Identification of permanent surface water in Bengawan Solo River downstream area, Indonesia using Sentinel-1 imagery

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Abstract. Permanent surface water is defined as area of the Earth continental surface corresponding to an accumulation of water, showing slight variations in water levels, retaining most of their volumes over the year and that do not dry up. Bengawan Solo watershed, especially in the downstream area is situated in East Java, Indonesia and is recorded as the longest and the largest river on Java Island. Thus, this river becomes one of the biggest water resources in Java, Indonesia. As a water resources, it is important to identify spatial distribution of permanent surface water in Bengawan Solo River. Synthetic Aperture Radar (SAR) is an effective way to detect surface water over large areas. Sentinel-1 is a new available SAR and its spatial resolution and short temporal baselines have the potential to identify permanent surface water. Thus, we propose an identification of permanent surface water using Sentinel-1 data. The quantitative evaluation shows relevant results with overall accuracy of more than 97%, F-measure provides value 0.79, also very low False Positive Rate and commission error. There are also morphological and land use change detected in the area. These results are encouraging and the first step for monitoring Bengawan Solo River.

1. Introduction
About 30% disasters which occurred in Indonesia are floods disaster. This hazard become continues disaster that take place every year [11]. Bengawan Solo watershed is one place where inundations happened almost each year [8]. On the other hand, based on water resources balances, Bengawan Solo watershed showed also water deficit [1]. Bengawan Solo River elongated from Central Java until East Java, Indonesia with two source come from Wonogiri and Ponorogo. As the largest and the longest river on Java’s island, Bengawan Solo become one of the biggest water resources in Java, Indonesia. Therefore, surface waters observation of Bengawan Solo River is crucial for water resources management. It is expected to help local government in manage optimally potential and risk of Bengawan Solo River.

In this research, study area will be focused on Bengawan Solo downstream which lie on three districts of East Java, i.e. Bojonegoro, Tuban and Lamongan [11]. This zone becomes our study area for this chapter due to its risk of floods and water deficit. Bengawan Solo downstream is a meeting place for two sources of the Bengawan Solo River. That is why this sub watershed has the highest floods risk. Another reason is erosion in upstream area of Bengawan Solo River which created sedimentation in
Bengawan Solo downstream. In addition, damage of catchment area leads groundwater decreasing and increasing in surface flow, then cause flooding in the rainy season and drought in the dry season.

Monitoring surface waters in Bengawan Solo downstream become really important for floods disaster management and water resources management. It is necessary to study spatial distribution of Bengawan Solo River, monitoring its river discharge and observing area along Bengawan Solo River. Permanent surface water is defined as area of the Earth continental surface corresponding to an accumulation of water, showing slight variations in water levels, retaining most of their volumes over the year and that do not dry up. As a water resources, it is important to identify spatial distribution of permanent surface water in Bengawan Solo River.

Synthetic Aperture Radar (SAR) is an effective way to detect surface water over large areas. SAR sensors offer clear advantages by providing their own sources of illumination, thus being able to operate in nearly all-weather/day-night conditions. For almost 20 years, spaceborne SAR sensors have increasingly been used for large-scale surface water mapping. In 2014, the European Space Agency (ESA) launched the Sentinel constellation including free available SAR data (Sentinel-1) with high revisiting time (about 12 days) and high spatial resolution (about 20 m). This constellation offers the possibility to increase the capture of genuine time series.

The objective of this work is thus to identify permanent surface water in Bengawan Solo River downstream area, Indonesia using Sentinel-1 time series images.

2. Study area and datasets
The study area is located in the Bengawan Solo watershed, especially in the downstream area. This area is situated in East Java, Indonesia and covers the Bojonegoro, Tuban and Lamongan districts. The downstream area of Bengawan Solo River is a meeting place of water flow from two sources of the river (sources come from Wonogiri and Ponorogo). That is why this area has the highest flood risk. Another reason is due to erosion in the upstream area of Bengawan Solo River which created sedimentation in the Bengawan Solo downstream. In addition, damage on the catchment area leads to a decrease in groundwater and increase in surface flow, therefore causing flooding during the rainy season and drought during the dry season.

![Figure 1. Study area of Bengawan Solo River downstream with Sentinel-1 & 2 coverage areas.](image)

Twelve (12) images of Sentinel-1 IW GRD are used. Those images were obtained in a one year period (2017), with one image for each month (Table 1). Coverage areas of the images used can be seen in Figure 1. The test areas are also represented in Figure 1. For the study area of Bengawan Solo, Sentinel-2 image is used only for qualitative assessment. Topographical map from the Indonesian Geospatial Information Agency [3] provides land use classes with a map scale of 1: 25,000. Water class from this map are needed to assess and analyze the result.
Table 1. Images used.

| Scene  | Track number | Levels | Sentinel-1 acquisition | SAR Acquisition Mode | Track number | Sentinel-2 acquisition | Cloud cover |
|--------|--------------|--------|------------------------|----------------------|--------------|------------------------|-------------|
| 1      | 3            | L1 GRD | 22/01/2017             | Descending           | /            | /                      | /           |
| 2      | 3            | L1 GRD | 15/02/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 11/03/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 04/04/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 10/05/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 15/06/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 09/07/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 14/08/2017             | Descending           | 89           | 07/08/2017             | 0.08%       |
| 3      | 3            | L1 GRD | 07/09/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 13/10/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 18/11/2017             | Descending           | /            | /                      | /           |
| 3      | 3            | L1 GRD | 12/12/2107             | Descending           | /            | /                      | /           |

3. Methodology

The general methodology is described in Figure 2. The detection of the surface water and the calculation on the probability of occurrence are carried out on the Sentinel-1 images time series with the Water-S1 method presented in [4]. The detected surface water in the form of posterior probability maps are combined using decision level methods presented in [5]. Finally, the fused result is called permanent surface water and evaluated.
3.1. Detection of surface waters to obtain posterior probability maps

The processing of Sentinel-1 images time series are based on the Water-S1 method described in [4]. The first step consists of a correction of orbital errors, speckle noise and geometric distortion of the data. The application of precise Sentinel orbits, the radiometric calibration of the SAR images to Sigma-nought images, the multi-looking, the filtering of speckle, and terrain relief is applied in the Sentinel Application Platform/SNAP [6, 10]. Due to relatively flat area in the study area, masked of using the Height above Nearest Drainage (HAND) terrain index is not performed.

Then, a statistical modified Split-Based Approach (SBA) is used in order to tile the input images into squared non-overlapping blocks of 10 × 10 km size and to select the tiles for class modelling. The strategy for tile selection consists of choosing only the image tile which contains some portions of surface water based on Hartigan’s dip statistic (HDS) value [7]. Class modelling is performed by applying Finite Mixture Models (FMM) [2]. The model parameters for each tile are calculated, then global sets of parameters are defined and posterior probability is computed. Finally, a labelling using Bilateral Filtering is applied to the posterior probability maps [9]. The filtered posterior probability maps are then used as input data for image fusion.

3.2. Extraction of permanent surface water using decision-level fusion rules

The extraction of permanent surface water is based on decision-level fusion rules described in [5]. The process applied Bayesian approach, based on the operator sum (Equation (1)).

$$P_{\text{fusion}}(x) = P_A(x) + P_B(x)$$  \hspace{1cm} (1)

Where $P_A$ and $P_B$ are the posterior probability maps. A threshold of 90% is used to differentiate the ‘permanent surface water’ (posterior probability > 90%) from other classes (posterior probability < 90%).

3.3. Evaluation procedure

The water class of the Topographical map from the Indonesian Geospatial Information Agency is used as the reference product for the evaluation. All the quantitative assessments are based on the calculation of confusion matrices and of indicators such as the Overall accuracy, the F-measure, the True Positive Rate (TPR), the False Positive Rate, and the Omission and Commission error. Qualitative assessment is also applied and presented. Observation of morphological and land use change is also performed.

4. Results

4.1. Mapping permanent surface water and detect morphological and land use change

Twelve posterior probability maps of surface waters are generated over one year period (2017 – details in Section 2). Permanent surface water in the study area is obtained using Sentinel-1 time series image fusion in decision level with Bayesian sum method as presented in Section 3. The result is then transformed into a binary image assigning all pixels with posterior probability of surface water greater than 90% as permanent surface water (4). The accuracy assessment (Table 2) is done using surface waters classes of topography map from Indonesian Geospatial Information Agency [3].
Figure 3. Permanent surface water result of Bengawan Solo River, downstream area.

Overall accuracy shows high value with more than 97%, F-measure provides value 0.79, also very low False Positive Rate and commission error. Only omission error give value about 34% since the reference map was created at 1999. False positives and false negatives appeared in border area because of dynamical changes of waters in the river banks (Figure 4a). Due to straightening, there are morphological changes in Bengawan Solo River which can be seen from false positive and false negative in Figure 4b&d. Land use changes, for example in Figure 4c&d, from small lake to agricultural area also created false negative. Some fishponds are also detected as permanent surface water in our result led to appearance of false positive (Figure 4d). Based on accuracy assessment and visual interpretation, we can conclude that our proposed and automatic method extract successfully permanent surface water in Bengawan Solo downstream.

Table 2. Quantitative evaluation of permanent surface water result in Bengawan Solo downstream from Sentinel-1 time series image fusion.

| Overall Accuracy | F-measure | True Positive Rate | False Positive Rate | Omission error | Commission error |
|------------------|-----------|--------------------|---------------------|----------------|-----------------|
| 97.64%           | 0.79      | 65.91%             | 0.01%               | 34.08%         | 0.29%           |

4.2. Water variability in one year period
In order to monitor the water variability, temporary surface waters are detected. Using permanent surface water of previous sub section as mask, temporary surface water can be extracted from each single date (12 images of Sentinel-1). Temporary surface waters from one year period are presented as a frequency
map in Figure 5. This map shows how many times temporary surface water pixels appear in the time period. Surfaces as river banks, fishpond and irrigation croplands are successfully extracted.

![Frequency map of temporary surface water from Sentinel-1 time series (12 images) in Bengawan Solo downstream.](image)

**Figure 4.** Frequency map of temporary surface water from Sentinel-1 time series (12 images) in Bengawan Solo downstream.

5. Conclusion
Using Sentinel-1 as free SAR data with wide area monitoring capabilities and image fusion method, permanent surface water can be extracted from one year period. The quantitative evaluation shows relevant results with overall accuracy of more than 97%, F-measure provides value 0.79, also very low False Positive Rate and commission error. There are also morphological and land use change detected in the area compared to reference data. Water variability in the one year period can also be monitored through frequency map. These results are encouraging and the first step for monitoring Bengawan Solo River.

6. References
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