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Country-wide flood monitoring service: methods, applications and functionalities

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ABSTRACT

The country-wide monitoring service generates CBK-Floods product, which provides the current surface water cover over Poland. The automatic detection algorithm has been developed. It uses Copernicus Sentinel-1 radar satellite images as well as proposed improved model of valleys derived from fusion of various data sources (e.g., Copernicus Riparian Zones, LIDAR, flood hazard zones). The overall accuracy of the algorithm is around 86%. The map is updated after each pass of the satellite and shows different stages of inundation: new water extent, areas with long-lasting water and those from which water has receded in the last days. Two kinds of information are generated: (1) flood water extent; and (2) hydroperiod regime. Information about flood water extent is of critical importance for rescue and crisis management activities. Availability of recent water cover maps can support rapid situational assessment and influence decision processes taken in regional and local crisis management centers during flood. Information about hydroperiod regime allows the proper management of water needed for agriculture and can be an indicator of the state of ecosystems present in the valley. In 2022 service worked in pre-operational mode and produced a series of surface water maps for the entire Poland. In 2023 service will go into operational mode. The water extent maps will be available to visualize in the Sat4Envi Crisis Management Portal and downloadable from its repository. In this paper, we aim to present the data processing chain applied in the flood monitoring system, including the surface water detection method and the way of visualizing the final product. We present the limitations of the service based on satellite radar data and give examples of the use of flood products.

Keywords: flood, automatic detection, Sentinel-1, radar, hydroperiod, inundation, Poland

1. INTRODUCTION

Floods are the greatest natural hazard that regularly affects Poland, causing huge material losses. During such situations, not only purely rescue operations are conducted, but there is also a lot of civil protection and logistical challenges. What counts is not only the effectiveness of decisions made by the commanders of rescue services, but also voivodes and local governments at various levels. For these reasons, it is extremely important to provide accurate and consistent information on the development of the flood situation, which is widely available through appropriate GIS systems. Satellite observation is a unique source of comprehensive and large-scale information, and together with distribution system, it can be an important element in supporting decision-making processes.

Apart of its great importance in crisis management, the service finds also a lot of environmental applications. Basing on the information about surface water presence in the area, the hydroperiod maps can be generated which provide data about flood regime, length of the surface water presence, and length of dry period. This data is also crucial for modeling of water circle in the environment of specific area. The analysis of interannual changes in hydroperiods/flood regimes, allows to evaluate the changes in habitats and a state of riparian ecosystems and hazards related to water deficit. This kind of information can be also used as driver for spread of invasive species. Moreover, this data is crucial for the management of agricultural areas. They show the availability of water in catchment, and permit to manage the artificial drainage systems. They allow to evaluate losses in the agriculture due to floods or droughts.

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The launch of radar satellites as part of the EU Copernicus Programme opened a new era for the use of satellite information. For the first time radar images are publicly available in an open access. Data is acquired in a regular and spatially continuous manner that enables provision of monitoring services. Meanwhile, several water detection methods were developed[1]. In order to take advantage of these opportunities, few years ago, we came up with the idea[2] of creating a service that could provide continuous detection of surface water and maps presenting areas currently affected by flooding and seasonal inundation in Poland. Since then, the research on the water detection method began, followed by the development of software and its implementation in the computing environment. The test version of the service went into preoperational mode in 2022. The software was transferred to a virtual machine and started to produce regularly a water mask and its visualization via Sat4Envi Crisis Management Portal[3]. After obtaining several months of data series, we decided to make adjustments to the visualization algorithm and the service will resume its operation in Q3 2023.

In the meantime, the Global Flood Monitoring (GFM)[4] service was launched by the Copernicus Emergency Management Service in December 2021. It provides new operational continuous monitoring of worldwide flood events. All incoming Sentinel-1 GRDH VV-polarization radar satellite images are processed and analyzed in near real-time with the use of an ensemble method comprising three water and flood detection algorithms: change detection in the form of backscatter difference of two images, hierarchical tile-based thresholding of one image and time series analysis per pixel. As a result, several information products are generated - water bodies: observed flood extent, reference water mask and observed water extent; quality-related products: exclusion mask, uncertainty values and advisory flags; footprint of Sentinel-1, schedule of the next acquisition and metadata; impact estimate: affected population and affected land cover. Products are available within 8 hours from the satellite data acquisition. The estimated accuracy is 94%. The authors point out that due to use of Sentinel-1 radar images, the service may produce false and missed alarms[5]. However, it is actually the first service of this kind, providing information for the whole world operationally with high spatial resolution, better timelines and accuracy[6].

Our service aims to provide national level products. Moreover, we deliver the information in the form required by Polish end-users.

2. METHODOLOGY

2.1 Materials

The automatic detection algorithm uses Copernicus Sentinel-1[7] GRDH radar satellite C-band images that have approximately 14 meters spatial resolution. They are acquired in 250 km wide paths at around 7:00 a.m. and around 6:30 p.m. (summer time) depending on whether the orbit is ascending or descending. Currently, with one satellite in operation, the return period is 12 days. When the second satellite is operational again (Sentinel-1B failed in the end of 2021 and Sentinel-1C is expected to be launched in the near future) the time interval will be shortened to 6 days. The radar instrument acquires image of any area regardless of weather conditions: cloud cover, fog, haze, smoke, with or without sunlight. There is uninterrupted data stream, which is especially important in case of raised water levels and resulting floods and inundations. The implemented procedure assumes that software processes every image that is acquired over the territory of Poland.

The extent of normal water level in rivers and lakes is derived from the land cover classification map for Poland in 2020. The classification was performed on Sentinel-2 images with use of S2GLC PL 2020 methodology[8]. The land cover has 10 m spatial resolution and the overall classification accuracy is at least 80%. The S2GLC PL2020 database is also used in the process of selection of random points needed for the random forest classification described below.

As the analysis is done only for river valleys/riparian zones, the following auxiliary datasets were used:

- At the regional level, Copernicus Riparian Zones[9] layer, flood hazard zones with the probability of occurrence equal Q0.2% (once in 500 years) and data from the Preliminary Flood Risk Assessment[10] (WORP) including: historical floods, inundation areas assessed through geomorphological analysis, areas at a risk of flooding after destruction of damming structures. The flood hazard zones and WORP database were obtained from the State Water Holding Polish Waters.
- At the local level, LIDAR DEM from IT Country Protection System (ISOK)[11] to delineate extended riparian zone area.

2.2 Processing chain

2.2.1 Riparian zone layer preparation

The riparian zone extent was created by merging four sources of data:

- Copernicus Riparian Zones,
- Preliminary Flood Risk Assessment and flood hazard zones,
- Hydrological map of Poland,
- LIDAR.

The first two datasets provided the borders for the main rivers in Poland. LIDAR data and hydrological map were processed to extract riparian extent for all other rivers in Poland; not included in the previous data sources.

To extract riparian zones from LIDAR data, we used geomorphological approach, which aimed to detect the edges of river valleys. Firstly, we generalized the DEM to integer values. Then we calculated the curvature of the terrain and we reclassified area into convex, flat and concave surfaces. The flat and concave areas which were located along the rivers derived from the Hydrological Map of Poland were selected and assigned as riparian zones.

S2GLC land cover map was used as a source of samples with stable water locations.

The final riparian zone extent was generated as a sum of riparian zone areas from all four data sources.

2.2.2 Flooded areas layer

To detect flooded areas the change detection algorithm was developed basing on Sentinel-1 satellite images. The algorithm contains the following main steps: Sentinel-1 data preprocessing, detection of changes, surface water classification, integration of datasets.

The preprocessing of radar images is conducted for both VV and VH polarization bands and includes the following steps: applying of orbit file, calibration, speckle filtration with the Lee Sigma filter (with 7x7 window size), terrain correction with the default use of SRTM 3sec DEM. When all images from one path are pre-processed, two mosaics are created for VV and VH images separately.

The change detection algorithm is based on ESA SNAP change detection tool, in which ratio between two images is calculated. We use mosaics of VV polarization from the same orbit (ascending or descending). The thresholds of changes were established using validation dataset with the interval of 0.1. The final values of thresholds provide slight overestimation of detected changes. We establish three classes using the following thresholds:

- values $<= -1$ indicate areas where possible water appeared,
- > 0.6 threshold indicates water disappearance,
- all other values indicate stable areas.

Next, the random forest classification is performed on the VV and VH stacked mosaic with the current date. The training points are randomly drawn from the land cover S2GLC PL 2020 raster layer. Samples of water (1500 points) and various non-water land cover classes (1000-10000; depending on class area coverage) have been randomly selected for each path. The samples were collected once at the beginning of system development and are stored for subsequent classification of images from a certain orbit. The raster resulting from classification (*classification_T2*) contains two classes: 1 – water, 0 – no water. To avoid the salt and pepper effect, the classification map was filtered with median filter.

To create the final map of the surface water dynamics within riparian zones, we fuse:

- change detection layer,
- surface water classification layer,
- riparian zone layer.

Figure 1 presents the rules of layers fusion in 10 different cases. Besides the fusion of three mentioned layers, the previous flooded areas map (*T1 map*, generated 12 days earlier) is incorporated for the cross-checking of change detection layer and classification of surface water of T2 day. Cases 1-4 represent the expected situation, where all three layers show consistent trends. Cases 5-8 describe the situations when the change detection algorithm overestimates, as it was intended during the thresholds setting. Finally, cases 9-10 show how results of classification T2 are corrected. As we established that the change detection algorithm underestimates ‘no change’ class so we assume that in the cases of the recognition of this class the change has not occurred and we maintain the value of T1 map.

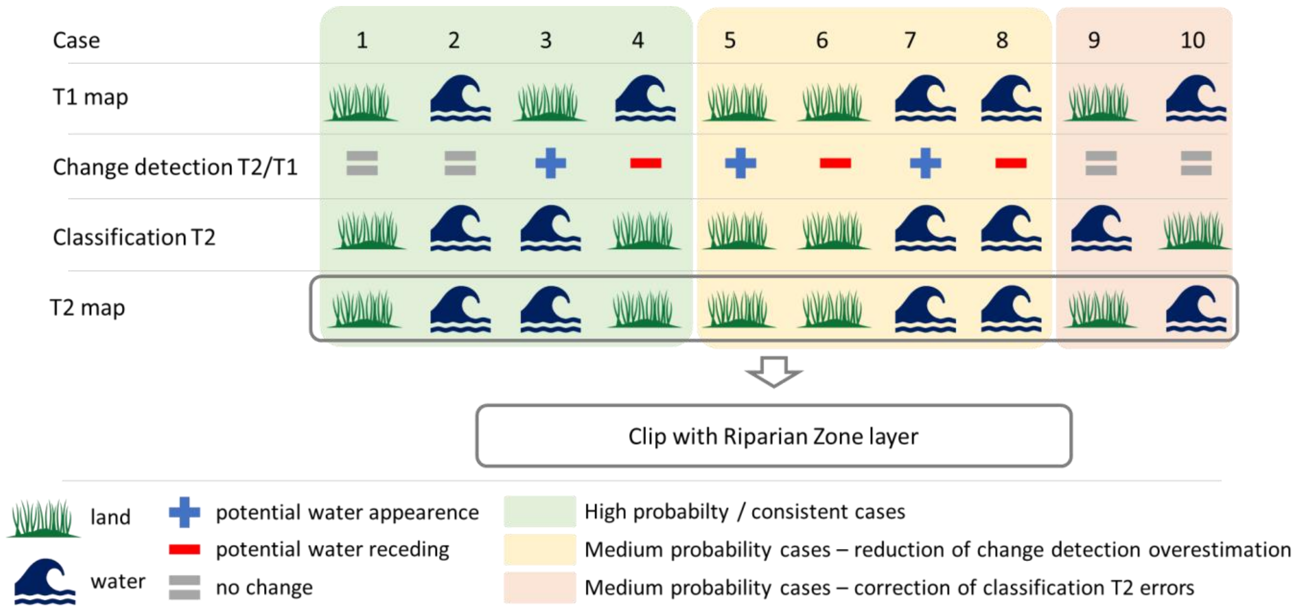

Figure 1. Creation of flooded area map for day T2. T1 map is flooded area map generated 12 days before T2.

At this moment, we obtain the classification of areas where new water appeared, or the water disappeared within riparian zone, or there was no change (for the following situations: water still remains or there was no water on both images). The process is repeated for each orbit, when the new image is acquired. In this way, we receive the result layers, used later in the visualization system.

2.3 Validation

To evaluate the accuracy of proposed solution, two pairs of images have been selected. For each pair, 1500 randomly located points have been sampled:

- 500 within potential changes of the riparian zone area,
- 500 within potential no changes of the riparian zone area,
- 500 within potential changes, outside the riparian zone area.

For each point, one of three classes:

- no change,
- change from water to no water,
- change from no water to water,

has been assigned by photointerpretation.

Basic accuracy metrics were calculated from error matrix: users' accuracy (UA), producers' accuracy (PA), F1-score (F1) and Overall Accuracy (OA). The test was carried out for two scenarios: flood development and post flood water receding.

3. SYSTEM DEVELOPMENT

3.1 Development environment

To deliver the results to the end-users, we developed fully automatic system of data processing, integration and visualization. The system uses cloud computing, and final products are delivered via Sat4Envi portal.

The initial preprocessing of radar images and change detection is carried out using ESA SNAP software components. The particular steps of processing chain and results visualization are mostly based on functions written in python programming language. We use various libraries, among others: gdal, numpy, ogr, scipy, scikit-learn.

3.2 Data visualization

The aim of the system is to deliver the most updated information about surface water dynamics to the end-users. Different regions of Poland are captured by Sentinel-1 with different frequencies and from different orbits. It means that every day, only a part of Poland is covered by new images. In order to update the country-wide products every day, the problem of data integration from different orbits (ascending and descending) had to be solved. Currently Sentinel-1 data are available every 12 days for specific orbit, but the system is designed to process also the data acquired every 6 days; when two Sentinel-1 satellites are operating.

The ascending and descending orbits create a complex mosaic of overlapping paths. Therefore, an appropriate method of visualizing the results had to be developed. When building a mosaic of the entire Poland, we apply the rule that the newest images always cover the older ones (Figure 2). The resulting final map is as up-to-date as the recently acquired images.

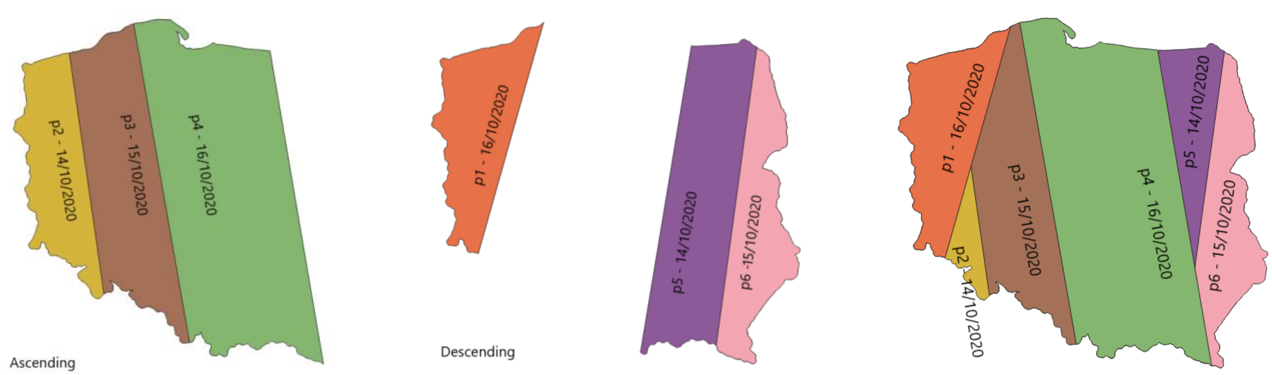

Figure 2. Building a mosaic of imagery paths from overlapping ascending and descending orbits.

For the end user, the information of water presence may be not sufficient, so we developed the visualization rules which allow to distinguish the 4 classes of inundation and 3 classes of water recession depending on the time it was detected, along with normal water and land classes. The general overview of applied rules is presented in Figure 3. The values from the T2 map are converted depending on the considered case and taking into account the date of and values saved in the last available visualization.

In the end, the final "CBK-Floods" product consists of two raster files: one with class values and the other accompanied by look-up table according to legend shown in Figure 4. They are delivered with appropriate metadata files. Pixel size of the products is 13.9 m. The products are written down and transferred to the output maps repository, from which they are published in the Sat4Envi Crisis Management Portal (Figure 4).

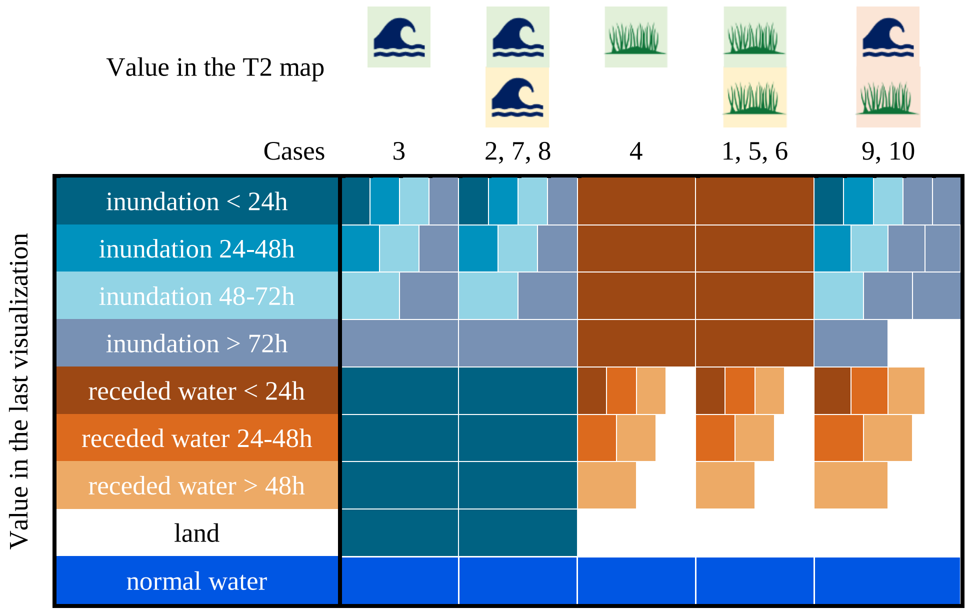

Figure 3. The rules of visualization of the results in Sat4Envi Crisis Management Portal.

4. RESULTS

4.1 Validation

Results of the validation are presented in the form of accuracy matrices. The accuracy varies, depending on the pair of images being used. Due to end users' requirements, the parameters of the algorithm were adjusted to the situation where slight overestimation of flooded water detection is preferred, comparing to flooded areas underestimation. The mean overall accuracy is 93.26% (Table 1). F1-score of 'Water appearance' class is lower, comparing to two other classes, due to overestimation which was declared by the end users as preferred constrain. For flood development scenario, the OA was 97.52%, while for post flood water receding, the OA was 89.20%. Lower OA in the second case, may be related to the fact that the vegetation which was covered by water, could be damaged and post flooded areas can have small roughness and be misclassified as water.

Table 1. Accuracy matrix of change detection products – combined values from two analyzed scenarios.

	Water appearance	**Water receding**	**No change**
Water appearance	105	0	70
Water receding	0	247	24
No change	20	81	2345
PA	0.84	0.75	0.96
UA	0.60	0.91	0.96
F1-score	0.70	0.82	0.96
OA	93.26%		

4.2 Sat4Envi Crisis Management Portal

The CBK-Flood products are available through the Sat4Envi Crisis Management Portal for logged in and authorized users. Our service provides daily updated interactive, high resolution maps presenting the dynamics of water surface (with 8 classes) in Poland (Figure 4). It is automatically activated after new data acquisition. The portal allows to display the maps as well as to overlay additional information through WMS services (e.g. embankments) or layers of administrative units available by default. An archive of daily data is created and the users can search for and display historical water surface. Apart from on-line access, the users can also store locally georeferenced products. The metadata is distributed along the products.

Figure 4. Example of inundated areas, Sat4Envi Crisis Management Portal. OpenStreetMap is in the background.

5. DISCUSSION

Until now, information on surface water extent was obtained from field reports, which were sometimes supported by aerial observations and photographs. It was usually not presented in the form of maps, because the received data was dispersed and insufficient for spatial presentation. The flood monitoring service is a step to make up-to-date water coverage maps widely available that will help to quickly assess the situation and to make decisions by regional and local crisis management authorities.

The service is fully automatic and available for authorized end users in Poland. It answers for the needs of national and regional civil protection entities. In comparison to GFM portal, the continuous information is delivered in complex form. It means that in one raster, we present the surface water history for at least last 72h. What is important from users' point of view, is the possibility of the observation of temporal water stagnation. It is very helpful for planning of rescue and recovery actions. Continuous generation of flood water cover maps enable collection of long series of data that can support risk assessment processes by generation of analyses on e.g.: maximum observed extent of water during a specific period of time, number of days with water cover, etc.

Apart from the application in crisis management, the developed method and the service find the use in the environmental and agricultural management. Basing on the delivered products, the hydroperiod for given areas can be calculated and in such way, we can establish periods of abnormal water presence. This information is helpful for the determination of potential water stress of crops, as well as a state of riparian zone vegetation communities.

By the fusion of information provided from two layers: change detection map and water/no water classification of T2 we introduce the cross check of the results. On the one hand, change detection reduces the potential errors related to the detection of smooth areas as water. On the other hand, the thresholds of change detection were defined in liberal way. It results in overestimation of number of detected changes. The overestimation of changes is minimalized by classification of T2 and application of riparian zones layer. Such approach allowed to obtain high quality products which satisfy the users' needs.

The service was originally designed to use data from two radar satellites, but since the failure of Sentinel-1B at the end of 2021, we had to modify algorithms and adjust processing chain in order to work properly with data from only one satellite. This event affects the usability of the service because there is significantly less data available. It can be harder to identify the moment of the largest flooded area. When analyzing the time series of water cover maps, the establishment of precise dates of continues water presence is more difficult. It is expected, that with the launch of Sentinel-1C satellite, the service will again provide more detailed temporal information.

Both, the detection of water on radar satellite images and the entire service based on this data have some specific limitations. Water cover map cannot be obtained for the whole Poland at one time, because Sentinel-1 acquires images in 250 km wide swaths. Some places will be provided with current information more often than the others because paths overlap lengthwise. The overlap is bigger in the north of Poland than in the south. For this reason, we decided to additionally to flood areas product, we deliver the raster with the date of the last image acquisition, of each pixel.

In some cases, water identification may be difficult due to the radar acquisition technique, the spatial resolution of an image and other sensor or terrain characteristics[6]. Some narrower rivers (less than 42 m wide) and small areas of surface water (less than 1800 m^2) may be indistinguishable in the image. Moreover, the inundated densely build-up areas[12,13], forests and other high vegetation[14] may influence the quality of water detection within this classes, using C-band satellite.

The service processes and publishes the data as soon as new acquisition is available. Delays in Sentinel-1 image delivery implicate the delay in our products distribution.

6. CONCLUSIONS

Presented CBK-flood product, which is served via Sat4Envi Crisis Management Portal is a response for needs from various types of end users communities, including specialists in crisis management, water management, agriculture, ecology, environment protection, etc.

Proposed method, thanks to cross validation procedure, allows to deliver fully automatically, high quality geospatial products as it mitigates the possible misclassifications related to water detection on radar images. The overall accuracy varies from ~89% to 97%, depending on tested scenario.

Sat4Envi Crisis Management Portal serves the geospatial products in easy to understand and interpret form. It delivers not only the most recent data, but offers also access to the archive of products and the possibility of downloading them. Developed procedures can operate with one or two Sentniel-1 satellites, depending on their availability.

In the future, more advanced functionality will be implemented in accordance to user requirement analysis.

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