ADVANCED OPERATIONAL FLOOD MONITORING IN THE NEW ERA: HARNESSING HIGH-RESOLUTION, EVENT BASED, AND MULTI-SOURCE REMOTE SENSING DATA FOR FLOOD EXTENT DETECTION AND DEPTH ESTIMATION

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ABSTRACT

Remote-sensed flood monitoring is rapidly advanced by the growing abundance of satellite data. This study presents the progress in building an operational system that harnesses the power of spatially high-resolution (HR), multi-source remote sensing data for event-based flood extent and depth mapping. By integrating pioneering extent retrieval—Radar Produced Inundation Diary (RAPID), Self-supervised Waterbody Detection (SWD), and depth retrieval processors, Global-LOCAL Solvers Integration Algorithm (GLOCAL), and the Emulated Flood Recession Algorithm (EFRA)—our proposed framework marks a significant leap in flood monitoring capabilities. The upgraded RAPID addresses the complexities of Synthetic Aperture Radar (SAR) flood mapping in diverse environments, including snow-covered and arid regions, enhancing adaptability and consistency across multiple SAR satellites such as ESA Sentinel-1, CSA RADARSAT Constellation Mission (RCM), MDA RADARSAT-2 (RS2), and Capella. Meanwhile, SWD brings a method to automatically map flood extents from high-resolution optical images, including Planet, Sentinel-2, and Landsat, during clear weather conditions. GLOCAL and EFRA are tailored for depth estimation from the generated HR remotely sensed flood extents, and HR or VHR topography. Both algorithms tolerate the error from extent and topography, with EFRA physically considering the influence of micro-topography. The proposed framework has proven to produce consistent flood extent results across multi-source, high-resolution satellite images and demonstrates robust depth estimation with various input DEMs. Validation against USGS high water masks yields 1.01 m RMSE when 1 m resolution DEM is used. With continuous development and integration into NOAA's near real-time operational platform, these approaches do not only improve the resolution and dependability of operational flood monitoring globally but also significantly bolster emergency response strategies.

Index Terms— Flood Extent, Flood Depth, Multi-source Remote Sensing, Operational System, High Water Mask.

1. INTRODUCTION

Near real-time (NRT) flood mapping products are pivotal in guiding flood emergency response and management. The surge in remote sensing imagery availability calls for systems that effectively utilize high-resolution, event-based, and multi-sourced data for detailed flood mapping, including extent and depth.

Synthetic Aperture Radar (SAR) imagery, noted for its ability to penetrate all-weather conditions, day and night,, is a key data source in remotely sensed flood mapping. Integrating multi-source SAR sources like Sentinel-1, RCM, RS2 can provide optimal temporal resolution for flood surveillance. Yet, a universal algorithm capable of processing various SAR images, irrespective of sensor and configuration differences, is currently vacant. Furthermore, distinguishing water from pixels with similar intensity distribution (e.g., snow, ice, deserts, and dry croplands) remains a challenge in SAR-based flood detection, particularly when only images taken during the flood event are available. Although optical imagery offers more spectral bands and higher signal-to-noise ratios, flood water reflectance varies greatly and is further complicated at higher resolution.

Incorporating DEM with flood extent to estimate depth can enhance the portrayal of flood severity. Existing depth estimation tools, designed for fluvial floods with accurate boundaries and topography, falter with high-resolution remote-sensed data showing fragmented and pluvial inundation. An algorithm that reconciles water level inconsistencies is vital for hazard support and operational utility. The significance of characterization of micro topography by very high-resolution (~1m) DEMs in depth estimation also deserves further investigation.

This study showcases advancements in the operational system for remote sensing-based flood extent and depth mapping, leveraging high-resolution, event-based, and multi-source satellite data. It includes several key algorithms: RAPID for multi-source SAR flood detection, SWD for optical image-based flood detection, and GLOCAL and EFRA for depth estimation from extent data. The impact of DEM resolution on depth accuracy is also examined using EFRA. Method overviews are presented in Section 2, results are in Section 4, and conclusions and future directions are in Section 5.

2. METHODOLOGY

The proposed framework for operational remote sensing flood extent and depth mapping is shown as Fig. 1.

The SAR flood mapping system, known as RAPID[1], is based on radar statistics and employs a self-supervised procedure. RAPID has been effective in detecting submerged floods across the CONUS area[2]. The upgraded version of RAPID[3] shows improved performance in complex environments, including snow and desert regions, and is compatible with multi-source SAR images. RAPID has been implemented on NOAA's cloud platform, and extensive validation processes are anticipated.

The optical flood mapping system, inspired by RAPID's self-supervised procedure, is named Self-supervised Waterbody Detection (SWD)[4]. SWD utilizes spatial priors from ancillary data and spectral index bimodality to automatically generate initial water pixel samples for each scene. It then learns and finely-tunes the spectral distribution from these samples for pixel-level flood water detection in optical images. Subsequently, SWD employs Felzenszwalb segmentation and a region growth method for compensating missing pixels, a process termed object-level detection. The design of SWD, enables the use of arbitrary spectral indices, not only compatibility with multi-source optical imagery but also enhances its suitability for operational applications.

Aiming to estimate depth operationally from remotely sensed flood extents, we introduce GLOCAL[5]. GLOCAL employs a local agent method for each flood polygon, determining water levels and depths from the boundaries based on the principle of optimal area matching. These individual water levels are then harmonized along river channels using a global tile-based processor, enhancing depth resolution across fluvial regions. Owing to multi-scale solver integration, GLOCAL has resilience to inaccuracies in flood boundaries and has a high degree of adaptability to diverse input DEMs.

To investigate the influence of DEM resolution on depth retrieval from flood extents, we developed EFRA[6]. EFRA employs a novel nested tree structure to identify the optimal water-level distribution within and across individual flood polygons. This nested tree is constructed using an emulated flood recession process, which accounts for micro topographic structures. EFRA tolerates extent and DEM error through a topography upscaling process and an enhanced region-growth approach. Additionally, EFRA facilitates the estimation of depth uncertainty, correlating it with the flood extent and topographic constraints. Utilizing EFRA, we attempt to determine how DEM resolution affects depth estimation accuracy.

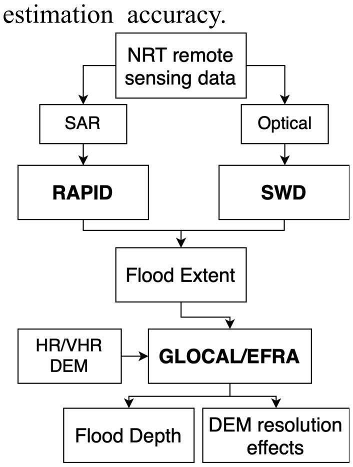

Figure 1. Proposed framework for operational remote sensing flood extent and depth mapping consists of four kernel algorithms: RAPID, SWD, GLOCAL, and EFRA.

3. STUDY CASES AND DATASETS

We select the spring flood event over the Red River of the North in 2023 to demonstrate the operational flood extent and depth mapping results from multi-source remote sensing images. To evaluate the DEM effects on depth estimation through quantitative validation, we select Hurricane Harvey in 2017 with abundance observation as the case. The input SAR images are from Sentinel-1, RCM, and RS2, with preprocess to Radiometric Terrain Corrected (RTC) products, and resolution ranging from 10m to 30m. The optical images are from PlanetScope Scene, we use the surface reflectance with 4 bands (i.e., RGB and NIR) as input. The DEMs involved in this study are from Copernicus Digital Surface Model (CDSM) in 30m [7], Forest And Buildings removed Copernicus DEM (FABDEM) in 30m [8], USGS NHD 10m, and USGS 3DEP 1m, respectively. We also use the post event water level surveyed data from USGS High Water Mask (HWM) for flood depth validation.

4. RESULTS AND VALIDATION

Figure 2 showcases the flood extent mapping results obtained from multi-source SAR and optical images using RAPID and SWD. Despite the variety of SAR sensors employed, RAPID's output exhibits consistent detection, effectively capturing the dynamics of the snow melt flood event. Such consistency across different SAR sensors is unprecedented. Additionally, SWD's results complement those from SAR, providing enhanced detail in smaller water bodies, a benefit derived from the higher spatial resolution (3m) of PlanetScope images.

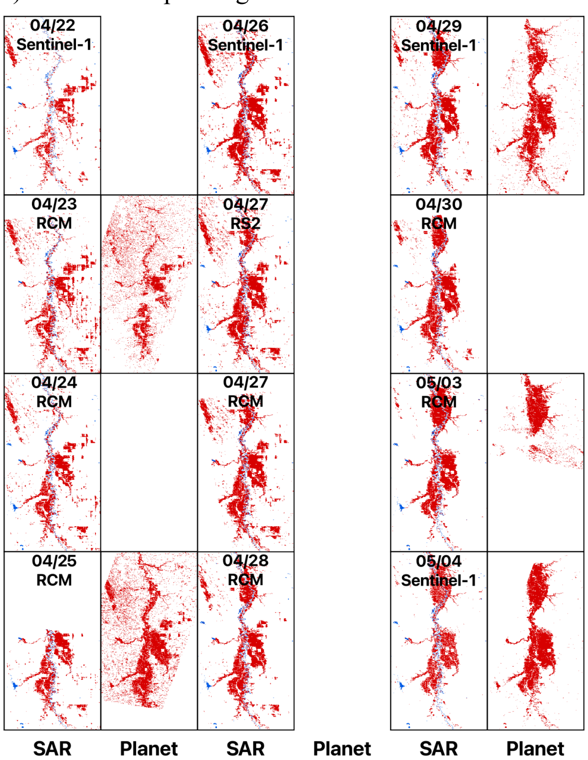

Figure 2. Extent of flooding along the Red River of the North from April 22, 2023, to May 4, 2023, mapped using SAR and optical imagery, processed with RAPID and SWD, respectively. Note: Images that were not available and pixels obscured by clouds have been excluded from the Planet based flood inundation maps.

Figure 3 displays the depth estimation results obtained from both optical and SAR-based flood extents using GLOCAL. Generally, consistent depth estimations are produced for identical flood extents, irrespective of the varying input DEMs used. Notably, the depth estimations for central flood polygons in results derived from Planet-based data tend to be deeper compared to those from SAR-based data, attributed to less fragmented flood boundaries. Furthermore, GLOCAL's ability to generate meaningful estimations, even when the upper flood polygon is incomplete in the case of Planet-based flood extents, underscores the algorithm's robustness.

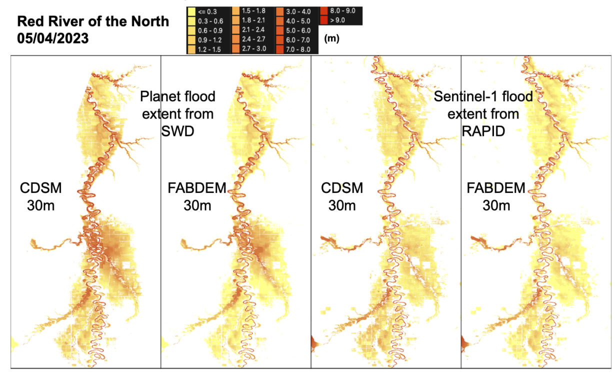

Figure 3. Flood depth estimation from optical and SAR based flood extent over Red River of the North on 05/04/2023, derived using GLOCAL.

Figure 4 presents the estimated minimum and maximum depths obtained using the EFRA method from the SAR-derived flood extent during Hurricane Harvey in 2017. The depth uncertainty is influenced by the local constraints related to flood extent and topography. Consequently, the uncertainty range (the difference between maximum and minimum depths) varies spatially, ranging from several centimeters to a few meters.

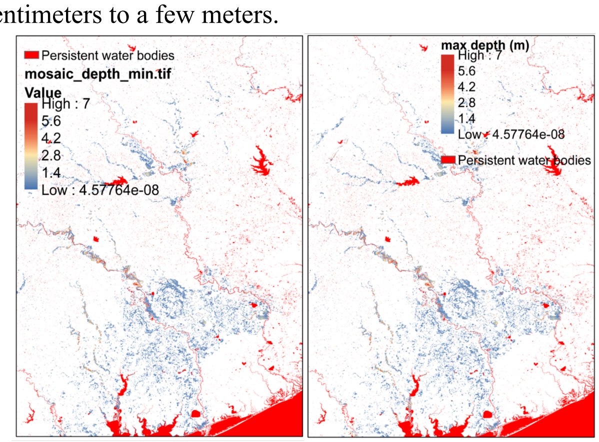

Figure 4. Minimum (left panel) and maximum (right panel) depth estimated from the SAR based flood extent using ERFA for Hurricane Harvey over the Huston area on 2017-08-29. Source DEM is USGS 3DEP at 1m.

Figure 5. presents the validation results of flood depth estimates from EFRA, compared against observed USGS HWM. The result clearly shows that EFRA provides accurate estimations of both flood stage and depth using both 10m and 1m input DEMs. However, there is a notable decrease in depth estimation accuracy as the DEM resolution coarsens, with the root mean square error escalating from 1.01 m using 1m DEM to 2.85 m using 10m DEM. These findings emphasize the significant impact of DEM resolution on depth estimation, likely attributable to the diminished representation of micro-topographic features at coarser resolutions.

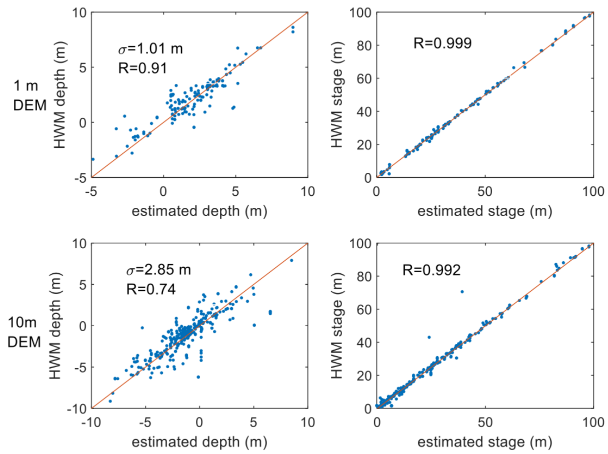

Figure 5. Flood depth validation against USGS HWM surveyed data during Hurricane Harvey 2017. Depth estimation using EFRA, input with 1m and 10m DEM, respectively.

5. CONCLUSION AND FUTURE DIRECTION

As we progress toward high-resolution, operational, remotely sensed flood monitoring, the RAPID and SWD algorithms demonstrate the efficacy of the self-supervised principle in processing multi-source satellite images for rapid, NRT flood extent detection. Cross-comparisons indicate that these multi-source flood maps are consistent with each other, capturing the intricate inundation dynamics of flood events. In terms of depth estimation, the GLOCAL and EFRA algorithms show significant promise for operational deployment, primarily due to their adaptability to various input DEMs and resilience to inaccuracies in flood boundaries. EFRA, in particular, underscores the necessity of very high-resolution DEMs (~1m) for effective remotely sensed depth estimation.

Looking ahead, addressing the challenges of SAR-based flood detection in urban and vegetated areas is a key area of focus. Exploring deep learning approaches for out-of-distribution detection presents a direction for urban flood mapping [9]. Additionally, the utilization of longer wavelength SAR sensors, such as L-band ALOS-2 and NISAR, could be instrumental in improving the detection of floods in vegetated regions. For optical detection, refining algorithms to manage multi-class spectral features of water pixels is imperative. Additionally, more extensive testing is required for depth estimation methods to uncover and resolve potential contradictions between DEM and flood extent. While missing flood extent due to terrain or vegetation obstacles can be accounted for in depth retrieval based on DEM, this process warrants further investigation and refinement. These advancements will continue to elevate the precision and applicability of flood monitoring systems, contributing to more effective emergency response and management strategies.

6. REFERENCES

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