, a graphical representation of the processing process in the form of a flowchart is available (Figure 2).

Figure 2. A Schematic flowchart of the water extraction process from SAR satellite images Sentinel-1 GRD
2.4. Accuracy Evaluation
The process of quantitative accuracy evaluation consists of comparing the pixels of the resulting extracted water masks with a reference background image. Based on this, the resulting images can be quantitatively categorized using four prestige indicators. It gives statistical percentage reliability of the results obtained. These indicators include Producer’s accuracy (PA) User accuracy (UA), Overall accuracy (OA), and Kappa statistical coefficient (Kappa).

\[
PA = \frac{TP}{TP + FN}
\]

\[
UA = \frac{TP}{TP + FP}
\]

\[
OA = \frac{TP + TN}{\text{total pixels}}
\]

\[
Kappa = \frac{\text{total pixels} \cdot (TP + TN) - [(TP + FP) \cdot (TP + FN) + (FN + TN) \cdot (FP + TN)]}{TP + FN}
\]

If the parameter TP represents the number of all correctly extracted pixels of water. The parameter FP represents the opposite, i.e. the number of incorrectly extracted pixels. TN parameter characterizes nonwater pixels extracted correctly. The last parameter FN describes pixels with incorrect water extraction.

3. Results and discussions
3.1. Calibration threshold and polarization selection results
A significant factor in SAR images is the polarization of the radar signal. Discrimination of inundated areas can be optimized by selecting the most suitable polarization of the radar waves [19]. Therefore, to choose the correct type of polarization of SAR images, there is a need to compare the backscattered signal strength values for both types of Sentinel-1 SAR image polarization. For this reason, were selected 25 terrain control points in specific areas adjacent to the Bodrog riverbed, subject to the inundation process (Figure 3).
For comparison, the intensity of pixels was used, converted into a physical quantity, which is called the backscatter coefficient, expressed in decibels (dB). In obtained values of intensity in dB, it is possible to see minimal differences between VV and VH polarization during the flood activity. They range from -27 to -23 dB for VH polarization and from -26 to -20 dB for the type of polarization referred to as VV. Based on the obtained intensity values, it is possible to evaluate that the VV polarization is significantly affected by the heterogeneity of the environment, but especially by the roughness of the terrain. In monitoring the extent of inundation with VH polarization in the selected temporal range (in the winter months), the results are affected by snow cover. Also, in the spring months by lightly waterlogged soil due to melting snow or long-lasting rains. Another advantage is the relative variability in intensity before and after inundation with the VV polarization type of Sentinel-1 images (Figure 4). It requires a clear definition of the Sigma 0 intensity threshold. In addition, smooth water surfaces cause an even more significant decrease in backscatter to lower negative values. In conclusion, a more suitable type of polarization for mapping water bodies is type VV.

![Graphical representation of backscatter intensity for VV and VH polarization types](image)

**Figure 4.** Graphical representation of backscatter intensity for VV and VH polarization types

### 3.2. Speckle noise filtering comparison results

Radar noise filtering is known to play a relevant role in SAR image processing. The results of the application of speckle filter tools to remove radar noise show that the images after applying the filters contain several times fewer random radar noise pixels. As for the width of the Bodrog riverbed and the extent of the inundated area, it is possible to say that the use of filters with a window size of 7x7 and 9x9 appears to be an inefficient way of eliminating radar noise.

This water mask comparing was also performed for other radar noise filtering tools, namely Lee with larger window size, Refined Lee, Gamma Map, and Lee Sigma filter. This comparison showed that the results contained statistically significant deviations depending not only on the filter used but also on the window size. Of course, an unfiltered image contains a lot of dark pixels of radar noise. Therefore, the resulting range of water bodies is above average and also not entirely accurate. Thus, it is possible to say that the application of any filter to reduce radar noise prevents errors in quantitative calculations. On the other hand, the usage of large windows (e.g., a Lee filter with a 7x7 window) causes part of the averaged pixels in the watercourse area to be reported as water-free after calculation (especially by changing the spatial resolution of the image). Therefore, its use is suitable for monitoring water areas of a large extent, not narrower riverbeds. Various types of scientific publications focus on the application of Lee and Lee Sigma filters in the study of water extraction.
from SAR images. From the obtained numerical and graphical results, the use of the Lee filter appears to be the most advantageous. The main advantage is the ability to effectively minimize the presence of pixels situated outside the inundated area (Figure 5).

![Figure 5. Graphical comparison of radar noise filtration results: Lee filter vs no filter](image)

The following table (Table 3) shows that suitable window sizes are 3x3 or 5x5. However, using a 5x5 window in selected places seemed to be a not appropriate tool due to the decreasing width of the Bodrog riverbed and thus the extent of water areas. For this reason, was selected the Lee filter with a window size of 3x3 for the radar filtration process.

![Table 3. Table of comparing total flooded in specific part of river Bodrog using different types of Speckle filtration tool](image)

3.3. Results of supervised classification

At the beginning of the classification process, new vector data samples (New Vector Data Container) were created, based on SAR images after field correction and filtration of radar noise with the Lee filter tool with a window size of 3x3. Polygons of data samples were assigned to the individual data samples, which represented the selected classification classes. After then were chosen two classification classes Water and NonWater, for better interpretation of results. After quantifying the extent of the water surfaces, the water surfaces were extracted into binary masks using the Band Maths tool in the SNAP platform. Subsequently, the statistical percentage reliability of the obtained results was calculated by quantitatively evaluating the accuracy of the obtained results of the extraction of water surfaces using the indicators PA, UA, OA, and Kappa (Table 4).
Table 4. Results of accuracy assessment of extracted water masks

| Temporal interval | Extraction method | PA (%) | UA (%) | OA (%) | Kappa |
|-------------------|-------------------|--------|--------|--------|-------|
| 11/2017           | threshold         | 83.2   | 60.2   | 84.0   | 0.297 |
|                   | classification    | 79.6   | 56.9   | 85.1   | 0.349 |
| 12/2017           | threshold         | 92.8   | 84.6   | 94.9   | 0.993 |
|                   | classification    | 93.4   | 82.2   | 94.3   | 0.904 |
| 01/2018           | threshold         | 90.6   | 81.9   | 91.7   | 0.616 |
|                   | classification    | 88.7   | 73.0   | 90.7   | 0.701 |
| 02/2018           | threshold         | 81.5   | 74.3   | 87.1   | 0.567 |
|                   | classification    | 84.9   | 70.7   | 93.0   | 0.793 |
| 03/2018           | threshold         | 82.4   | 61.6   | 89.4   | 0.910 |
|                   | classification    | 88.3   | 83.7   | 91.6   | 0.843 |
| 04/2018           | threshold         | 98.6   | 90.6   | 99.6   | 0.986 |
|                   | classification    | 97.1   | 84.7   | 98.9   | 0.942 |

From the achieved graphical and numerical results, it is possible to see that the implementation of the supervised classification method Random Forest Classifier brings relatively reliable results. These results are comparable with the principle of manual segmentation of threshold values by the Otsu principle (Figure 6).

![Figure 6. Graph of temporal evaluation of changes in water bodies and comparison of both methods of water surface extraction in the Bodrog river basin using SAR images](image)

4. Conclusions

Regarding the results of the temporal processing of SAR images of Sentinel-1, it is possible to say that almost all data are appropriate for water extraction. Thanks to the ability of the SAR system to operate even in adverse weather conditions, a significantly greater temporal range is available. These data thus provide up-to-date information on changes in a relatively short period (exceptionally even a few hours after river flow variation). Of course, the use of SAR data for the water bodies extraction brings several disadvantages to the processing, including in particular: inaccuracies in mapping some edges of watercourses and areas caused by the presence of vegetation in the bank areas.
For SAR images of Sentinel-1, the water surfaces show a strong contrast with backscatter intensity. Comparisons of different parameters show that the use of the polarization configuration VV has a more significant effect on the intensity of backscatter radiation from water surfaces. If we look at speckle-noise effect elimination, we can say that this process partially reduces the image resolution quality. For this reason, when filtering tools, Lee filtration with a window size of 3x3 with sufficient exclusion of false-positive values was chosen as the most suitable option. The threshold segmentation, based on the Otsu algorithm, is an appropriate way of interpreting the results. The results of the supervised classification method Random Forest Classifier indicate a relatively identical size of water bodies like the thresholding method. In conclusion, these outputs are a suitable tool for other ways of comparing the extraction of water bodies using images of the optical spectrum of remote sensing of the Earth.

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