Enhancing Water Resources Management with Open-Source Remote Sensing: Flood Mapping and Climate Change Insights on Kupa River case area

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Abstract

Flooding is one of the most damaging natural disasters, intensified by climate change, urban development, and land-use changes. Effective flood monitoring and management are crucial to mitigating the negative impacts, especially in regions with complex hydrological dynamics. This study focuses on the Kupa River basin in Croatia, a flood-prone region, and presents an integrated approach for flood mapping and climate impact assessment using open-source Earth observation (EO) data and free tools. Combining a different remote sensing datasets; Sentinel-1 Synthetic Aperture Radar (SAR), Sentinel-2 Normalized Difference Vegetation Index (NDVI), and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) precipitation datasets, all accessed through Google Earth Engine (GEE), this research demonstrates a cost-effective and scalable solution for monitoring flood dynamics and climate change insights on a focused area. Sentinel-1 SAR, with its cloud-penetrating capabilities, is used to detect surface water changes, while Sentinel-2 through the NDVI complemented vegetation health before and after flood events. CHIRPS data, with daily precipitation estimates, contextualizes the meteorological conditions that contribute to flooding. The integration of these datasets offers a comprehensive analysis of flood events and their environmental impacts, providing actionable insights for local flood management and climate change adaptation. The use of open-access and freely available data and free tools highlights the potential for replicable flood monitoring in regions with limited infrastructure, further supporting the development of early-warning systems and informed decision-making.

1. Introduction

Floods are among the most frequent and destructive natural disasters globally, causing extensive damage to infrastructure, ecosystems, and human life. Their intensity and frequency are projected to increase due to the combined effects of climate change, land-use transformation, and urban expansion. Consequently, it is now more important than ever to have flood-monitoring systems that are reliable, quick, and affordable.

Traditional methods for flood mapping and analysis, such as field surveys and aerial observations, are often limited in spatial and temporal scope, especially during extreme weather events. In contrast, Earth observation (EO) technologies, particularly satellite-based remote sensing, offer systematic and consistent data acquisition over broad regions. This capability enables effective detection, monitoring, and assessment of flood events, even in inaccessible or cloud-covered areas. The growing availability of open-access satellite data and free cloud-based geospatial platforms, such as Google Earth Engine (GEE), has further enhanced the feasibility of using remote sensing in environmental monitoring, especially water systems, lakes and floods (Zhang et al, 2024, Ali et al, 2024, Johary et al, 2023). This study explores the integration of Free Open Source EO datasets and free tools and Softwares for geospatial application (FOSS4G) at flood assessment and climate-related analysis in the Kupa River basin, located in central Croatia. The objective was to analyze how combining Synthetic Aperture Radar (SAR) data, vegetation indices, and precipitation datasets could improve a comprehensive picture of flood dynamics and their environmental impact at Kupa River Basin.

Flooding is recognised as one of the most damaging and least predictable natural hazards in Central Europe. In Croatia, more than 25 % of the national territory is officially categorised as flood-prone, with annual direct losses that routinely exceed €140 million euros (EEA Report, 2024). The Kupa River basin is a particularly sensitive subsystem because it drains a karstic catchment where water can rapidly alternate between surface and subterranean flow. This dual hydrological regime complicates both hydraulic modelling and real-time situational awareness (Bonacci et al, 2006).

In karst areas, standard gauges often fail to detect short-term surface floods that appear when the underground channels fill up and become saturated. Remote-sensing approaches have therefore become indispensable. Over the past decade, satellite remote sensing has become indispensable for flood monitoring. SAR is cloud-independent and delivers reliable water delineation at ten-metre resolution (Schlaffer et al, 2015, Nhangumbe et al, 2023, Wu et al, 2023). Optical missions, notably Sentinel-2, provide vegetation-based proxies through indices such as Normalized Difference Vegetation Index (NDVI), facilitating the assessment of post-event ecological damage (DeVries et al, 2020, Demissie et al, 2023, Tan et al, 2022).

On the hydro-meteorological side, the CHIRPS rainfall ensemble is now widely employed to relate precipitation anomalies to flood occurrence, particularly in data-sparse region (Tote et al, 2015). Although recent open-source efforts have demonstrated the usefulness of multi-sensor (Foroughnia et al, 2022) flood mapping in large alluvial systems such as the Danube (Bloschl et al, 2013) and the Po (Conversi et al, 2023), those basins exhibit relatively shallow groundwater tables, low hydraulic losses, and well-instrumented gauge networks.

By contrast, the Kupa drains a highly fragmented karst aquifer in which rainfall can disappear into epikarst conduits and reemerge tens of kilometres downstream hours to days later. Such rapid surface–subsurface exchanges, short warning times and invalidate gauge-only stage–discharge relationships, often cause that many floods go unnoticed and unrecorded by conventional sensors. There are rather few recent studies combining variety of multiple remote sensing datasets for the enhanced water management (Belay et al, 2025) and since there were no similar peer reviewed studies for a karstic dynamics area combining the variety of multiple remote sensing data, our work addresses a clear knowledge gap by demonstrating how freely available EO assets can capture both the hydrological signature and the ecological footprint of karst-driven floods under data-poor conditions.

The main objective of this study is to integrate multiple open-access datasets into a cohesive, reproducible workflow for studying flood events in the Kupa River basin. By combining Sentinel-1 SAR backscatter data, Sentinel-2-derived NDVI values, and CHIRPS precipitation data, this study tried to explore the added value of a combined comprehensive analysis of flood dynamics and their environmental impacts. Specifically, the workflow detects inundation by analyzing multi-temporal SAR backscatter differences, assesses vegetation damage through NDVI changes, and connects hydrometeorological conditions to observed floods using rainfall data.

This integrated approach, which relies solely on openly licensed data and free software, demonstrates how combining different datasets can overcome individual limitations and enhance the understanding of complex flood events. By utilizing this methodology, the study offers a valuable tool for stakeholders working on disaster-risk reduction and climate-change adaptation strategies in flood-prone regions. The approach relies entirely on freely accessible, open-source data and free software, demonstrating how a multi-sensor perspective can mitigate the limitations of individual datasets.

2. Study Area and Data

2.1 Study Area

The Kupa River basin (45°18′–46°10′ N, 14°30′–16°45′ E) covers approximately ∼10 200 km^2 of which 8 350 km^2 in Croatia and the remainder in Slovenia. It drains a diverse landscape of fluvio-karstic plateaus, alluvial plains, and urban areas before joining the Sava River at Sisak. The mean annual discharge at Karlovac is ≈283 m^3 s^{-1}, but during peak spring and autumn floods, flows often exceed 1 000 m^3 s^{-1}. Flood risk is further amplified by a network of subterranean conduits, which release stored groundwater into surface channels when hydraulic thresholds are exceeded. Approximately 350,000 inhabitants live within the floodplain, with the cities of Karlovac, Ozalj, and Ogulin being particularly vulnerable. The region includes agricultural land, forests, wetlands, and urban settlements. Key economic assets include high-value arable land (maize, wheat, and forage crops), transport infrastructure (A1 and A6 motorways), and Natura 2000 wetlands.

The climate is humid continental with warm summers (mean July temperature 20°C) and cold winters (mean January temperature - 1°C). Annual precipitation ranges from 1,100 mm in lowlands to 1,600 mm in orographic ridges, primarily from Atlantic and Mediterranean weather systems. Due to its geomorphology and hydrological conditions, the basin is highly prone

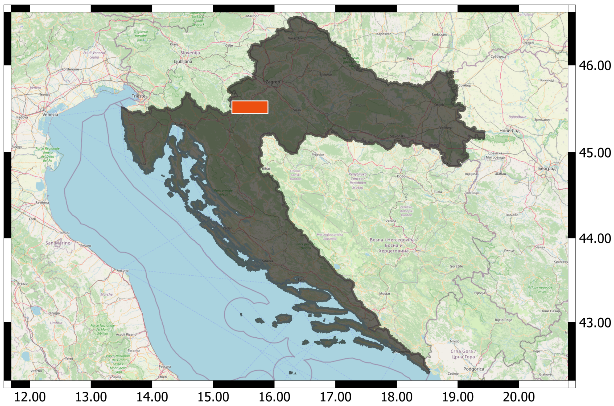

Figure 1. Study area: grey is the are of Croatia and red are marks the study area for the flood event in May 2023 over the Kupa River Basin

to flooding, especially during spring and autumn, when rainfall is abundant and snowmelt elevates river levels. In recent years, several notable flood events have affected the Kupa River basin, causing damage to infrastructure and agriculture, particularly in low-lying areas. These characteristics make the region an ideal case study (Figure 1) for evaluating remote sensing applications in flood detection and environmental impact assessment. With its complex hydro-climatic conditions and karst hydrology, the Kupa basin serves as a natural laboratory for testing EO-based flood-monitoring strategies.

2.2 Data

This study utilizes a range of open-access EO datasets to map flooding and assess the impacts of climate change on water resources in the Kupa River basin. The primary data sources are Sentinel-1 SAR, Sentinel-2 multispectral imagery, and CHIRPS precipitation data, all of which are freely available through Google Earth Engine. Sentinel-1 SAR is particularly useful for flood detection, as its radar backscatter can penetrate clouds and operate in all weather conditions. This is crucial for mapping floods in regions where optical imagery is often obstructed by clouds. Sentinel-2 data, with its fine spatial resolution, is used to assess flood-related changes in vegetation health via the NDVI. CHIRPS rainfall estimates provide critical information on precipitation patterns, essential for understanding the hydrometeorological context of flooding events.

These datasets are processed and analyzed within free online tool GEE, which enables efficient handling of large-scale geospatial data. It is a cloud-based platform which allows seamless integration of the datasets, and automated pre-processing tasks such as noise removal, calibration, and terrain correction, and supports advanced temporal analysis of flood dynamics and climate variables. By leveraging GEE, the study provides an effective, cost-efficient method for monitoring floods and assessing the impacts of climate change on water resources, with the flexibility to process large datasets without the need for extensive local computing infrastructure.

Main characteristics of used open-access datasets to analyze flood dynamics and related environmental conditions are shown in Table 1). Sentinel-1 SAR is a C-band radar data from the European Space Agency's Copernicus program, acquired in Interferometric Wide (IW) swath mode. The data are used to detect surface water through changes in radar backscatter intensity, with high temporal frequency and all-weather capability. Sentinel-2 MSI (Multispectral Instrument) is a optical data used for calculating vegetation indices, such as NDVI, to assess changes in land surface condition before and after observed events. CHIRPS is a daily precipitation dataset that combines satellite imagery and in-situ data to provide spatially continuous rainfall estimates, useful for identifying meteorological conditions leading to flooding.

Dataset	Sensor/Band	Spatial res.
Sentinel-1 GRD	C-band SAR (VH,VV)	10 m
Sentinel-2 L2A	MSI (B2–B12)	10–20 m
CHIRPS v2.0	Gauged IR rainfall	0.05 °C

Table 1. Main characteristics of datasets used in this study.

The period selected for this study (April–June 2023) was chosen not only to capture the flood event on May 19th, 2023, but also to account for the temporal resolution of each dataset and the broader hydrological and meteorological conditions influencing the event. Sentinel-1 GRD data, with a spatial resolution of 10 meters, provides high temporal frequency with a revisit time of 6 days (or 3 days with dual satellites). This allows for pre- and post-event flood monitoring, ensuring that both the flood event itself and the preceding and following conditions are adequately captured. Sentinel-2 L2A imagery, with spatial resolution ranging from 10 to 20 meters, has a revisit time of 5 days, making it suitable for monitoring vegetation changes before and after the flood event, as well as capturing any recovery of vegetation within the wider period of April to June 2023. CHIRPS v2.0, with a spatial resolution of 0.05°C, provides daily precipitation estimates, which are critical for analyzing the meteorological context leading up to and during the flood event. The 3-month period from April to June 2023 allows for a more comprehensive analysis of rainfall patterns that influenced the flooding, providing insight into antecedent conditions and rainfall anomalies prior to the event on May 19th. The combination of these datasets, with their specific temporal and spatial resolutions, enables an in-depth analysis of flood dynamics, vegetation impact, and the meteorological conditions associated with the flood event.

3. Methodology

The methodological framework integrates SAR-based flood detection, NDVI-based vegetation monitoring, and precipitation trend analysis using CHIRPS data, all conducted within the Google Earth Engine environment. Data ingestion and preprocessing were carried out within GEE. This step included importing all datasets and performing necessary transformations to ensure compatibility for further analysis. The Sentinel-1 data underwent thermal-noise removal, radiometric calibration, and Range–Doppler terrain correction using the SRTM 30 m digital elevation model. A 3×3 Lee speckle filter was applied to improve image quality. Sentinel-2 data were processed by applying a cloud mask with a threshold of 20% cloud cover and scaling reflectance values by a factor of 0.0001. For CHIRPS precipitation data, daily rasters were summed over the basin polygon, and cumulative rainfall for 7- and 30-day periods was derived to capture the meteorological context leading up to the flood event. All raster data were re-projected to EPSG 32633 at a spatial resolution of 10 meters to ensure consistency across datasets.

Flood mapping was primarily based on change detection using Sentinel-1 SAR imagery. Changes in radar backscatter between pre- and post-flood images were used to identify areas of inundation. Pixels with significant changes in backscatter were flagged as flooded. Validation of the results was carried out using 37 field polygons and the JRC Global Surface Water mask, with the overall accuracy and Intersection-over-Union metrics computed to assess the effectiveness of the flood detection.

The impact on vegetation was assessed using NDVI derived from Sentinel-2 imagery. The vegetation change was calculated by comparing NDVI values before and after the flood, with thresholds established to identify areas of vegetation decline or recovery. A negative change in NDVI values (below -0.20) indicated vegetation damage, while positive changes (above 0.20) suggested recovery. The precipitation forcing was analyzed using CHIRPS rainfall data, with cumulative rainfall for 7 and 30 days before the flood peak used to assess how precipitation patterns aligned with the flood event. Time-series charts were generated to visualize rainfall maxima in relation to SAR-derived flood extents.

Finally, the analysis combined all data layers into three main categories: areas impacted by flood only, areas affected by both flood and vegetation damage, and unaffected land. Area statistics were exported for further analysis, and an RGB overlay was generated to visually represent the combined results, with red representing areas of vegetation decline, green for recovery, and blue for SAR-derived flood areas. All geoprocessing was executed in GEE, a free-to-use, cloud-based geospatial analysis platform that provides efficient handling and access to openly licensed remote sensing data used in this study; large datasets archives such as Copernicus and CHIRPS archives. All data processing and temporal analysis in this study were conducted using GEE. Although GEE's server-side code is proprietary, its zero-cost access model and public API align with the core FOSS4G principle of unrestricted data and computational availability. To ensure full open-source reproducibility, all visualization, figure generation and map layouts were completed in QGIS 3.34 (GNU GPL) and Python 3.11 libraries (Rasterio, GeoPandas, Matplotlib).

3.1 Flood Mapping with Sentinel-1 SAR

The analysis focuses on the period from May 1st–15th, 2023 (pre-flood) and May 16th–19th, 2023 (post-flood). The selected periods are crucial for capturing the effects of the flood event, as they represent a stable baseline of conditions prior to the event and a snapshot immediately following the flood. Specifically, the pre-flood period includes four Sentinel-1 SAR images, ensuring a robust and reliable baseline, while the post-flood period includes a single image for a clear post-event comparison. This setup ensures that flood-induced changes, particularly in surface water areas, are clearly visible, as changes in radar backscatter are most pronounced in such regions.

The Sentinel-1 SAR data is first processed to compute the median value for each time period, which helps reduce noise and provides a more stable representation of surface conditions. The difference in backscatter between the pre- and post-flood images is then calculated. Backscatter measures how much radar signal is reflected back to the sensor, with lower values typically indicating water surfaces. The flood areas are identified by significant reductions in backscatter following the flood event. A threshold of 1.0 dB is applied to flag areas where there is a noticeable decrease in backscatter, distinguishing flooded regions from normal land surfaces. This threshold was chosen based on its ability to reliably capture the flood event while minimizing detection of minor variations caused by other environmental factors.

A second threshold of -15 dB is applied to the post-flood images, as this is a commonly used value in SAR studies for identifying water surfaces. Water typically reflects radar signals much less than land surfaces, resulting in low backscatter values. As a result, areas with backscatter values below -15 dB are classified as flooded.

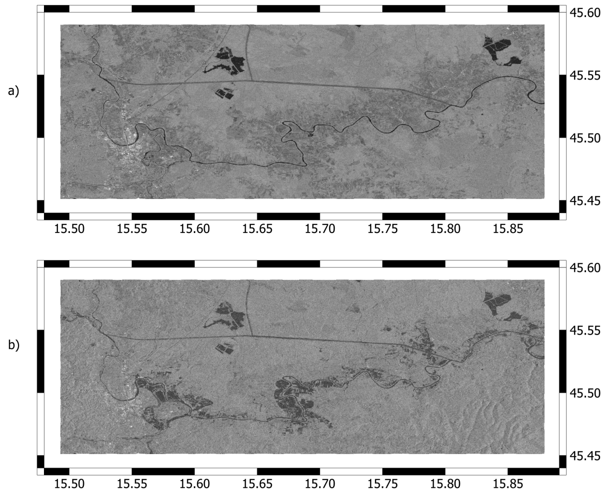

Figure 2. SAR analysis a) before and b) after the flood event in May 2023 over the Kupa River Basin

The Figure 2 displays the before and after flood Sentinel-1 SAR images (a and b). On the left, Figure 2a) shows the pre-flood conditions with the typical radar backscatter from land surfaces. On the right, Figure 2b) presents the post-flood image, where a significant reduction in backscatter values can be observed in the flood-affected areas. These changes, especially near the river and floodplains, are indicative of the inundation caused by the flood event.

The Figure 3 shows the difference between the pre- and post-flood images. This difference map highlights the areas where the greatest reductions in backscatter occurred, which are indicative of the flooded zones. This difference map provides a clear, visual representation of the extent of the flood, making it an essential tool for flood monitoring and risk assessment.To exclude permanent water bodies, such as lakes, the Global Surface Water (GSW) dataset was used to ensure that only flood-induced water changes were included in the final flood mask.

3.2 NDVI-Based Vegetation Impact Assessment

In this study, Sentinel-2 imagery was utilized to assess the vegetation impact during the flood event in the Kupa River Basin. Specifically, the NDVI was calculated for pre-flood and post-flood periods to identify changes in vegetation health due to the inundation. The NDVI is a widely used remote sensing index that highlights vegetation cover by measuring the difference between near-infrared (NIR) and red bands. Positive NDVI values correspond to healthy vegetation, while negative values indicate barren land or water bodies.

For this analysis, Sentinel-2 images from the before flood period (May 1st–15th, 2023) and the after flood period (May

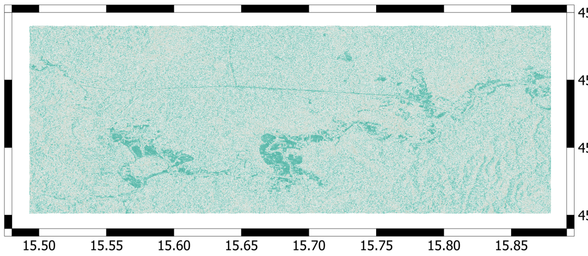

Figure 3. Differences from the SAR analysis before and after the flood event in May 2023 over the Kupa River Basin

16th–19th, 2023) were used. These periods were selected to best capture the flood impact on the landscape. The NDVI difference between these two periods was computed to evaluate the impact of flooding on vegetation health. A threshold of $\Delta\text{NDVI} < -0.10$ was applied to classify areas with vegetation loss due to inundation, which indicates a reduction in vegetation cover caused by water exposure.

The first part of the process involved calculating the NDVI for both periods. The Sentinel-2 images were processed to extract the NIR and red bands, which were then used to compute the NDVI. The pre-flood NDVI and post-flood NDVI were calculated and merged into one image for each period. The next step was to calculate the difference in NDVI between the pre- and post-flood images, producing a NDVI difference image that highlights areas where vegetation was significantly impacted by flooding.

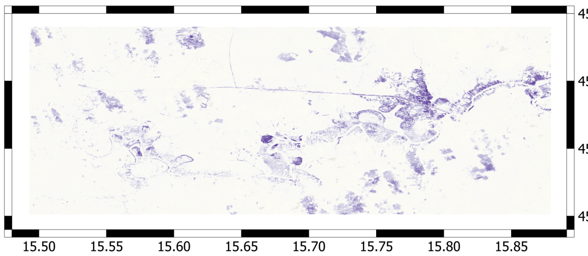

Figure 4. Differences from the Sentinel 2 NDVI analysis before and after the flood event in May 2023 over the Kupa River Basin

The resulting image, shown in Figure 4, illustrates the vegetation changes in the region. The areas with the greatest loss of vegetation due to flooding appear as dark purple regions, while areas with minimal impact or recovery are lighter in color. These changes are most evident in the floodplain areas, where water exposure during the flood event led to a significant reduction in vegetation cover. The NDVI difference map helps to visualize how the flood event affected vegetation health, providing a clear indication of flood extent and the areas most affected by waterlogging.

3.3 Precipitation Analysis Using CHIRPS

The CHIRPS dataset was used to analyze daily and monthly precipitation trends in the Kupa River Basin from May 2017 to May 2024. The CHIRPS dataset combines satellite-based infrared data with ground station data to provide high-resolution daily and monthly precipitation estimates. The spatial resolution of CHIRPS is 0.05°C, making it suitable for both local and regional scale hydrological analysis.

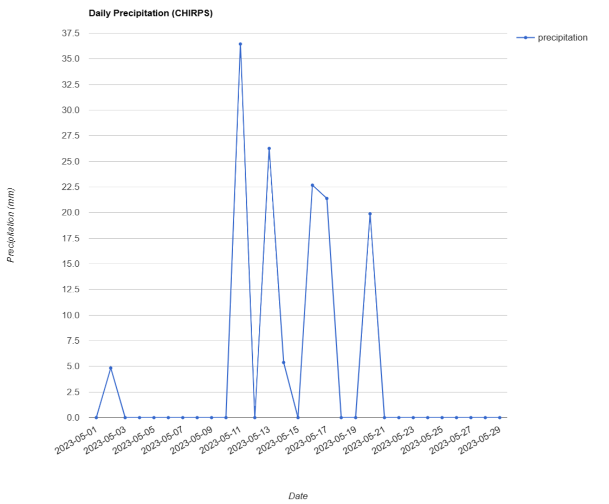

Figure 5. Daily Precipitation from CHIRPS model for the Kupa River Basin

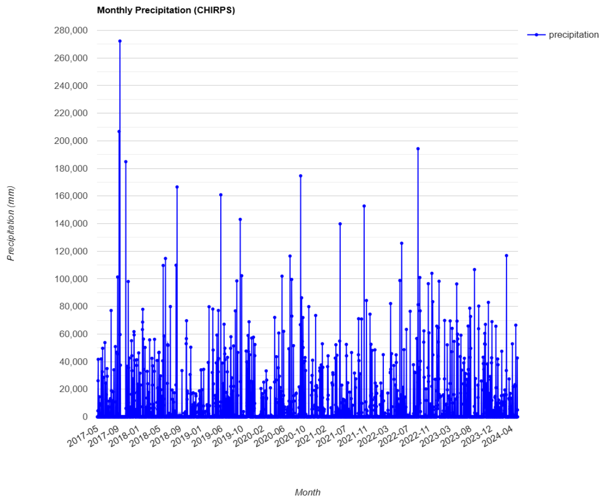

Figure 6. CHIRPS Time series of Monthly Precipitation for the Kupa River Basin

The Figure 5 illustrates the daily precipitation over the course of May 2023, showing notable fluctuations. The precipitation spike around May 11th, 2023 stands out with more than 35 mm of rainfall in a single day. This peak is particularly relevant, as it likely contributed significantly to the flood event observed in the Kupa River Basin during the same period. Smaller precipitation events, such as those on May 13th, 17th, and 19th, also contributed to the cumulative rainfall, indicating that the flood was likely a result of a series of heavy rainfall events. These spikes in precipitation are critical for understanding the hydrological forces that drive flooding in this region, as they correlate with both SAR-derived flood maps and NDVI vegetation changes.

The Figure 6 shows the monthly precipitation for the Kupa River Basin from 2017 to 2024, illustrating the variability of rainfall over the years. There are clear seasonal patterns, with significant rainfall peaks occurring during certain months each year, likely driven by Atlantic frontal systems and Mediterranean cyclones. This chart also highlights months of extreme precipitation where values exceed 150 mm, such as the months of May 2018 and May 2023. These extreme events align with higher flood risks and highlight the need for monitoring precipitation as part of flood prediction models.

3.4 NDVI Time Series Analysis

In addition to the flood detection using Sentinel-1 SAR and vegetation change via Sentinel-2 NDVI, a historical NDVI time series from 2017 to 2025 was analyzed to gain a deeper understanding of the long-term trends in vegetation health in the Kupa River Basin, shown in Figure 7. NDVI values serve as a reliable indicator of vegetation vigor, with higher values typically representing healthy, growing vegetation, and lower values indicating stress, drought, or damage caused by extreme weather events.

The NDVI time series reveals the seasonal cycle of vegetation, with higher NDVI values observed during the growing season (spring and summer) and lower values during dormant periods (fall and winter). However, significant and rapid drops in NDVI were observed, which align with historical flood events. This sharp decrease in vegetation health is often associated with flood-induced waterlogging or direct physical damage to vegetation, highlighting the susceptibility of vegetation to hydrological stress in flood-prone regions.

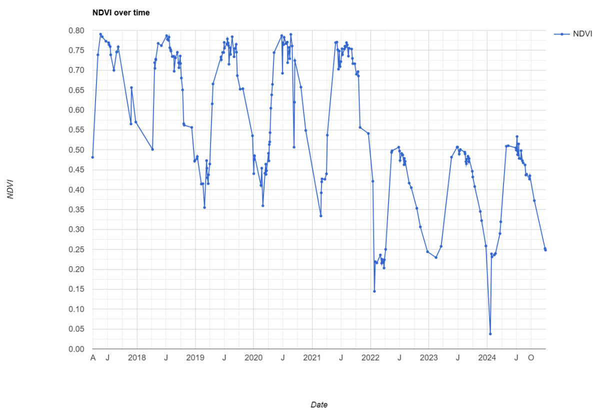

Figure 7. NDVI time series (2017–2025) for the Kupa River Basin, showing vegetation health trends over the period with a 10% cloud mask applied

During the period surrounding the May 2023 flood event, a substantial decline in NDVI values was observed, which correlates with the flood's occurrence. This vegetation loss indicates a direct impact of the flood on plant health, most likely due to excess water that leads to soil saturation, reduced oxygen availability to plant roots, and the physical displacement of vegetation. The observed drop in NDVI is indicative of acute flood damage, which could lead to a longer recovery period, particularly for sensitive vegetation types such as crops or young plants.

The long-term NDVI trend shows a recurrent pattern of vegetation stress, especially during peak flood periods, but with significant seasonal recovery. The time series analysis provides valuable insight into the flood resilience of the region's vegetation, with recovery patterns that could be indicative of the region's adaptive capacity to recurrent flood events. However, if the NDVI values continue to show large declines during every flood event, it may indicate decreasing flood resilience, with a potential shift in land use or vegetation types over time. By integrating this temporal context with SAR flood maps and NDVI difference maps, the study gives a more complete picture of flood dynamics and vegetation recovery over time.

4. Results

Figure 8 presents the fusion layer obtained by intersecting the Sentinel-1 flood mask with the Sentinel-2 ΔNDVI image. Dark-maroon pixels mark locations where radar backscatter dropped by more than 1 dB and NDVI declined by at least 0.10, indicating areas simultaneously inundated and biologically stressed. Pale background cells represent land that was either not flooded or showed no measurable vegetation loss.

The spatial pattern confirms the diagnostic value of this fusion. Continuous belts of impacted pixels trace the active Kupa channel and its oxbow remnants, demonstrating that genuine hydraulic connectivity—rather than simple proximity—governs flood damage in this karst floodplain. Southeast of Karlovac, large agricultural blocks form coherent maroon clusters, consistent with field reports of waterlogged maize and forage fields after the 19 May peak. In contrast, upland forest patches display only scattered signals, suggesting that well-drained soils and canopy interception shortened flood residence time and limited NDVI decline. The scarcity of spurious detections over urban surfaces illustrates how the dual-threshold logic (tresholds ¿ 1 dB and NDVI ¡ –0.10) suppresses artefacts from radar lay-over and shadow.

By requiring concurrence between hydraulic and vegetative indicators, the fusion layer reduces the gross SAR flood footprint by roughly 40% and focuses attention on zones where both ecological integrity and economic assets are at risk. This integrated output exemplifies the main advantage of multi-sensor, open-source workflows: it converts disparate satellite streams into an immediately actionable product for water-resource managers—prioritising post-event field inspections, guiding recovery funding, and supplying high-resolution evidence for calibrating future hydrological-crop models—without reliance on proprietary data or specialised local computing.

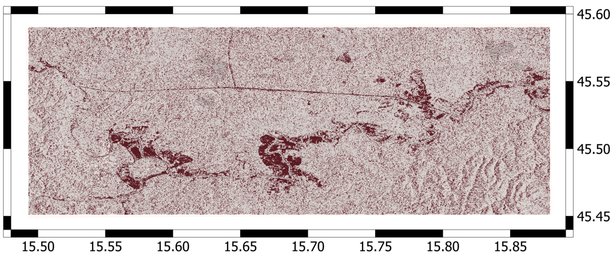

Figure 8. NDVI time series (2017–2025) for the Kupa River Basin, showing vegetation health trends over the period with a 10% cloud mask applied

The integrated workflow developed in this study demonstrates how open-source Earth-observation assets can be fused into a single decision-support layer for enhanced water-resource management. Sentinel-1 SAR pinpoints the spatial extent of inundation even under cloud cover; Sentinel-2–derived NDVI quantifies the concomitant loss—or recovery—of vegetation vigour; and CHIRPS precipitation series supply the hydrometeorological trigger that explains when and why the flood wave occurred. When these three datasets are overlaid in Google Earth Engine, they reveal not only where water spread but also how it altered green infrastructure and which rainfall thresholds preceded critical discharge. The resulting multi-sensor maps isolate zones of recurrent flooding, highlight croplands that experienced both deep water and severe NDVI decline, and link those impacts directly to antecedent 7- and 30-day rainfall totals. This openly licensed, cloud-based approach therefore turns disparate satellite archives into an actionable toolset for basin managers—supporting real-time emergency response, prioritising riparian restoration, and informing climate-adaptation planning without the need for proprietary data or high-end local computing.

5. Discussion

This study effectively demonstrates the integration of open-source satellite data and free softwares to map and monitor flooding in the Kupa River Basin. By combining Sentinel-1 SAR, Sentinel-2 NDVI, and CHIRPS precipitation datasets, the research presents a comprehensive and cost-effective method for assessing flood dynamics and their environmental impacts. The Sentinel-1 SAR data provides reliable flood detection through changes in radar backscatter, offering advantages in terms of all-weather capability and high spatial resolution, which are essential for flood monitoring in cloud-prone and data-scarce regions. The use of NDVI derived from Sentinel-2 imagery complements the SAR analysis by identifying vegetation health changes due to inundation. Additionally, CHIRPS precipitation data plays a crucial role in contextualizing meteorological conditions leading up to the flood, highlighting the role of precipitation anomalies in flood occurrence.

However, while the method demonstrated here is powerful, especially in the areas with limited approach, it also has some limitations. For example, the SAR backscatter difference relies on specific thresholds, which may not be universally applicable for all regions or flood types. The threshold of 1.0 dB used to flag flood-induced backscatter changes is based on observations specific to the Kupa River basin, and different flood events in different regions may require adjustments to this value for more accurate detection. Similarly, the -15 dB threshold used to identify water surfaces could exclude areas of shallow or temporary flooding, leading to a potential underestimation of flood extent. Future work could involve optimizing these thresholds through machine learning approaches or field validation to improve the accuracy and robustness of flood mapping in karst terrains.

The NDVI-based vegetation impact analysis is another critical component of this study. The difference in NDVI before and after the flood reveals significant vegetation loss, particularly in floodplain areas. The negative NDVI change indicates the stress and damage caused by prolonged waterlogging, which could have long-term ecological and agricultural consequences. However, the NDVI approach also has its limitations, as it cannot distinguish between vegetation damage caused by flooding and other environmental factors, such as drought or pest infestation. To address this, multi-temporal analysis or the incorporation of additional vegetation health indices could further enhance the understanding of flood impacts on ecosystems.
The integration of precipitation data through CHIRPS adds an important layer of context to the analysis. The precipitation spikes observed in May 2023 align with the onset of the flood event, providing valuable insights into the hydrometeorological forces that drive flooding. However, precipitation data alone does not fully explain flood dynamics, as the interplay between

surface and subsurface water in karst regions complicates the relationship between rainfall and flooding. The study region's karst hydrology, with rapid surface–subsurface exchanges, requires further investigation to better understand how groundwater flow contributes to flooding in these areas. This could be achieved by combining the current dataset with hydrological models that simulate the movement of water in karst landscapes.

A significant strength of this study lies in its use of open-source data and free software, which makes the methodology highly replicable and accessible to researchers and practitioners in other flood-prone regions. The Google Earth Engine platform facilitates the efficient handling and processing of large datasets, enabling the seamless integration of multi-sensor data for flood monitoring. This approach has the potential to be extended to other regions affected by floods, particularly in areas with limited monitoring infrastructure or where traditional methods are less effective due to complex hydrological conditions.

In addition to the primary datasets used in this study (Sentinel-1 SAR, Sentinel-2 NDVI, and CHIRPS precipitation), several other datasets were considered but ultimately deemed unsuitable or ineffective for this specific analysis. These datasets include Sentinel-3 (S3), CLC (Corine Land Cover), and MODIS Land Surface Temperature (LST) data. Below is a review of these datasets, including critical explanations of why they were not applicable for this study, mainly due to limitations such as lower spatial resolution, longer revisit times, and cloud contamination.

The Sentinel-3 (S3) OLCI (Ocean and Land Colour Instrument) dataset was initially considered for monitoring vegetation and flood impacts, as it provides multispectral imagery with a spatial resolution of 300 meters, covering a wide range of bands. While the Sentinel-3 mission is designed to support a variety of applications, including water quality monitoring and vegetation analysis, it has limitations for this type of flood mapping study. The spatial resolution of Sentinel-3 (300 meters) is far coarser compared to Sentinel-2 (10–20 meters), which is more suitable for detailed flood mapping and vegetation monitoring in the Kupa River basin. The lower resolution of Sentinel-3 OLCI reduces the accuracy of detecting small-scale flood extents or vegetation damage, especially in densely vegetated or urban areas, where fine spatial detail is required.

Furthermore, Sentinel-3 OLCI data lacks the temporal resolution that Sentinel-1 and Sentinel-2 provide. Sentinel-3's revisit time can be longer, which makes it less effective for monitoring the rapid changes that typically occur during flood events. In this study, the decision was made to focus on Sentinel-1 for flood detection, which provides higher temporal frequency and is more suited for monitoring dynamic and transient events such as floods. Therefore, while Sentinel-3 may be useful in certain contexts, it was not appropriate for this specific flood event analysis.

The Corine Land Cover (CLC) dataset provides information on land cover types, which could theoretically be useful for understanding how different land use types (e.g., urban areas, forests, agricultural lands) are affected by flooding. However, the spatial resolution of the CLC dataset (100 meters) was found to be insufficient for flood mapping purposes in the Kupa River Basin. The dataset provides broad categories of land cover, but it lacks the fine spatial detail required to identify small-scale land use or changes in vegetation during flood events.

Moreover, the CLC dataset is updated every few years, meaning it does not reflect recent changes in land cover that may have occurred due to flood events or land use changes. This time lag makes it difficult to correlate current flood events with real-time land cover data. While CLC data is useful for long-term land use mapping and environmental monitoring, it does not offer the necessary temporal resolution or fine spatial detail needed for flood impact analysis on a monthly or event-based scale, which is critical for accurate flood monitoring.

MODIS Land Surface Temperature (LST) data is frequently used for monitoring surface temperature changes over large areas. However, in this study, the MODIS LST data proved to be less applicable for several reasons. The spatial resolution of MODIS LST data (1 km) is relatively coarse compared to other datasets like Sentinel-2 and Sentinel-1, making it difficult to capture small-scale temperature changes in flood-prone areas. The 1 km resolution is particularly problematic when trying to detect subtle variations in vegetation stress or localized water surface changes.

Another significant limitation of MODIS LST data is its cloud contamination, which can severely affect its quality in regions with frequent cloud cover, like the Kupa River Basin. In flood events, cloud cover is often prevalent, rendering MODIS LST data ineffective during critical periods. The high frequency of cloud cover in flood events reduces the usefulness of MODIS LST, as it impedes the accurate monitoring of temperature changes related to flooding and vegetation stress. Given these challenges, MODIS LST data was deemed unsuitable for this analysis, especially in comparison with Sentinel-2 NDVI data, which provides more reliable and high-resolution information on vegetation health and flood impacts.

The findings emphasize the value of multi-sensor approaches, which offer enhanced flood monitoring capabilities, and critical importance of selecting the right datasets for specific applications, particularly in regions with frequent cloud cover and dynamic hydrological conditions, particularly in data-scarce and complex regions like the Kupa River Basin.

6. Conclusion

This study researched in what extent open source satellite data and free tools can work together to give a clear view of the May 2023 flood in the Kupa River basin, Croatia, without even visiting the field. By overlaying Sentinel-1 SAR mapping the water and Sentinel-2 NDVI mapping the plant stress, we defined the flood extent and its ecological impact purely from remote sensing. About 60 % of the areas flagged as flooded by SAR also showed a clear drop in NDVI, confirming that our combined layer marks places hit by water and where vegetation was harmed. We also used CHIRPS rainfall data to link those impacts to actual rainstorms: heavy precipitation in the week before the peak flood explained why certain zones were inundated. Although other datasets (Sentinel-3, CLC, MODIS LST) proved too coarse or too cloudy here, CHIRPS could be even more useful if combined with higher-resolution radar rainfall products or local gauge data to refine timing and intensity of flood triggers. Due to usage of every step of the procedure ran in free tool Google Earth Engine and open-source tools QGIS and Python, anyone can repeat the workflow anywhere in the world by changing only the study boundary and a few threshold values.

Local authorities and community leaders could use this integrated, open-data approach to make more informed decisions before, during, and after a flood—even when field access is difficult or impossible. By combining Sentinel-1 SAR and Sentinel-2 NDVI, a clear map of exactly where water spread is and which areas of urban areas, crops, natural vegetation are most threatened can be made. In practice, this means emergency teams can focus their limited resources on the hardest-hit zones while from time series farmers could plan crop rotations or flood-tolerant planting in areas with repeated NDVI loss. At the same time, decision makers should be aware of the method's limits—thresholds may need local tuning, and very small or very brief floods can escape detection—so this satellite-based workflow works best when paired with selective field checks and local gauge data. However, this method provides a fast, low-cost tool to guide flood-risk reduction and water-management strategies in karst regions like the Kupa basin.

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Code Availability: Full author's own GEE processing script used in this study is publicly available at GitHub (Bjelotomić Oršulić, 2025) for reproducibility and adaptation to other study areas.

References

Zhang, Q., Zhang, Z., Wang, X., Xu, Z., Wang, Y. Monitoring of Glacier Area Changes in the Ili River Basin during 1992–2020 Based on Google Earth Engine. 2024. *Land*, 13, 1417. https://doi.org/10.3390/land13091417

Ali, M., Ali, T., Gawai, R., Dronjak, L., Elaksher, A. The Analysis of Land Use and Climate Change Impacts on Lake Victoria Basin Using Multi-Source Remote Sensing Data and Google Earth Engine (GEE). 2024. *Remote Sens.*, 16, 4810. https://doi.org/10.3390/rs16244810

Johary, R., Révillion, C., Catry, T., Alexandre, C., Mouquet, P., Rakotoniaina, S., Pennober, G., Rakotondraompiana, S. Detection of Large-Scale Floods Using Google Earth Engine and Google Colab. 2023. *Remote Sens.*, 15, 5368. https://doi.org/10.3390/rs15225368

European Environment Agency. (2024). European Climate Risk Assessment Executive summary, EEA Report, 01/2024, European Environment Agency.

Bonacci, O., Ljubenkov, I., & Roje-Bonacci, T. Karst flash floods: An example from the Dinaric karst (Croatia). 2006. *Natural Hazards and Earth System Sciences, 8*(6), 1119–1128. https://doi.org/10.5194/nhess-6-195-2006

Schlaffer, S., Matgen, P., Hollaus, M, Wagner, W. Flood detection from multi-temporal SAR data using harmonic analysis and change detection, 2015. *International Journal of Applied Earth Observation and Geoinformation*,Volume 38, 2015, Pages 15-24, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2014.12.001.

Nhangumbe, M., Nascetti, A., Ban, Y. Multi-Temporal Sentinel-1 SAR and Sentinel-2 MSI Data for Flood Mapping and Damage Assessment in Mozambique. 2023. *ISPRS Int. J. Geo-Inf.* , 12, 53. https://doi.org/10.3390/ijgi12020053

Wu, X., Zhang, Z., Xiong, S., Zhang, W., Tang, J., Li, Z., An, B., Li, R. A Near-Real-Time Flood Detection Method Based on Deep Learning and SAR Images. 2023. *Remote Sens.*, 15, 2046. https://doi.org/10.3390/rs15082046

DeVries, B., Huang, C., Armston, J., Huang, W., W.Jones, J., & W.Lang, M., T. K. Rapid and robust monitoring of flood events using Sentinel-1 and Landsat data on the Google Earth Engine. 2020. *Remote Sensing of Environment*, Vol 240, 111664. https://doi.org/10.1016/j.rse.2020.111664

Demissie, B., Vanhuysse, S., Grippa, T., Flasse, C., & Wolff, E. Using Sentinel-1 and Google Earth Engine cloud computing for detecting historical flood hazards in tropical urban regions: a case of Dar es Salaam. 2023. *Geomatics, Natural Hazards and Risk*, 14(1). https://doi.org/10.1080/19475705.2023.2202296

Tan, J., Chen, M., Ao, C., Zhao, G., Lei, G., Tang, Y., Wang, B., Li, A. Inducing flooding index for vegetation mapping in water-land ecotone with Sentinel-1 & Sentinel-2 images: A case study in Dongting Lake, China. 2022. *Ecological Indicators*,Volume 144, 109448. https://doi.org/10.1016/j.ecolind.2022.109448.

Toté, C., Patricio, D., Boogaard, H., Van der Wijngaart, R., Tarnavsky, E., Funk, C. Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique. 2015. *Remote Sensing*, 7, 1758-1776. https://doi.org/10.3390/rs70201758

Foroughnia, F., Alfieri, S.M., Menenti, M., Lindenbergh, R. Evaluation of SAR and Optical Data for Flood Delineation Using Supervised and Unsupervised Classification. 2022. *Remote Sensing*, 14, 3718. https://doi.org/10.3390/rs14153718

Blöschl, G., Nester, T., Komma, J., Parajka, J., Perdigão G. Blöschl, T. Nester, J. Komma, J. Parajka, and Perdigão, R. A. P. The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. 2013. *Hydrology and Earth System Sciences*. Vol 17, 2013, 12, pg 5197-5212, https://doi.org/10.5194/hess-17-5197-2013

Conversi, S., Carrion, D., Norcini, A., Riva, M. Integrating optical and radar imagery to enhance river drought monitoring. 2023. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XLVIII-1/W2-2023

Belay, H., Melesse, A.M., Tegegne, G., Kassaye, S.M. Flood Inundation Mapping Using the Google Earth Engine and HEC-RAS Under Land Use/Land Cover and Climate Changes in the Gumara Watershed, Upper Blue Nile Basin, Ethiopia. 2025. *Remote Sensing*, 17, 1283. https://doi.org/10.3390/rs17071283

Bjelotomić Oršulić, O. 2025. Kupa Flood Analysis with Google Earth Engine. GitHub repository. Available at: https://github.com/obo-code/kupa_flood_analysis_gee