CHARACTERIZATION OF NATURAL WETLANDS WITH CUMULATIVE SUMS OF POLARIMETRIC SAR TIMESERIES

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ABSTRACT

Wetlands are among the most productive natural ecosystems in the world, generally being important biodiversity hotspots. However, the complex nature of these landscapes together with the fragile and dynamic relationships among the organisms inhabiting these regions, make wetland ecosystems especially vulnerable to environmental disturbance, such as climate change. Thus, developing new automated systems which allow continuous monitoring and mapping of wetland dynamics is crucial for preserving their natural health. Synthetic aperture radar (SAR) systems have proven useful in monitoring and mapping the hydrological processes of wetland ecosystems through the use of polarimetric change detection techniques. Nonetheless, most of these flood change detectors rely on static detection approaches, generally covering a limited period of time (e.g., pre and post flooding scenario comparison), thus failing in providing continuous information about the diverse hydrological mechanisms. In this context, this research presents a novel approach for monitoring the hydrological dynamics of wetlands in a continuous and near-real-time manner using dense Sentinel-1 image time-series. In this work, we have enhanced our recently developed algorithm based on cumulative sums (SAR-CUSUM), to include polarimetric information, which allows to classify the type of change due to the flood. The new processing stack exploits the polarimetric information of dual-pol Sentinel-1 dense time series for detecting floods and provide some separation between open water and flooded vegetation areas.

The outcomes derived from this study emphasize the capabilities of dense SAR time-series for environmental monitoring while providing a useful tool which could be integrated into rapid response and wetland conservation management plans.

Index Terms— Change detection, SAR, PolSAR, flood monitoring, Wetland monitoring.

1. INTRODUCTION

Wetlands are recognised to be among the most productive ecological systems. These complex landscapes perform important eco-hydrological functions such as food supply, climate change mitigation, biodiversity hot-spots, water store and purification [1], [2]. Unfortunately, recent studies [1], [3], [4] indicate a loss of 87% of the world's wetlands since 1700, in places where data exists, with accelerated loss occurring between 1970 and 2015 of 35%, three times the rate of forest loss. In addition, the remaining wetlands are expected to experience further degradation as a consequence of their frequent exposure to rapid changes driven by human or climate processes [5], [6]. These facts demonstrate the need to develop new tools and methods that, through continuous monitoring and evaluation of the state of conservation, support preservation of these ecosystems. This can be achieved by taking advantage of high-resolution remote sensing data archives and the latest advances made in Earth Observation (EO) platforms such as Google Earth Engine.

Among the wide spectrum of Remote Sensing technologies, Synthetic Aperture Radar (SAR) systems emerges as the most valuable alternative for exploring wetland hydrological dynamics in tropical regions. The active nature (non-dependency of an external source of light) of SAR allows it to penetrate extensive and persistent cloud cover, typical in tropical regions. In addition, the high sensitivity of SAR backscatter response to variations in the physical properties of objects on the Earth's surface enhances the potential of this technology for environmental monitoring applications. Natural disturbances, such as flood events, generally alter some parameters of the objects (e.g., surface roughness, moisture content, geometry) which results in a variation of radar backscatter values. Therefore, applying change detection techniques that focus on the investigation of SAR signal amplitude variation, it is possible to detect the spatiotemporal changes such as hydrological dynamics within wetland ecosystems.

This research focuses on developing a new SAR-based monitoring tool which provides near-real time information on the extend and typology of seasonal floods in the North Rupununi region, Guyana. In our research, we set out to explore the accuracy of open water and flooded vegetation monitoring applying our novel change detection algorithm, based on the use of cumulative sums, to a dense Sentinel-1 SAR timeseries data within the Google Earth Engine Platform,

2. STUDY AREA

The North Rupununi Wetlands, situated in the southern interior of Guyana, South America, are characterised by low topography and seasonal flooding which have recently attracted the interest of major agricultural business, particularly for rice cultivation. This natural ecosystem supports a high terrestrial and freshwater biodiversity, supplying Indigenous communities with a range of livelihood activities, including subsistence fishing and ecotourism.

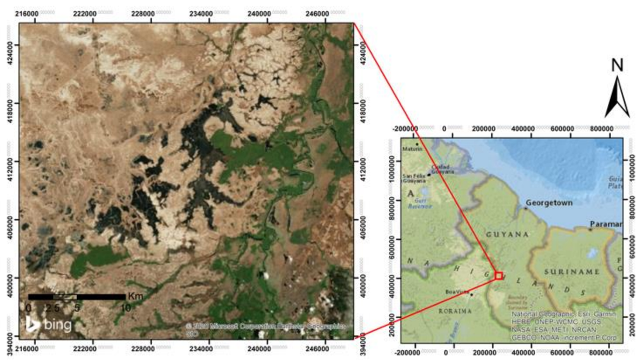

Figure 1. Reference map of the region of study, the North Rupununi natural wetlands, Guyana.

Guyana is a Development Assistance Committee (DAC) listed country, and pressure to convert natural habitats into large-scale industrial farms or mining concessions and associated infrastructure, especially access roads, is having an increasing impact on the North Rupununi Wetlands. These land use transformations are increasing habitat destruction risks, resulting in the loss of species in general and ecological connectivity in particular.

Increasing pressures from climate change (e.g., recurrent extreme weather events including flooding and droughts) is further threatening biodiversity and Indigenous populations in the region. A key strategy to make sure further development is sustainable is to carry out large-scale assessments, which require periodic surveys. Surveying the North Rupununi Wetlands is very time demanding due to the remoteness and the logistic difficulties of reaching these vast areas during the peak floods in the wet season (April to September) when most roads become impassable. Additionally, many features are more easily identifiable from above (e.g., location and distribution of open water). Indigenous communities and key decision makers are therefore in need of inexpensive, simple and rapid methodologies that are able to provide periodic surveys of the hydrological and ecological status of their surrounding landscape. Our research is therefore an attempt to demonstrate that applying change detection analysis of dense Sentinel-1 SAR timeseries within the Google Earth Engine Platform could be a key tool in achieving this.

3. DATA

We used a dense timeseries of GRD Sentinel 1 images acquired for the period of study (01/01/2017 - 01/01/2021) at a 12-day temporal resolution and with the same orbit path (164) and mode of acquisition (ascending). The resulting timeseries was formed by a total of 118 dual polarisation (VV, VH) SAR acquisitions, which were already automatically pre-processed in GEE using the following steps: 1. Thermal Noise Removal, 2. Radiometric Calibration, 3. Terrain Correction and 4. Linear to dB transformation.

To evaluate the accuracy of our surface water detection, ground-truth data was collected by a field team on a regular basis (12-day) coinciding with the Sentinel-1 pass. Handheld GPSs (position accuracy +- 9m) were used to map the land/water edge (up to 600 m in length), for six distinct sites, representing different hydrological sub-catchments within the North Rupununi wetlands.

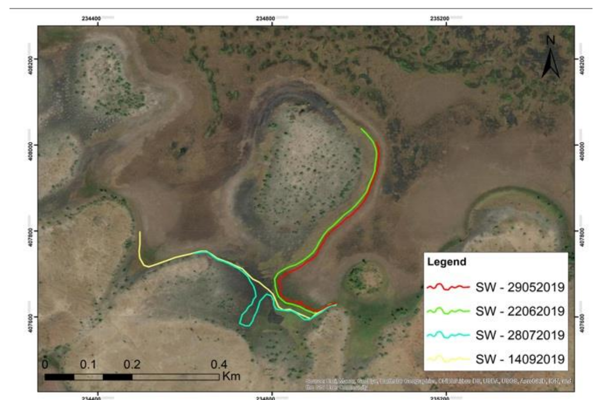

Figure 2. Example of the land/water edge data used for validation. Amoko lake, 29/05/2019 (red), 22/06/2019 (green), 28/07/2019 (blue) and 14/09/2019 (yellow).

Similarly, High-Resolution cloud-free optical imagery from Planet was utilised for performing accuracy assessments of final Open Water and Flooded Vegetation classification maps.

4. METHODS

The proposed flood change detector is an adaptation of the recently developed SAR-CUSUM algorithm [7]. The principle of the SAR-CUSUM method relies on a two-step process: on the first step, a reference mean value, is subtracted from each image of the time-series. In this context, this reference was computed using the three driest images of each year; and on the second step, each difference image is added to the previous one, enhancing any possible recurrent variation which takes place over time. The standardization of the CUSUMs, using the Z-scores, allowed us to perform an accurate investigation of the backscatter signals over different land classes. Using a threshold based on the histograms of regions, open water and flooded vegetation areas were masked out. To fully exploit the polarimetric information of the time-series, the change detection analysis was carried out using both the co-polarisation (VV), the cross-polarisation channel (VH) and their Ratio (VH/VV).

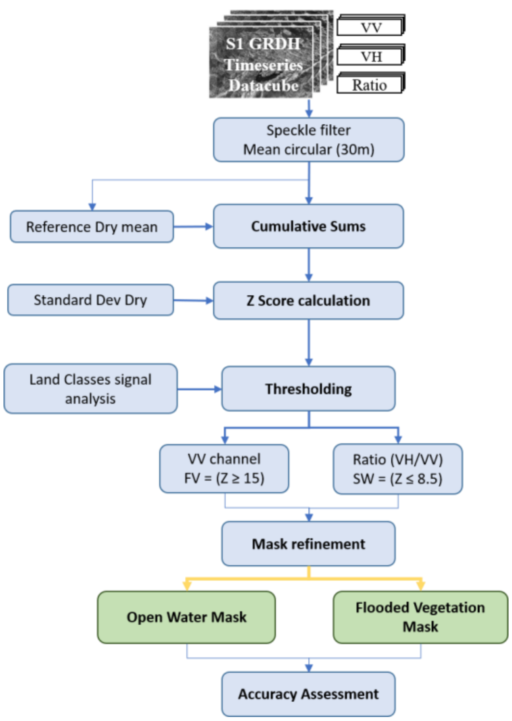

Figure 3. Flow chart of the proposed SAR-CUSUM Sentinel-1 flood change detection analysis.

Once open water and flooded vegetation masks were obtained for each of the images of the timeseries, these were refined using additional EO datasets with the aim of reduce the presence of false positives. This process followed five steps: 1. Forest penalty, 2. HAND analysis, 3. Permanent water bodies addition, 4. DEM-slope analysis and 5. Sieve filter. First, a Landsat-8 derived forest mask was used to apply a penalty to the Z-score values over highly vegetated areas as we assume that floods occurring at under canopy level are undetectable due to the low penetrability of Sentinel-1 radar signal. Secondly, Global (30 m) Height Above Nearest Drainage (HAND) dataset served to mask out all regions located at a height greater than five meters from the drainage network of the study area. Third, JRC global surface water map was used for adding all permanent water bodies (>10 months/year). Later, WWF HydroShed DEM allowed us to remove all flooded pixels located in steep terrain (slope >5%), since we assume that water will not significantly accumulate on terrains with such characteristics. Last, the sieve connectivity filter helped us to eliminate those smaller and isolated flooded areas, generally caused by noise or geometric distortions. All flooded pixels connected to 15 or fewer neighbours were removed.

Finally, accuracy assessments were carried out to validate the results obtained from the flood change detection analysis. A first spatial proximity analysis, performed using the surface water edge ground truth data, provided us with some preliminary information about the open water detection accuracy. A more thorough evaluation of both Open water and Flooded vegetation maps was carried out using a visual classification assessment over Planet High-Resolution Imagery.

5. RESULTS

5.1. SAR-CUSUM flood detection

The exploration of the cumulative sum values on different land cover classes allowed us to identify the most suitable polarization channel for each flood typology. Wetland areas showed a progressive decrease in the backscatter intensity, which begun with the first rains and remained stable for the entire wet season. These low intensity values, typical of open water areas, was significantly noticeable in the Ratio (VH/VV) channel. In contrast, open vegetation areas showed temporary increases in the signal intensity which coincide with severe precipitation events that occurred during the wet season. The co-polarisation channel (VV) showed the higher degree of separability for dry and flooded vegetated areas. The use of thresholds over the CUSUMs derived Z-score values; Open water ($Z_{ratio} \leq 8.5$) and Flooded vegetation ($Z_{vv} \geq 15$), allowed us to effectively classify floods based on their typology.

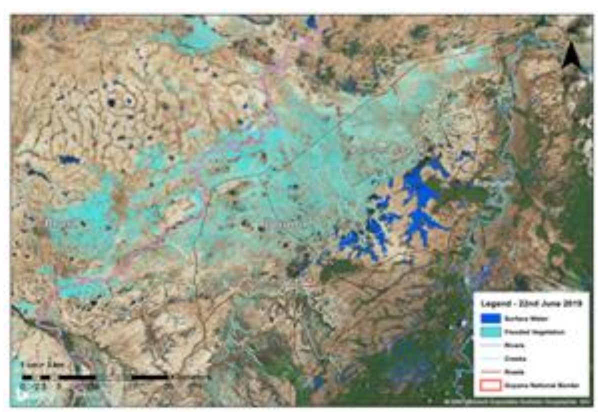

Figure 4. Example of a flood map obtained for the North Rupununi region on 22nd June 2019.

5.2. Flood detection accuracy assessments

The results obtained for both accuracy evaluations showed optimal performance in the detection and characterization of flood dynamics for the study area. The accuracy assessment performed for the Open water classification, Overall Accuracy (OA) = 0.93; Kappa = 0.87, showed a high detection performance of surface water bodies and a clear delineation of the edges. Results obtained for the combined (Open water & Flooded vegetation) classification map showed a lower performance (OA = 0.77). As shown in table 1, the observed lower overall performance responds to an overestimation of the flooded vegetated areas. The high sensitivity of the proposed methodology to subtle changes led to higher classification errors for the flooded vegetation class driven by biomass variation in non-flooded areas.

Table 1. Confusion matrix showing the performance of the SAR-CUSUM derived flood classification map. Results generated for the Sentinel-1 image acquired on 19th September 2020. (*OW: Open water, *FV: Flooded vegetation, *NW: No-water area; Total sample = 150 randomly distributed points [OW=33%, FV=33% and NW=33%]).

	OW	**FV**	**NW**	**User (%)**
OW	26	6	1.33	78
FV	0.67	21.33	11.33	64
NW	1.33	2	30	90
Prod. (%)	92.86	72.73	70.31	
OA%: 77.33%, Kappa: 0.66				

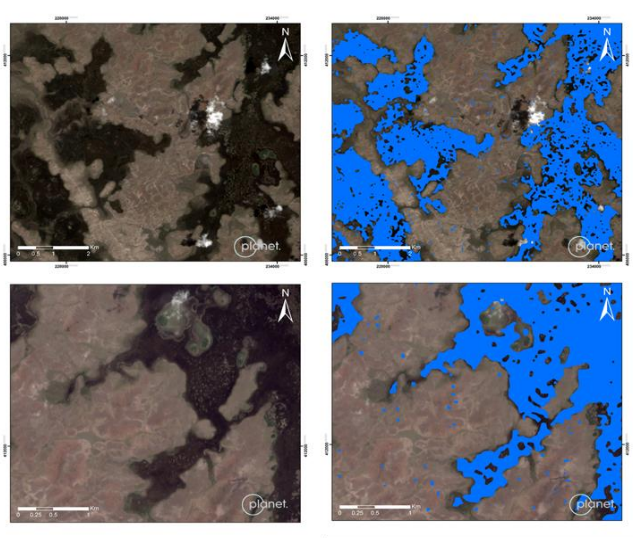

Figure 5. Example of the comparison of the SAR-CUSUM derived Open water detection mask (19th September 2020) with HR Planet image acquired on 20th September 2020.

6. CONCLUSIONS

The use of the SAR-CUSUM change detection analysis on Sentinel-1 synthetic aperture radar data offered rapid information about the hydrological dynamics of the North Rupununi natural wetlands.

This research highlights the benefits derived from the use of high temporal SAR timeseries for near-real time wetland monitoring. The computing capabilities, extensive data archive and user-friendly environment of Google Earth Engine confirm its position as a powerful platform for the development of new environmental remote sensing tools.

7. FUTURE WORK

We are currently working on the adaptation of the SAR-CUSUM flood detector for the natural wetlands of the Doñana National Park, in southwestern Spain. Preliminary results have shown and optimum performance in the detection and characterization of temporary floods. The implementation of the SAR-CUSUM into the exiting monitoring system will lead to a notable improvement of the temporary resolution, thus contributing to enhancing the studies on the hydrological dynamics and state of conservation of this natural reserve.

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