

IMPROVING RELIABILITY IN GLOBAL FLOOD MAPPING BY GENERATING A SEASONAL REFERENCE WATER MASK USING SENTINEL-1/2 TIME-SERIES DATA

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ABSTRACT:

Variable intra-annual climatic and hydrologic conditions result in many regions of the world in a strong seasonality of the water extent throughout the year. This behaviour, however, is usually not reflected in satellite-based flood emergency mapping. This may lead to non-reliable representations of the flood extent and to misleading information within disaster management activities. In order to be able to separate flooding from normally present seasonal water coverage, up-to-date, high-resolution information on the seasonal water cover is crucial. In this work, we present an automatic methodology to generate a global and consistent permanent and seasonal reference water product based on high resolution Earth Observation data, specifically designed for the use within flood rapid mapping activities. The water masks are primarily based on the time-series analysis of optical Sentinel-2 imagery, which are complemented by Sentinel-1 Synthetic Aperture Radar-based information in data scarce regions. The methodology has been developed based on data of five globally distributed study areas (Australia, Germany, India, Mozambique, and Sudan). Within this work results for Australia and India are demonstrated and are systematically compared with external reference water products. Results show, that by using the proposed product it is possible to give a more reliable picture on flood-affected areas in the frame of disaster response.

1. INTRODUCTION

Earth Observation data are instrumental in providing time-sensitive information about the extent and impact of flood events and thus significantly contribute to emergency response and hazard management efforts. This crisis information can be derived with increasing frequency and quality due to a steadily growing number of satellite missions and advances in image analysis (Twele et al., 2016; Chini et al., 2019; Li et al., 2019; Martinis et al., 2018, Wieland et al., 2019). In order to accurately distinguish flood from “normal” hydrologic conditions, up-to-date high-resolution information on the extent of seasonal water bodies is crucial. This information is usually neglected in disaster management activities and may lead to a non-reliable representation of the inundation extent, mainly in areas with highly dynamic hydrologic conditions.

In this study, an automated approach for computing a global permanent and seasonal reference water product at 10-20 m spatial resolution is presented. The approach is based on Copernicus Sentinel-1 and Sentinel-2 time-series data and has been specifically designed for its application in global flood mapping activities. The methodology has been developed based on data of five test areas located in different climate zones (Australia, Germany, India, Mozambique, Sudan). The computed reference water product is systematically compared to existing external reference water masks by conducting statistical cross-comparison and is applied on satellite data acquired during real flood situations in Australia and India.

2. STUDY AREAS

As study regions, five areas of interest (AOI) covering different climatic zones according to the Köppen-Geiger climate classification are chosen. The location and size of the AOIs as well as the respective number of used Sentinel-1 data and Sentinel-2 tiles are listed in table 1. AOI 1 is situated in the eastern part of Australia. AOI 2 is located in the South of Germany. AOI 3 is located in the Southwest of the Indian subcontinent and covers parts of the Indian state Kerala. AOI 4 covers parts of Mozambique and AOI 5 is located in the southern part of Sudan covering the capital Khartoum.

AOI	Area [km ²]	Climate zone	Number S-1 data	Number S-2 tiles
1. Australia	12464	Cfa, Cfb	169	659
2. Germany	11955	Dfb, Dfc, ET	758	660
3. India	1189	Am	89	836
4. Mozambique	32890	Aw, BSh	168	982
5. Sudan	69982	BWh	290	1033

Table 1. Study sites.

3. DATA SET

For the processing of a consistent global reference water product we rely on data of the Copernicus Sentinel-1 C-Band Synthetic Aperture Radar (SAR) and the Sentinel-2 optical satellite mission, both consisting of two satellite sensors, which perform data acquisition according to a pre-defined and conflict-free observation scenario of the European Space Agency (ESA).

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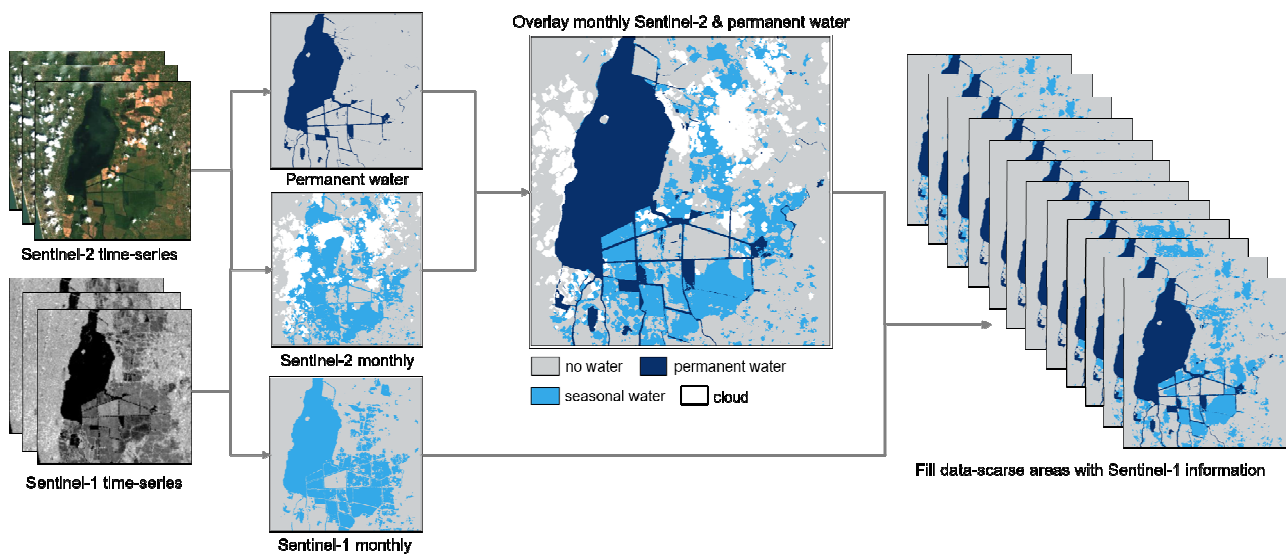


Figure 1. Methodology for generating permanent and monthly seasonal reference water masks using times-series analysis and fusion of Sentinel-1 and Sentinel-2 data.

The repeat cycle for the Sentinel-1 constellation is 6 days and for the Sentinel-2 constellation 5 days. For the computation of the reference water product we use Sentinel-1 Ground Range Detected (GRD) Interferometric Wide (IW) swath VV-polarized imagery with a pixel spacing of 10 m (spatial resolution of ~20 m) and the six Sentinel-2 spectral bands B2 (blue), B3 (green), B4 (red), and B8 (near-infrared) at 10 m and B11 and B12 (short-wave infrared 1 and 2) at 20 m spatial resolution. The tiling grid of Sentinel-2 data with the reference system WGS 84 at 10 m spatial resolution is used as base grid. As most spectral bands of Sentinel-2 are characterized by higher spatial resolution of 10 m in comparison the Sentinel-1 GRD IW products and as water detection based on Sentinel-2 is less affected by water look-alikes, a more detailed mapping of water bodies, mainly of rivers, is possible with Sentinel-2 during clear-sky conditions. Therefore, Sentinel-2 is used as primary information source, which is complemented only in data scarce cases (e.g. due to permanent cloud cover) by Sentinel-1-based information as this SAR sensor enables data acquisition also during cloud coverage due to its singular emission in the microwave part of the electromagnetic spectrum.

4. METHODOLOGY

The proposed approach combines two processing chains of the German Aerospace Center (DLR) for automatic flood monitoring based on Sentinel-1 C-band radar data (Sentinel-1 Flood Service) and Sentinel-2 multi-spectral imagery (Multi-Spectral Flood Processor).

Sentinel-1 data are processed using hierarchical tile-based thresholding and fuzzy logic-based post-classification (Martinis et al., 2009; Martinis et al., 2015; Twele et al., 2016). Sentinel-2 data are resampled to a common spatial resolution of 10 m and are analysed by a deep learning approach using a convolutional neural network (CNN) trained on globally stratified reference data (Wieland and Martinis, 2019). The network architecture combines a U-Net decoder with an EfficientNet-B4 encoder that has been trained on a reference dataset of 90 images with respective quality-controlled water annotations. In addition, each sample is accompanied by

topographic slope information derived from the Copernicus Digital Elevation Model (Airbus, 2020).

In order to generate an up-to-date Permanent Reference Water Mask (P-ReWaM) and Seasonal Reference Water Masks (S-ReWaM) we use a time-series approach to combine the single-temporal Sentinel-1 and Sentinel-2-based water masks over a pre-defined time range (01/01/2019-31/12/2020). The reference period of two years is empirically chosen in order to rely the computation on a sufficient number of satellite data, to reduce the effect of hydrological extreme events occurring only once in consecutive years as well as to exclude long-term hydrologic changes, which would be integrated in the water product if longer time periods would be considered.

P-ReWaM is computed based on all valid Sentinel-1 and Sentinel-2 acquisitions of the reference period 01/01/2019 – 31/12/2020 (see figure 1). S-ReWaM is calculated on a monthly basis for the reference period of two years in order to consider seasonal effects, i.e. the usual water extent of a respective period. This results in twelve seasonal reference water products, which are all complemented by the permanent water mask. Both P-ReWaM and S-ReWaM are derived by thresholding the relative water frequency f_r , which is a measure for the occurrence of surface water within a defined time-period. It is calculated by dividing the absolute frequency of water detections by the frequency of valid observations during the defined time range.

A truly permanent and seasonal water area would mean that there was observed water coverage in every single valid satellite observation of the considered reference period, which would be related to a value of $f_r = 100\%$. Within this work a slightly relaxed threshold of 90% is used in order to account for potential hydrological extreme events and for uncertainties in the single Sentinel-1 and Sentinel-2-based water classifications. This value is derived by performing a sensitivity analysis where the impact of different values of the threshold of f_r (range: 70-100%; increment: 1%) on the water coverage within the five study sites is investigated (figure 2). Abrupt changes of water coverage can be seen in most cases (Australia, Germany, India, and Sudan) at values of $f_r > 95\%$, in Mozambique at a value above ~92%, while relative water coverage is only slightly

declining with decreasing relative water frequency below a value of 92-95%.

As during clear-sky conditions a more detailed mapping of water bodies is feasible with Sentinel-2 imagery, this data is used as primary source for the generation of the reference water product. In data scarce regions, complementary information derived from data of the Sentinel-1 mission is fused with the Sentinel-2-based results. This mainly occurs in regions which are continuously cloud-covered within the selected reference periods.

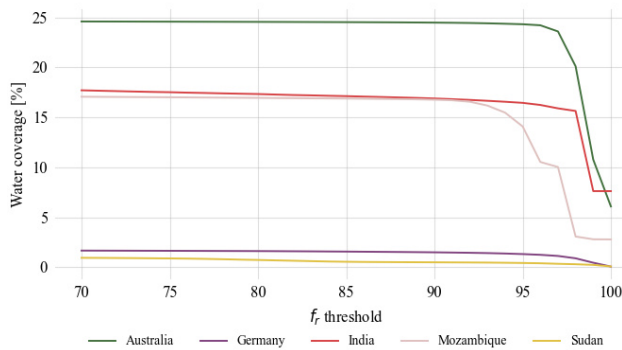


Figure 2. Sensitivity analysis for the definition of the threshold value of the relative water frequency f_r within the range 70-100% for the five test areas in Australia, Germany, India, Mozambique, and Sudan.

5. RESULTS

The reference water product is generated in five study areas in India, Australia, Germany, Mozambique, and Sudan. The results are systematically cross-compared with already existing external and freely available reference water products: The 90 m Shuttle Radar Topography Mission (SRTM) Water Body Data (SWBD) (NASA JPL, 2013), the 30 m JRC GSW “Seasonality” and “Monthly History” layer of the Global Surface Water product derived from Landsat time-series data (Pekel et al., 2016) and the 30 m CopDEM Water Body Mask (WBM), mainly based on data of the TerraSAR-X mission acquired within the years 2011-2015 (Airbus, 2020). To ensure comparability, all products are resampled to match the pixel spacing of the reference product (~10 m) and are re-projected to the WGS84 spatial reference system, if necessary. We use several binary accuracy metrics in order to perform a relative comparison of the product derived by our proposed methodology and the external products: the HIT-rate, Intersection over Union (IoU), Precision (P) and Recall (R) as well as the F1-Score.

Figure 3 and 4 exemplarily depict the results of the proposed approach within the AOI of Australia and India, respectively. P-ReWaM was derived from all valid Sentinel-1 and Sentinel-2 acquisitions during the 01/01/2019–31/12/2020 observation period. The monthly seasonal water masks are based on all valid Sentinel-1/Sentinel-2 data acquired during each specific month of the same observation period (e.g. the computation of S-ReWaM for the month April is based on data of the months April 2019 and April 2020).

In the AOI of Australia, 3156 km² (~25.4 %) of the selected study site is covered by permanent water surfaces. The monthly products indicate a relatively low seasonal variability throughout the years. It ranges from additional 0.2 % (5.8 km²) seasonal water extent in October to a maximum of 3.3 % (104 km²) in June. P-ReWaM relies on a large average number of 112 Sentinel-2 observations, therefore no filling with Sentinel-1

information is necessary. For generating the 12 monthly S-ReWaM masks, the highest average number of 15 valid Sentinel-2 observations occurs in August, whereas in February, on average only 4 observations are available. Averaged over the 12 months, 1.8 % of the pixels in S-ReWaM are filled with SAR-based information due to low availability of valid Sentinel-2 observations, with the highest rate of 17.7 % filling performed in February.

16.8 % (199.6 km²) of the AOI in India is covered by permanent water bodies. The results show a very high seasonality present in S-ReWaM, ranging from additional 3.6 km² (+ 1.8 %) water coverage in January to 216.2 km² (+ 108.3 %) in June. This is related to the seasonal Monsoon rainfall events, which lead to a high hydrologic dynamic. The seasonal water bodies are distributed across the whole AOI, mainly covering agricultural land. It can be observed, that due to increased cloud cover, less valid observations from the optical sensor are available between May and October. On average, 60 valid Sentinel-2 observations are available in order to compute P-ReWaM. From April to October, ~63 % of the S-ReWaM mask is filled with Sentinel-1-based information. In August occurs the highest rate of radar-based information-filling (~ 81 %).

The performed cross-comparison of the permanent water masks show that permanent water body detection resulting from the proposed methodology is largely in-line with other state-of-the-art products. The levels of agreement, however, differ in the selected study sites. In general, the reasons of the observed deviation can be grouped into i) data basis and observation time frames of the used data, ii) spatial resolutions of the considered products and iii) thresholding and definitions of permanent water extent.

Further, the proposed seasonal reference water data set is compared with the JRC GSW “MonthlyHistory” product of Pekel et al. (2016) on a monthly basis for the year 2020. In Australia, the JRC product is not available from April to August and from September to March, respectively.

For the remaining months high levels of 0.87 in IoU, 0.82 in precision, and 0.79 in recall can be observed throughout the year, respectively, indicating high similarity between the products. In India, where a high seasonal variability in the water extent is detected, a drop in IoU and precision can be stated roughly during the time of highest levels of seasonal water. The minimal IoU of 0.39 and precision of 0.41 is reached in June. Recall, however, rises to a value of 0.91 at this time. This indicates a significantly higher estimation of the water extent by S-ReWaM than observed in JRC GSW “MonthlyHistory”. This is linked to the integration of additional SAR-based information in S-ReWaM during times of low availability of valid optical data.

In order to demonstrate the product for the purpose of flood mapping, we applied S-ReWaM as well as the external water products to real flood events in the AOI of Australia (March 2021) and India (August 2018). To derive the flooded areas the observed water extent extracted from Sentinel-1 flood data by the method of Twele et al. (2016) is compared to the monthly seasonal reference water products computed from the previous two years.

The resulting flood masks differ strongly depending on the used reference water product. In Australia (figure 3), the use of SWBD leads to the highest predicted inundation extent of ~354 km². By using the other permanent water products (CopDEM WBM, JRC GSW “Seasonality”, P-ReWaM), similar results could be derived.

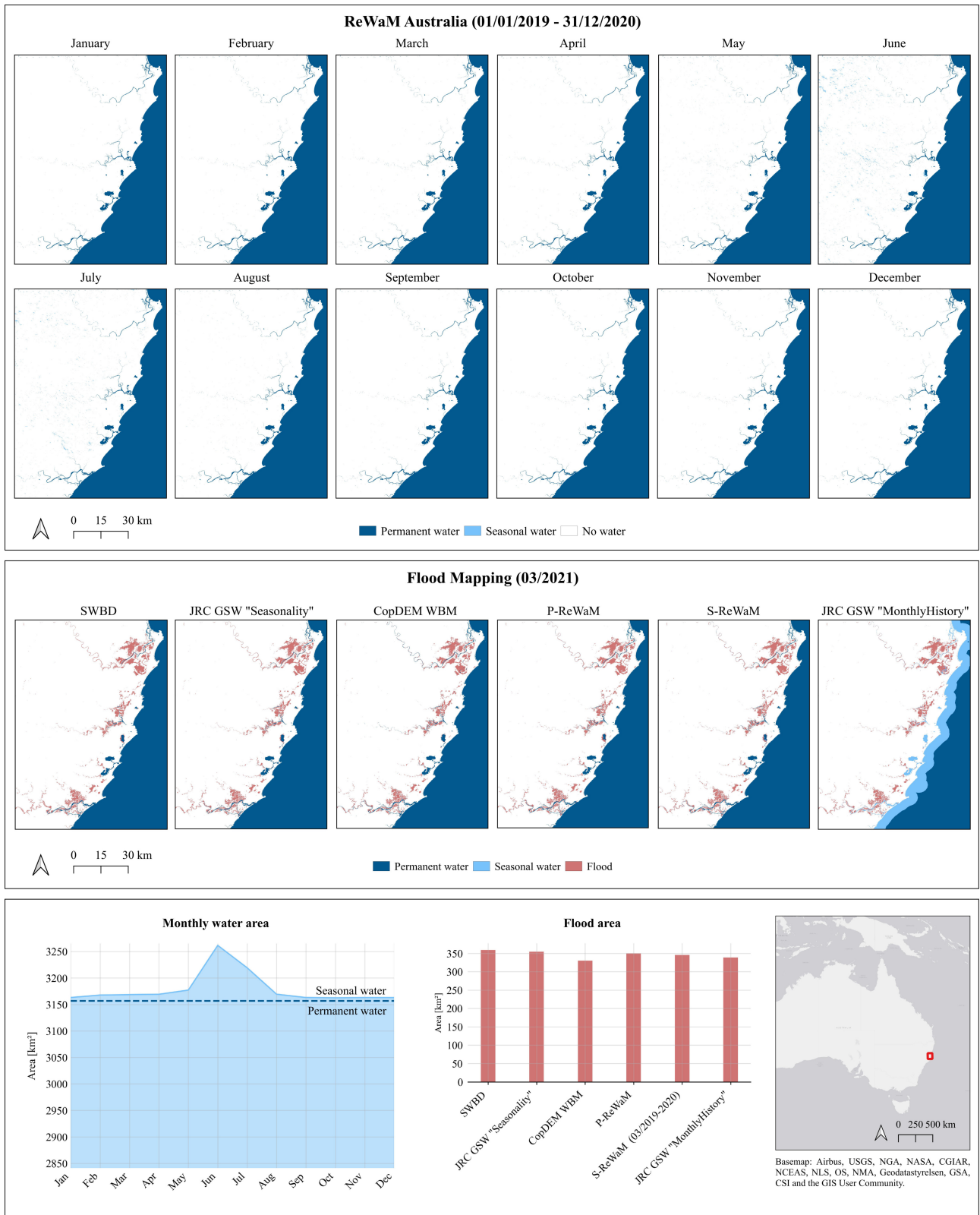


Figure 3. Reference water extents of P-ReWaM and S-ReWaM for the study area in Eastern Australia, derived from Sentinel-1/2 time-series data (observation period: 01/01/2019-31/12/2020). Comparison of flood mapping results in Australia using P-ReWaM and S-ReWaM with external reference water masks; flood extents are derived from Sentinel-1 data acquired during a real flood event in March 2021. The S-ReWaM of the month March is used as seasonal reference water mask. Corresponding flood extents are visualized as bar charts.

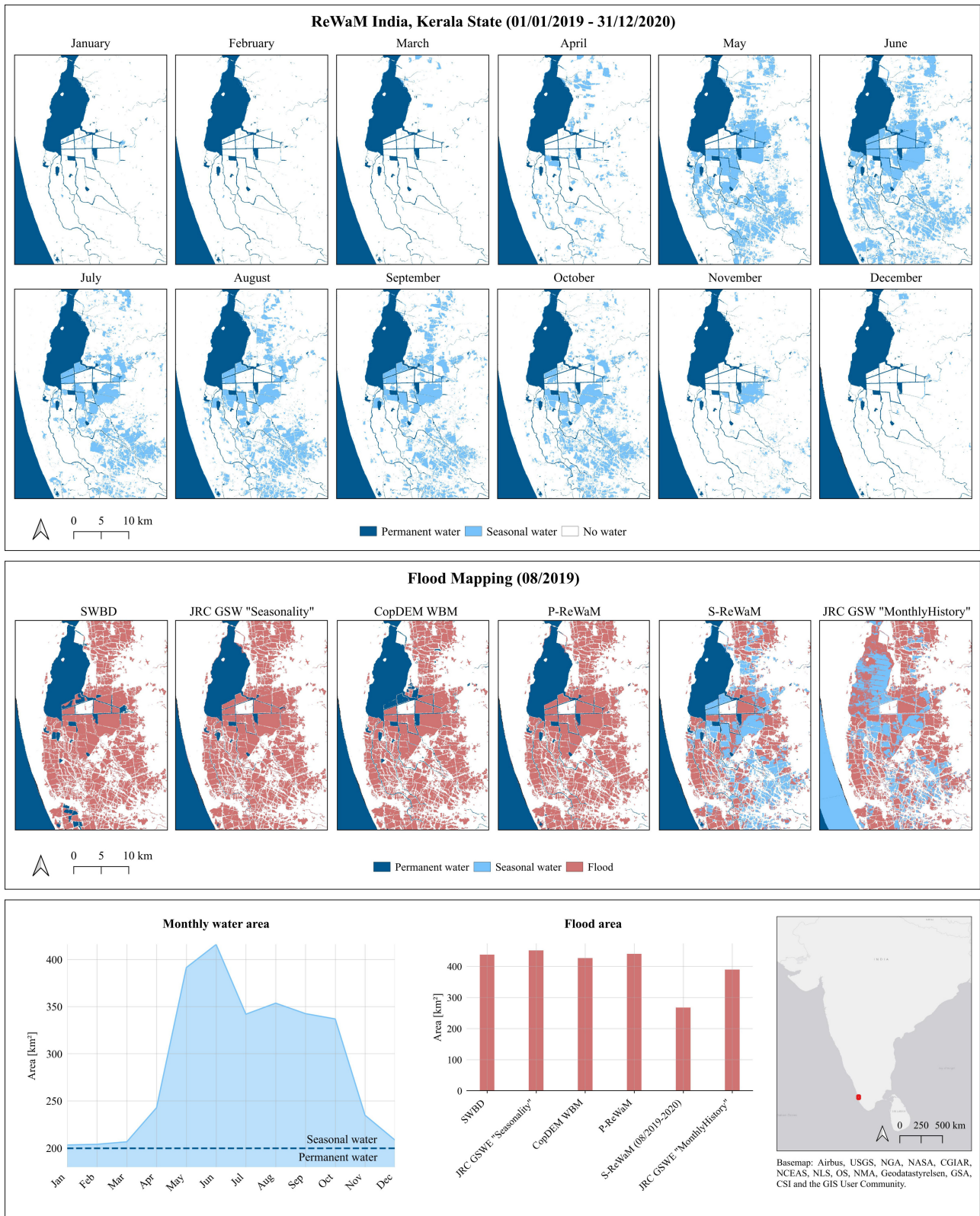


Figure 4. Reference water extents of P-ReWaM and S-ReWaM for the study area in India, Kerala State, derived from Sentinel-1/2 time-series data (observation period: 01/01/2019-31/12/2020). Comparison of flood mapping results in India using P-ReWaM and S-ReWaM with external reference water masks; flood extents are derived from Sentinel-1 data acquired during a real flood event in August 2019. The S-ReWaM of the month August is used as seasonal reference water mask. Corresponding flood extents are visualized as bar charts.

S-ReWaM decreases the predicted flood area by 8.5 km². In the AOI of India (figure 4), the difference between permanent reference water products and S-ReWaM is highest, leading to 39.1% of less inundation extent than using P-ReWaM. This demonstrated that the consideration of seasonality of water bodies, especially in regions with highly dynamic hydrological conditions, is of paramount importance as it reduces potential over-estimations of the inundation extent and provides a more reliable picture on flood-affected areas than the exclusive use of permanent water masks.

6. DISCUSSION AND CONCLUSION

In this study we presented a novel approach to generate a global high-resolution permanent and seasonal reference water product based on Sentinel-1 and Sentinel-2 time-series data, which is specifically designed for a systematic and operational flood mapping.

For selected study areas we provided an up-to-date data set, that considers hydrological dynamics of water bodies on a monthly basis computed from data of a time-range of two years. The proposed algorithm for water body detection and reference water mask generation is completely automatic and is suitable for integration in already existing rapid mapping workflows. The multi-sensor data fusion approach enables to exploit the advantages from both optical and radar systems. It can be stated that this multi-sensor-based seasonal reference product offers a significant advantage compared to fully optical data-based water masks, especially in regions with high rates of annual cloud cover, while using the advantages of Sentinel-2 optical data in water mapping.

The demonstration of the product during real flood events showed that the consideration of seasonality of water bodies, especially in regions with a pronounced hydrological dynamic, is highly important. Over-estimations of the inundation extent are reduced and the product gives end users more reliable information on flood situations by separating permanent water bodies, areas normally water-covered during a certain time in the year and inundation-affected areas. This helps to prioritize relief operations and to focus on regions with potential lower consciousness for flood protection, which might be related to a higher flood impact.

Future work focusses on upscaling the proposed methodology towards a global computation of the reference water product.

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