The Journal of High School Research

Seeing Floods from Space: How Sentinel-1 Helps Map Floods in New York City

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Submitted: 12 October 2025 **Accepted:** 15 October 2025 **Publication date:** 29 October 2025

DOI: 10.70671/bce5na79

Abstract: Flood susceptibility maps are highly effective tools for identifying and mitigating areas at risk of flooding, but they require extensive historical flood data from either in situ or remote sensing data collection. This study demonstrates how publicly available Sentinel-1 Synthetic Aperture Radar imagery can be used to generate flood maps for New York City's five boroughs. Sentinel-1 provides high spatial, geometric, and radiometric resolution, making it ideal for detecting surface water under all weather conditions. Using the European Space Agency's Sentinel Application Platform for data preprocessing and QGIS and Google Earth Pro for visualization, we processed and analyzed Sentinel-1 data to identify flood-prone zones. The results highlight Sentinel-1's effectiveness as a low-cost, reliable resource for urban flood analysis and demonstrate its potential for supporting flood monitoring and resilience planning in major metropolitan areas like New York City.

Author keywords: Urban flooding; Sentinel-1; SAR; Remote sensing; New York City

Introduction

Urban flood risks in New York City

Urban flooding is the result of the inflow of stormwater surpassing the capacity of a drainage system to permeate water into soil or carry it away.[1]

Arguably, the main cause of urban flooding is precipitation, specifically heavy rainfall, which has the greatest impact on urban flooding.[2] Rainfall intensity is vital in determining the design flow rate, a key parameter when designing drainage structures. Rainfall intensity is often accompanied by formulated relationships drawn between rainfall intensity, storm duration, and return period in intensity–duration–frequency curves. NYC's exposure to pluvial and coastal flooding is illustrated in Fig. 1.

Another cause of urban flooding is topography, particularly slope and elevation.[2] There tends to be an increase in water velocity and discharge with larger slope angles. Consequently, there is a lower mean water depth and peaks in stored runoff in areas with larger slope angles, which explains why flatter surfaces are at a higher risk of flooding. Areas low in elevation are more vulnerable to flooding. For example, urban areas 10 meters above sea level have a flood risk of 1.3%, whereas urban areas 10 meters below sea level have a flood risk 3.77 times higher than that. Areas close in elevation to the ocean or a lake are also vulnerable to storm surges, sea level rise, or regional precipitation, which make them more prone to flooding. Notably, the rate of global mean sea level rise has increased from ∼2.1 mm/year in 1993 to ∼4.5 mm/year in 2023,[3] which increases the potential for urban areas near the coast to flood.

Land features and infrastructure also have an impact on urban flooding.[2] Engineered impervious surfaces, such as sidewalks or buildings, increase the risk of flooding. Imperviousness and drainage constraints are summarized in Fig. 2. The runoff coefficient is the infiltration ability of an area and it is directly related to the peak runoff rate (water discharge). Impervious surfaces have a runoff coefficient between 0.70 and 0.95, whereas green surfaces like grass and soil range between 0.05 and 0.35. The higher runoff coefficient of impervious surfaces and the direct relationship between the coefficient and rate suggest that there is higher discharge for impervious surfaces. In particular, buildings prevent infiltration, increase runoff, and affect where and how the water flows. As a result, catch basins are crucial for rainwater to enter the sewer system. When clogged, they can be a primary

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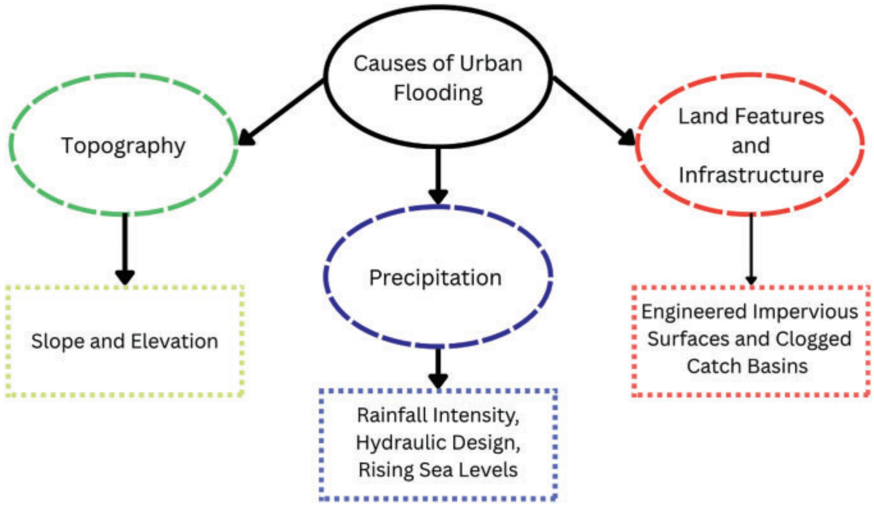

Figure 1. Causes of urban flooding

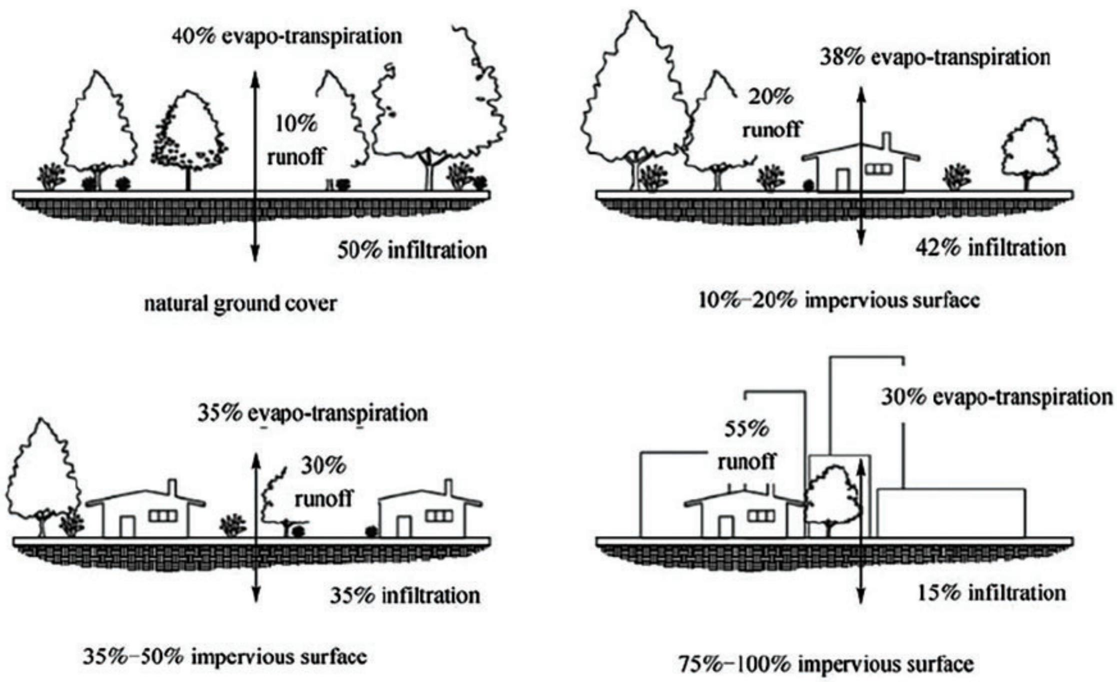

Figure 2. Impervious surface changes due to urbanization and its impact on local hydrology[2]

indicator of an incoming flash flood, making areas with less-maintained catch basins more susceptible to flash floods. Clogged catch basins remain a prevalent problem in New York City (NYC), with significant complaints reported in nearly half (47%) of the city's ZIP codes between 2010 and 2019.[2]

Need for research and impacts of urban flooding

In New York, the sea levels have risen 304.8 mm since 1900 and are projected to increase by as much as 1645.92 mm by 2100, leading to increased flooding. By the 2050s, a storm like Hurricane Sandy, with wind gusts of up to 80 mph at landfall and surging rainfall that the city was not prepared for, could cause $90 billion in economic damage, which would be nearly 5 times Sandy's impact.[4] Sea level rise for New York from 2020 to 2050 is shown in Fig. 3, derived from the U.S. Sea Level Change (2024)[5] projections.

Two particularly vulnerable groups to urban flooding are elderly people and low-income families.[6,7] Elderly people and those with limited mobility are the most vulnerable to coastal storm-related injuries and fatalities, considering how crucial a swift evacuation becomes during a flash flood.[6] Repairing a home or replacing belongings can place a significant financial strain, especially on low-income families. For instance, the damage from Hurricane Ida, during which 3.75 inches of rain fell per hour, was concentrated in Queens, Brooklyn, and the Bronx, which are populated with lower-income and immigrant communities.[7] More than a dozen people died because of basement flooding.

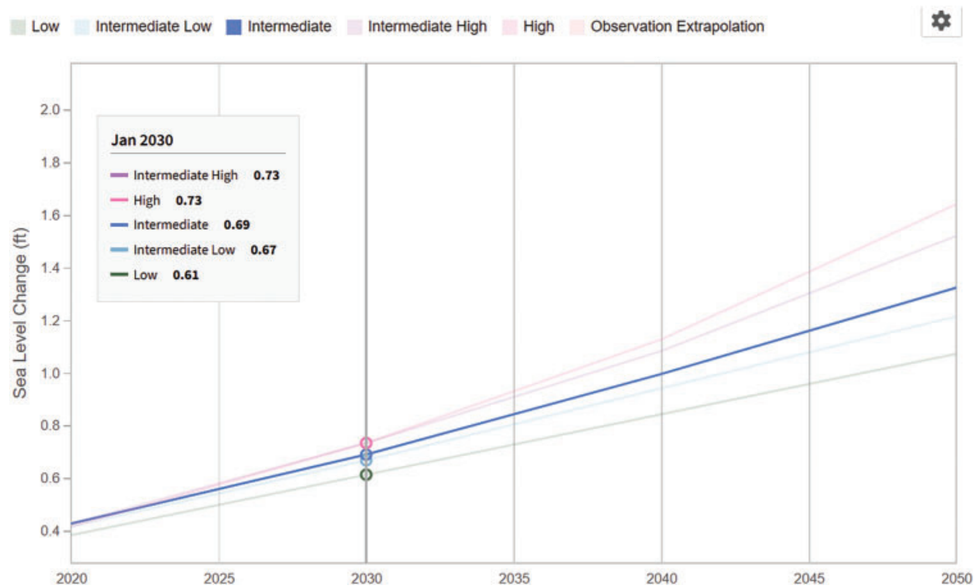

Figure 3. Sea level rise for New York from 2020 to 2050[5]

There are two methods of collecting rainfall data: in situ and remote sensing. In situ involves a direct measurement instrument, namely, a rain gauge.[2] The instrument error of a rain gauge decreases with rainfall intensity, but the distance between rain gauges is problematic, particularly for small-scale urban drainages, as the spacing issue can contribute to up to 20% of total uncertainty. Although remote sensing has certain disadvantages, such as cloud top reflectance and thermal radiance, using radar and satellite data can provide sufficient spatial distribution for rainfall estimations.

The substantial impacts of flooding and the huge risk of flooding in NYC present a need to find and create tools to prevent and map flooding in NYC. Flood susceptibility maps (FSMs) show the probability of flooding in a particular area and are one of the most effective strategies for flood prevention and mitigation.[3] Identifying the appropriate method, resolution, and parameters of data sources is crucial to obtaining reliable results. A crucial component is the analysis of past flood data to identify which areas are vulnerable to floods and to pinpoint potential improvements that can be made in areas with similar characteristics, such as slope angles and elevation.

Although physical mapping is essential in urban flood research, there is a contemporary incorporation of statistical and machine learning techniques to analyze patterns in historical data and make predictions.[2] Instead of competing these methods against each other, it is beneficial to utilize them together to solve intricate environmental problems.[4]

Potential solutions

Engineers and employees in public policy alike have proposed improvements to the city's infrastructure that would minimize the risk of severe flash flooding in vulnerable regions, thereby reducing detrimental costs from damages, and protecting the public health of NYC residents.

The combined sewer systems currently implemented in New York are able to hold 1.75 inches of rainwater and sewage water per hour, where both rainwater and sewage water are transported to a sewage treatment plant via a single pipe, see Fig. 4 for a general illustration of a combined sewer and runoff management.[7] However, when faced with heavy rainfall during severe weather events, the sewers are unable to handle the excessive water. As a result, this combined system makes flash floods and the contamination of water more likely.[9] Based on this, the Extreme Weather Response Task Force of NYC writes that it is vital to invest in an upgraded sewer system that has separate pipes for rainwater and sewage, also known as a municipal separate storm sewer system (MS4), particularly in high-risk areas with low elevation.[10] Although this upgrade process can cost up to 100 billion dollars to effectively manage and complete, these infrastructural changes can drastically improve NYC's defense against severe weather, making advocacy a crucial factor in investing in sewer infrastructure.[8]

As mentioned, the materials used in NYC's infrastructure development tend to be impervious surfaces that make it difficult for water to absorb into the surface without manifesting in a flash flood. Plus, impervious surfaces encourage the urban heat island effect because they absorb more heat, which results in hotter surface temperatures.[11] Combating the issue of the urban heat island effect in NYC and other urban areas alike remains a crucial aspect of protecting the city from flash flood events. The lack of vegetation in parts of NYC is also a major contributor to the urban heat island effect. A way to combat both flash flooding and the urban heat island effect has been the implementation of rain gardens that would work to collect and manage stormwater that are on the sidewalks.[12] However, these rain gardens are currently limited in development and may not cover all areas that are susceptible to flooding, especially when looking at locations near low-elevation shorelines.[12] This connects to socioeconomic segregation because, as evidenced by multiple

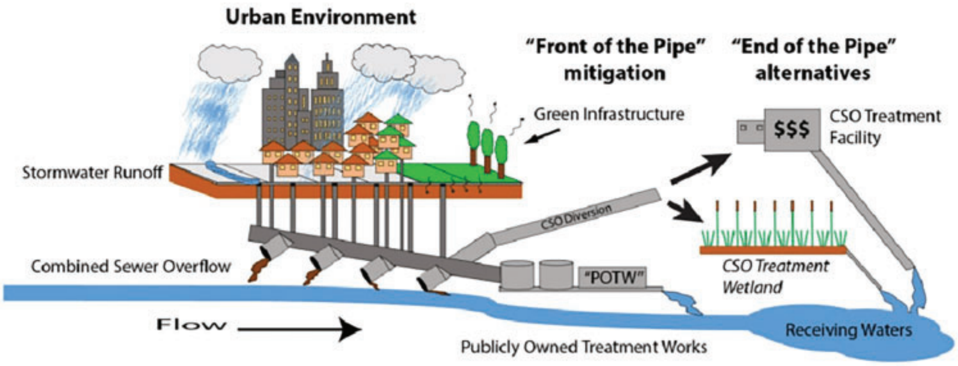

Figure 4. Process diagram illustrating urban runoff and combined sewer overflow management[13]

urban areas, lower-income residents are more susceptible to the urban heat island effect alongside flash flooding.[14]

Government officials have made strides to invest in flood warning systems across NYC that would prevent fatalities and injuries and protect assets from being damaged during a flash flood.[15] In contrast, a flood with a delayed warning would cause more damage to people and their property. Simultaneously, providing grants and funds for flash flood research can improve the predictability of flash floods caused by severe weather.[16] As previously mentioned, FSMs can be used to directly identify high-risk flood areas based on previous outcomes of severe weather. With this data, infrastructure improvements that prevent flooding can be concentrated in those areas, benefiting the city both economically and humanely.

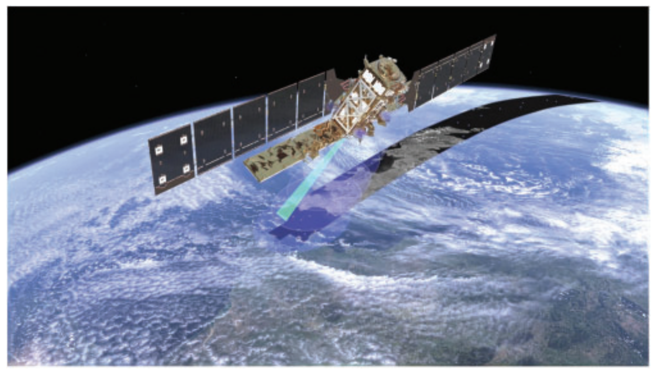

Figure 5. Sentinel-1 detects maritime traffic[19]

Description of Sentinel-1

Sentinel-1 (Fig. 5), according to the GMES Sentinel-1 mission, is a polar-orbiting, two-satellite constellation that routinely operates all day via conflict-free, 6-day exact operations with a medium resolution of 10 m for observations.[17] The majority of its products aim to improve the quality of emergency response systems, marine surveillance, sea-ice monitoring, and the detection of subsidence and landslides. The products of Sentinel-1 are publicly available through the Copernicus Browser in Level-0 (raw data), Level-1 (complex SLC imagery for interferometric applications + ground range detected geo-referenced imagery, GRD), and Level-2 (geolocated geophysical products, specifically ocean products with data including wind and waves), within four modes of operation and four polarization channels (Sentinel-1 Burst ID Map).

As shown in Fig. 6, the four different modes of operation found within Sentinel-1 data collection vary in swath width and geometric resolution. The most common is Interferometric Wide-swath mode (IW) with a 250 km swath width and a high geometric resolution of 5 m × 20 m. It is equipped with a ScanSAR mode for progressive azimuth scanning and TOPSAR (Terrain Observation by Progressive Scan) to harmonize performance and reduce the radar scalloping phenomenon.[18]

Wave mode (WV) captures vignettes of 20 km × 20 km size with a 5 m × 5 m ground resolution in intervals of 100 km, with a low bit rate through a unique single-polarization mode (HH or VV), while others use dual polarization. Strip Map mode maintains a 5 m × 5 m resolution and a swath of 80 km, which ultimately cover access ranges of up to 375 km. During each swath, the antenna is configured to generate a beam of fixed azimuth and elevation pointing. Extra Wide-swath mode has a swath of 400 km at a medium resolution of 20 m × 40 m, which is, once again, equipped with ScanSAR fast beam elevation scanning and TOPSAR. For the purposes of flood research in NYC, using Sentinel-1 Level-1 GRD data, IW operational mode, and VV + VH amplitude polarization channels will be used.

Sentinel-1 works by measuring and reflecting Synthetic Aperture Radar (SAR) energy to determine the radar cross section in decibels, which can be used to identify land cover types and severe weather events like floods in a process called interferometry, where waves are overlapped and information is extracted. The satellite requires internal and external calibration, culminating in more accurate satellite imagery, making it an extremely high-resolution, high geometric, and high radiometric resolution satellite. Internal calibration follows a process that sends a radar pulse to its own receiver and assesses changes in amplitude in order to readjust itself. External calibration defects outliers and dictates proper radar signaling for those areas. If there is an inconsistency in radar signaling, its constant is recalculated to accommodate. With a life cycle of 15–20 years, the satellite's quality of

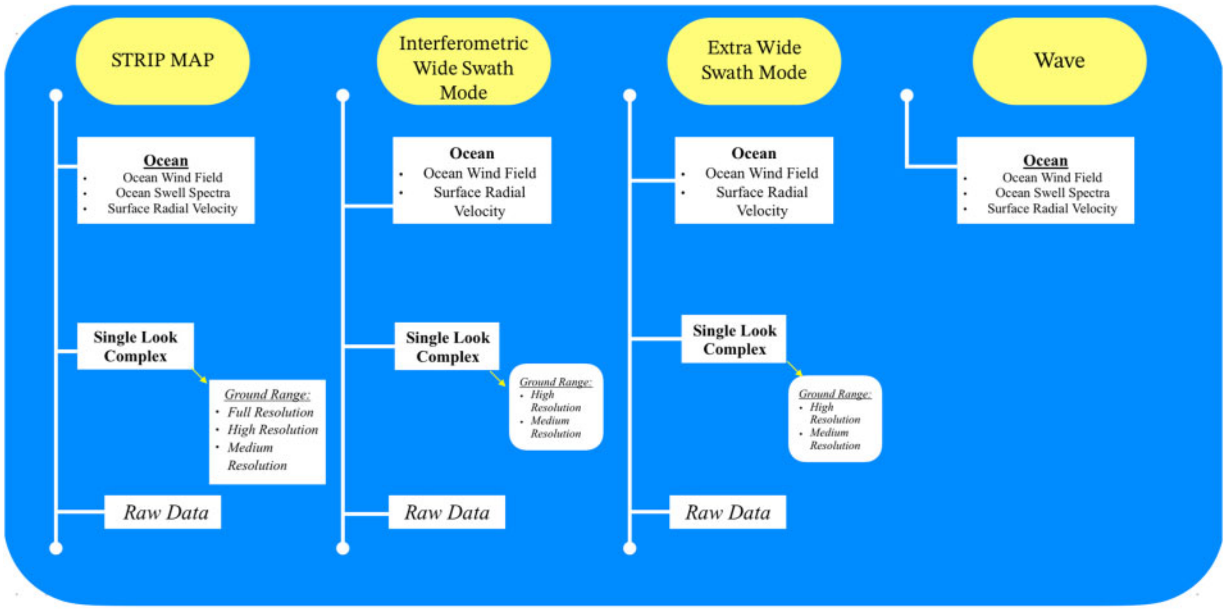

Figure 6. Sentinel-1 data products[19]

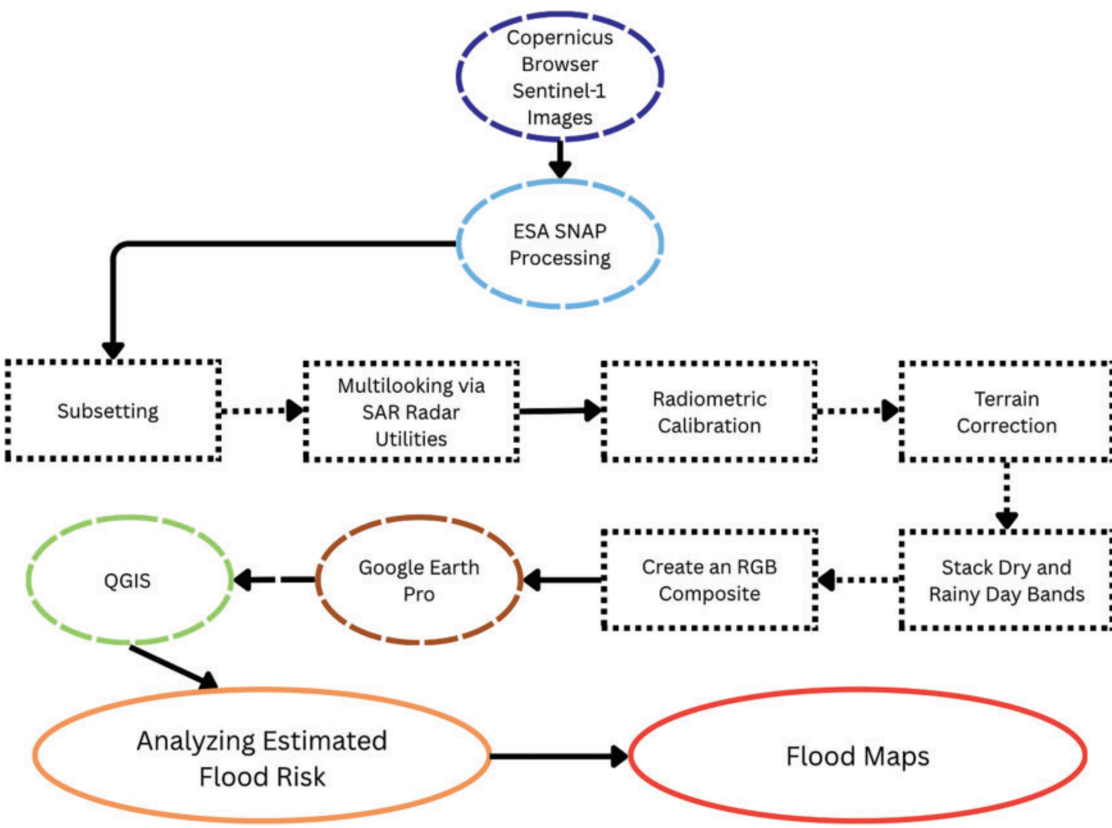

Figure 7. Methodology to create processed Sentinel-1 images

products may decay over time due to the weakening potential to send/receive signals and carry out proper calibration protocols.

For our data collection purposes, accessing the publicly available data provided by the European Space Agency (ESA) is vital to our methodology and flood research, making this aspect of Sentinel-1 unique compared to privately owned satellites that may restrict data behind a paywall or require advanced permissions.

It is well established that Sentinel-1 data products have effectively helped researchers create flood maps for certain regions, such as Morocco.[20] However, these studies have not been conducted in NYC, where urban flooding is a crucial problem. The primary goal of our study was to determine whether the Sentinel-1 satellite's data products can be used to detect urban flooding in NYC.

Methodology

Copernicus browser Sentinel-1 data

The end-to-end preprocessing workflow is presented in Fig. 7. Data collection was a matter of accessing the ESA Copernicus Browser, where the public can freely access Sentinel satellite data. For the purposes of flood research, we used Sentinel-1 data sources for its radar imagery capability, specifically Level-1 GRD. Products were to be delivered immediately upon request without further processing times for data access. Our polygonal area of interest was limited to the five boroughs of NYC, but the satellite would focus on a larger area, which would provide a satellite reading area of 43613.20 km^2. Time observation dates were within 1 day after the flood for the data source from March 24, 2024, where there was a total of 2.9 inches of rainfall recorded on the previous day.[21] We picked a data source on the day of the flash flood for July 16, 2023, where there was 1.7 inches of rain, making for a significant comparison in the resulting flood outlook made visible by the Sentinel-1 satellite.[22] A summary of all Sentinel-1 scenes is provided in Table 1.

Table 1. Sentinel-1 data summary

S-1 scene	UTC	EDT	Rainfall within the last 24 h
2024-03-24	22:51:30	18:51:30	2.9 in
2023-07-16	22:51:31	18:51:31	1.7 in

ESA SNAP

Sentinel Application Platform (SNAP) (version 11) was developed by the ESA[23] for visualizing Sentinel data and was a crucial tool in visualizing the floods.

Subsetting the image

We narrowed our area of interest to NYC by subsetting the initial raster GeoTIFF layer to make our data clearer and increase the speed of preprocessing.

Multilooking through SAR radar utilities

Multilooking a SAR image is crucial for reducing the speckle noise present in the image to improve the resulting visualization and analysis.[24] SNAP is able to carry out the multilook method through space-domain averaging, where the SAR image is a single-look complex image averaged with a small sliding window. Furthermore, selecting the number of range and azimuth looks is based on a GR square pixel, where the range look value for our purposes is 3, while azimuth looks are set to the default value of 5.

Radiometric calibration

In order for these SAR images to be acceptable for quantitative use, calibration of the image, where pixel values are related to radar backscatter, is crucial.[24] SNAP is able to perform this through simple radar calibration to ensure that radiometric bias is kept to a minimum, improving the visual interpretability of the SAR images. Once completed, convert the bands from linear to decibels.

Terrain correction

We performed terrain correction to correct geometric distortions due to the perspective of the sensor view angle and ground terrain.[24,18] The algorithm traverses each grid cell in the Digital Elevation Model (DEM) to simulate the SAR imagery with the DEM. The simulated and original SAR imagery are co-registered, and a WARP function maps the simulated SAR imagery to the original SAR imagery in its corresponding position. The algorithm computes its corresponding pixel position in the simulated SAR imagery for each cell in the DEM grid. Using the WARP function, the corresponding pixel position in the original SAR image can be found, which allows the algorithm to obtain the pixel value for the orthorectified image using interpolation.[25]

Stack the dry day and rainy day bands

To effectively see the flooded areas in our SAR images of NYC, we need to co-register the two products by stacking them. Here, we used the Create Stack operator where the flood day SAR image is resampled to share the same geographical information and dimensions as the dry day SAR image.[24] Immediately after, ensure that the bands are still measured in decibels.

Create an RGB composite

The final step for SNAP preprocessing is to overlay a color map that integrates three separate bands, which indicate different prominent geographic features, into a single GeoTIFF file. Band assignments and color interpretation are listed in Table 2.

QGIS

QGIS (version 3.44) is a widely used free and open-source software for visualizing geographic data. For our purposes, QGIS was used to present flood maps processed in SNAP in a concise and informative manner, with a proper title, appropriate legend, and scale, along with a compass indicating the north direction following the corrected terrain.

Results

We researched two floods, occurring on July 16, 2023, and March 24, 2024 with a substantial amount of rain, flood maps of both days are shown in Figs. 8 and 9, respectively. Table 2 outlines how each color band in the flood maps corresponds to specific surface or flooding conditions.

Fig. 10 shows a flooded portion of Staten Island, specifically Freshkills Park in Staten Island, which was converted from a landfill into a park.[26,27] The red band represents flooded regions 5 hours after it rained. Around $2 million was invested in this area to convert it into a park, but Freshkills Park gets flooded easily. Fig. 10 shows a substantial part of the park being flooded along the waterways. This persistent flooding raises concerns about the long-term viability and cost-effectiveness of the investment. Each flooding event not only damages park infrastructure but also disrupts recreational use and poses environmental risks, such as soil erosion and water contamination.

The central areas of NYC are situated at a higher elevation compared to the surrounding coastal regions. Additionally, the city has mostly impervious surfaces such as concrete,

Table 2. Band representation

Band color	Flood difference
Red band	Red indicates areas with a decrease in backscatter on the flooded day, consistent with *smooth water surfaces* detected by SAR. This decrease typically **represents surface water flooding.**
Blue band	Blue indicates areas with an increase in backscatter on the flooded day, consistent with *rough surfaces* detected by SAR. This increase typically represents **land cover/structural changes.**

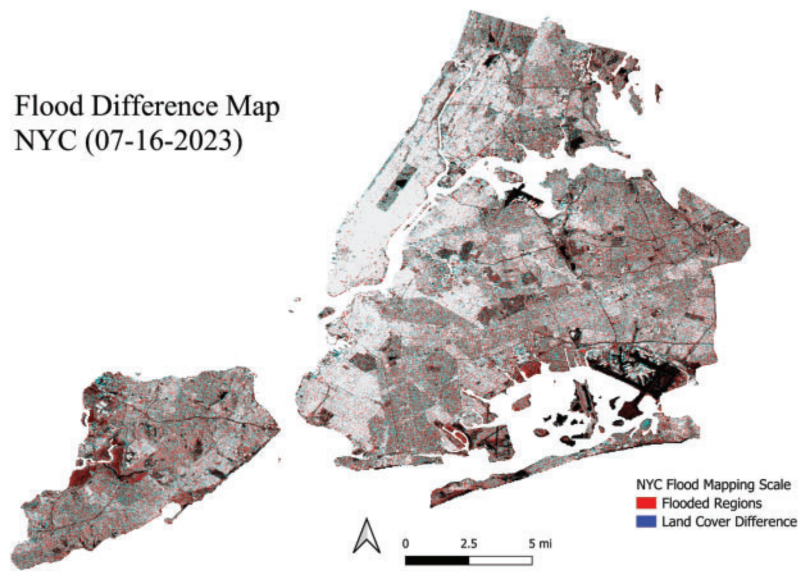

Figure 8. Flooded areas in 5 boroughs of New York City on July 16, 2023

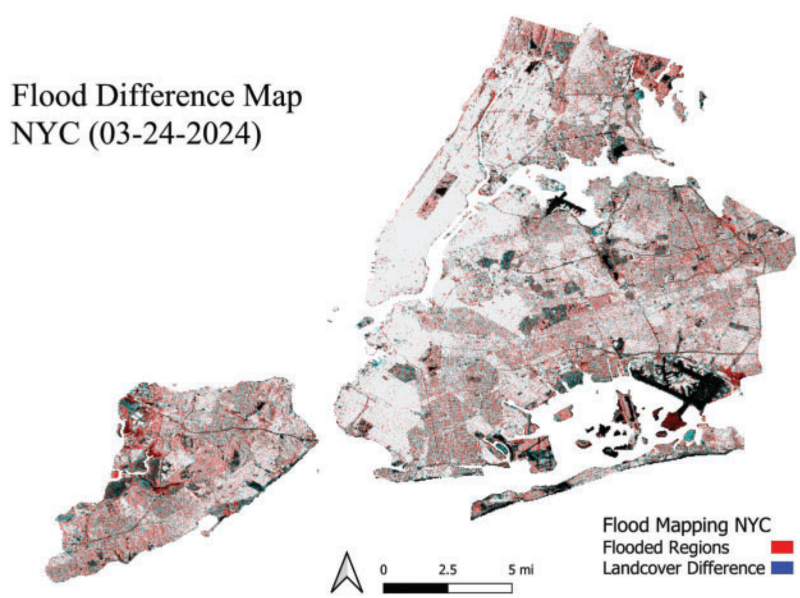

Figure 9. New York City on March 24, 2024

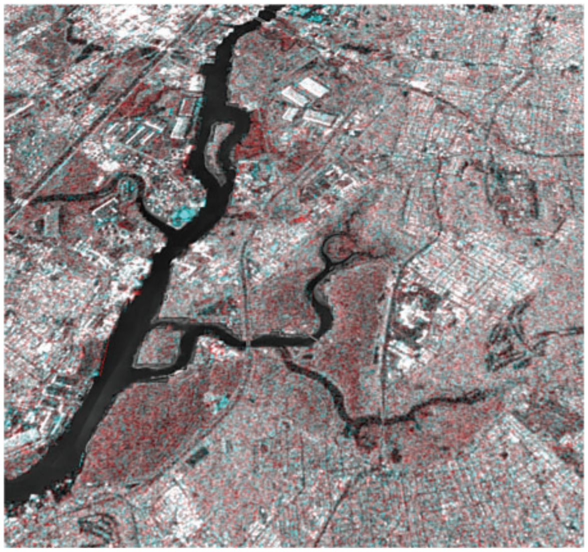

Figure 10. Staten Island on July 16, 2023

asphalt, and buildings, which result in a higher water runoff rate toward lower elevations. As previously mentioned, this runoff significantly increases the risk of flooding in coastal and low-elevation zones. About 30% of NYC is covered by an MS4 drainage system, which makes flood management in these areas more difficult. Additionally, flooding in these areas may result in water contamination and raise health concerns, as the sewage and drainage systems are combined.[9]

Fig. 9 shows flood detection results for NYC on March 24, 2024, based on Sentinel-1 imagery acquired at 6:51 PM EST on March 23, 2024. Rainfall data from March 23, 2024, indicate consistent precipitation from 5:00 AM to 3:00 PM, increasing from 0.163 inches per hour to 0.559 inches per hour and totaling approximately 2.943 inches over a 10-hour period.[28,29] This sustained rainfall was expected to cause localized flooding; however, the SAR acquisition occurred approximately 30 hours after peak rainfall, potentially reducing visible inundation in the radar imagery as water either drained or evaporated.

Our flood detection map for March 24, 2024, reveals inundation primarily in coastal and low-lying regions such as Freshkills Park in Staten Island (shown in Fig. 11) and the Jamaica Bay area in Brooklyn. These regions exhibited pronounced decreases in backscatter intensity, suggesting the presence of residual surface water. In contrast, higher-elevation and densely built areas, including Manhattan and the Bronx, displayed minimal flood signatures, likely due to efficient drainage and rapid surface runoff from impervious materials such as concrete and asphalt, which prevented prolonged surface water accumulation detectable by SAR.

The flood maps demonstrate Sentinel-1's sensitivity to subtle surface changes in complex urban environments. These observations validate the satellite's capability to detect flooding patterns in NYC, even with delayed acquisition times. The resulting SAR flood layers generated through our processing form the basis for the subsequent comparison and validation in the Discussion section.

Discussion

We validated these satellite images signaling a flood through news articles covering the floods that occurred on that day. On March 24, 2024, it was found to be the third wettest March day in NYC history.[30] Additionally, roads were severely flooded, leaving drivers stranded and in need of rescue.[31] On July 16, 2023, the rainy outlook was predicted on the same day and addressed by Kathy Hochul, with copious amounts of rain expected to fall on the city, resulting in major flooding in the borough of Brooklyn.[32]

To further validate our SAR-derived flood observations, we compared the March 24, 2024, Sentinel-1 flood extent with FEMA's Preliminary Flood Insurance Rate Maps for NYC, as shown in Fig. 12. The comparison showed that areas exhibiting decreased backscatter in our SAR-derived map, most notably the shoreline zones of Jamaica Bay and nearby low-lying neighborhoods such as Howard Beach and Spring Creek Park, aligned with FEMA's designated V and A flood risk zones (1% annual-chance flood areas). The correspondence between our observed inundation signatures and these modeled high-risk zones confirms that Sentinel-1 detects water residue in the same vulnerable geographies highlighted by FEMA's long-term hydrological modeling. This comparison supports the credibility of SAR-based flood detection and demonstrates that Sentinel-1 can serve as a near-real-time complement to existing flood risk mapping systems.

This study, while demonstrating that Sentinel-1 can successfully detect floods when properly preprocessed and displayed, did expose weaknesses in Sentinel-1's data collection frequency and how these weaknesses can make Sentinel-1 ineffective in producing enough data for accurate flood prediction. As mentioned before, Sentinel-1 routinely passes by NYC every 6 days, which can make it difficult to obtain data for certain major meteorological events that are not within Sentinel-1's reach of NYC; however, Sentinel-1's 6-day cycle allows relatively consistent observation for a year-long period. The spaced-out periods make Sentinel-1 efficient for observing topographic changes by month. There are geostationary satellites that are consistently pointed at the continental United States, such as NASA's GOES series, which sound accurate in theory until the loss in resolution is considered, and come with a satellite further from the surface of the Earth.

In terms of materials and methodology, we came to realize that QGIS, a program considered crucial for analyzing Sentinel-1 flood maps, was not integral to our final process in analyzing NYC flood data. After encountering error screens and indefinite GeoTIFF loading sequences, our team took a different approach to comparing Sentinel-1 satellite data with actual terrain features seen in NYC to identify high-risk areas. The majority of the visualization took place in Sentinel-1's signature software, SNAP, combined with comparison and analysis using Google Earth Pro, which proved far more efficient than our previous attempts in QGIS. QGIS's role was minimized to simply masking the five boroughs and creating a proper GIS map format of the flood data.

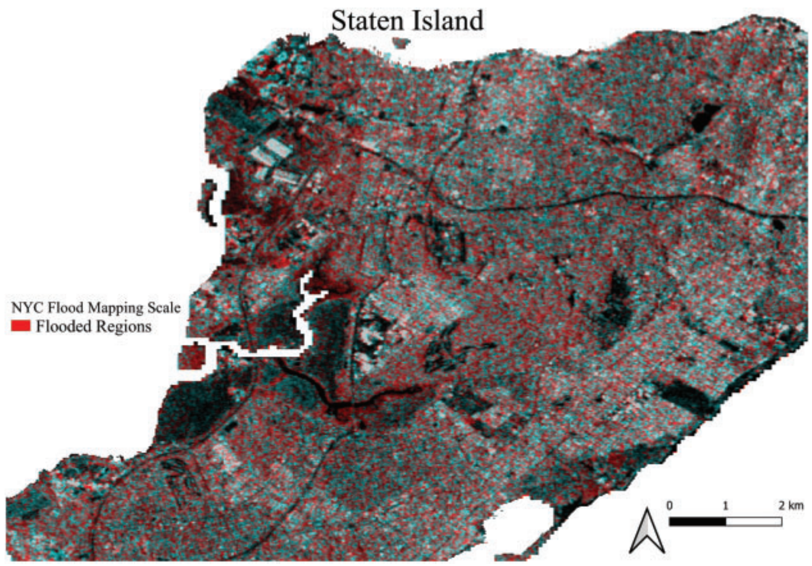

Figure 11. Staten Island on March 24, 2024

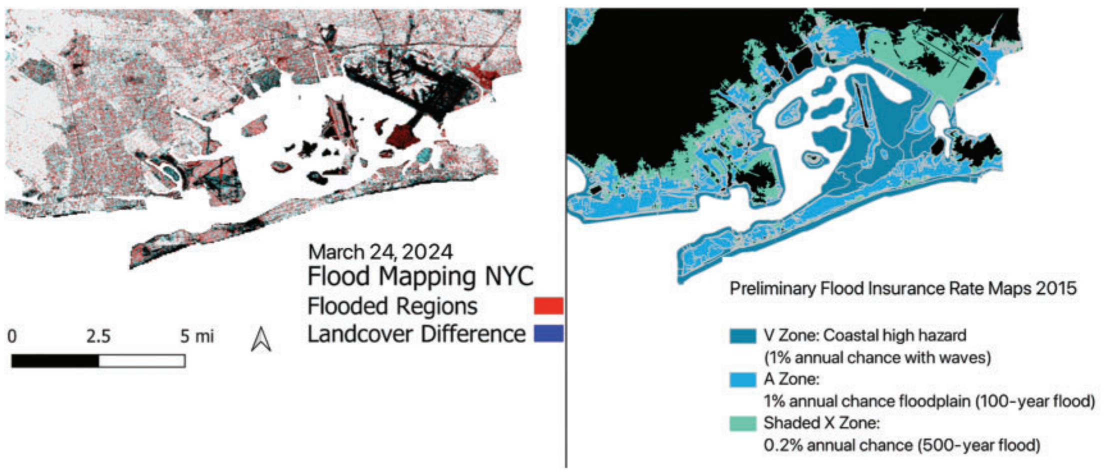

Figure 12. Comparison of Sentinel-1 SAR flood mapping results (March 24, 2024) with FEMA's Preliminary Flood Insurance Rate Map (FIRM) for New York City, obtained from the NY.gov ArcGIS Flood Hazard Viewer

A similar study was conducted in Morocco in 2020 using Sentinel-1 satellite data, further proving the versatility of the satellite regarding its ability to obtain datasets from across the globe.[20] Their method for the final analysis to visualize vulnerable flood areas was to use backscatter coefficients of the various Inaouene watershed floods, where lower values are equal to water and high values are equal to non-water areas, to isolate areas that have been flooded. Despite the slightly differing methodology, both processes ultimately lead to similar results where the presence of a flood is proved both visually and analytically.

Conclusion

We obtained data products from Sentinel-1 through ESA's publicly available Copernicus Browser directory. Then, the satellite's personalized SNAP software was used to preprocess the images and highlight the flooded areas for the respective dates on the data products were obtained, using RGB bands and image stacking. Once fully preprocessed, comparisons were made between the red, high-risk flooded areas that we visualized in Google Earth Pro.

Sentinel-1 has immense potential to provide high-quality data for flood mapping in New York. Future work may involve combining the data from Sentinel-1 with contemporary methods in flood mapping, such as statistical analysis and machine learning, to prevent and minimize the damage of floods. Additionally, optical sensors could be implemented to enhance the temporal resolution of Sentinel-1. Overall, Sentinel-1 serves as a proper foundation, indicating how future satellites can be used to mitigate the impacts of floods.

Acknowledgements

Our deepest gratitude is extended to Prof. Naresh Devineni for his guidance during the project. We also wish to thank the Director of CUNY CREST HIRES, Dr. Shakila Merchant, and the United Nations University (UNU) Hub on Remote Sensing and Sustainable Innovations for Resilient Urban Systems (R-SIRUS) at The City College of New York for making this research possible and for providing accessible engineering education to students across NYC.

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