FLOOD RISK MODELING IN THE SAW MILL RIVER WATERSHED

Report to the Saw Mill River Coalition and Westchester County
September 2023

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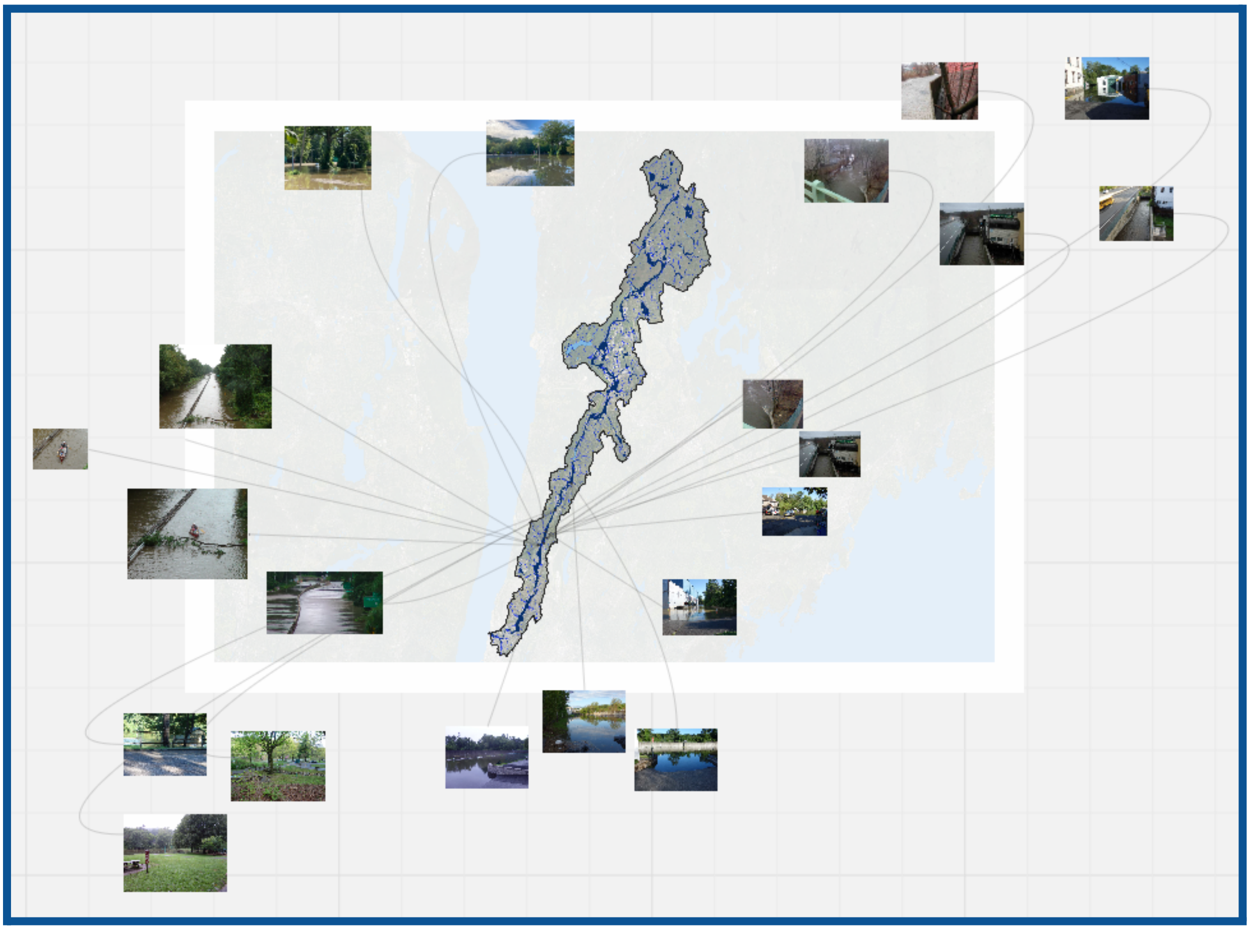

Observations of flooding in the Saw Mill River Watershed

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Introduction

This Saw Mill River Watershed Flood Vulnerability Modeling Project was developed by the Saw Mill River Coalition (SMRC) to make progress on one of the top priorities in its recently approved 5-year Watershed Action Plan[1], a document that was completed in 2020 with support from the New York State Hudson River Estuary Program (HREP). It is specifically intended to help the watershed community prepare for the consequences of a warmer, wetter, and more extreme climate and potential catastrophic flooding associated with anticipated regional and global atmospheric changes (USGCRP, 2018). The analysis provided here was conducted by The New School's Urban Systems Lab (USL) and supported by a grant from HREP.

The initiative has two main objectives:

- One, is to identify areas most likely to be impacted by rising amounts of precipitation in the future due to climate change and to model the hydrodynamics of the site;
- And second is to use that analysis to formulate land-use plans that can mitigate long-term flood risks around these areas while also achieving the habitat, water quality, public access, environmental justice, and education goals of the SMRC.

Not only will it provide timely information to watershed towns to increase awareness and preparedness for such risks, but it will also generate key planning documents that can be used to secure funding for urgent flood management and riparian restoration efforts.

The SMRC was organized by the nonprofit Groundwork Hudson Valley (GWHV) more than 20 years ago to champion the restoration of the Saw Mill River Watershed, a 25-mile watershed in Westchester County, NY, just north of New York City. The collective effort was greatly needed because the Saw Mill River (SMR) has been historically one of the most impaired tributaries to the Hudson River and is also one of the most culturally important waterways to the development of Westchester County in the 19th and 20th centuries (Groundwork Hudson Valley, 2019; USGS, 1984). Moreover, the stream meets the Hudson River in the environmental justice (EJ) community of Southwest Yonkers which ultimately receives the bulk of the watershed's upstream pollution and impairments. Over the last two decades, the SMRC has involved all of the key stakeholders in its watershed work, among them 12+ political jurisdictions, including the City of Yonkers, the third largest city in New York State; along with Westchester County's Department of Environmental Planning; various County legislators such as David T. Imamura currently whose district lies across the watershed; the U.S. Fish & Wildlife Service, a regional and national partner with GWHV; and many other leading nonprofits, businesses, school districts, and affordable housing providers around the river. Major SMRC achievements include the daylighting and ecological

[1] Groundwork Hudson Valley (2020). Saw Mill River Coalition 5-Year Action Plan 2020. Retrieved from https://www.groundworkhv.org/programs/climate-resilience/saw-mill-river-coalition/coalition-documents/

restoration of the Saw Mill River in downtown Yonkers, the annual Great Saw Mill River Clean Up, the eradication of acres of invasive plants and the corresponding restoration of the riparian corridor with thousands of native trees and shrubs. Other achievements also include the construction of extensive public access trails, and the formation of many active stewardship groups. In addition, the Green Team, GWHV's highly regarded paid urban conservation corps involving youth from the EJ community of Southwest Yonkers, has been involved in many of the aforementioned accomplishments.

To build on this great work, the SMRC received a grant from the HREP to chart a path forward in a new era of climate change. The funding led to two strategic planning documents: A State of the Watershed Report (SOTW) and an updated 5-year Action Plan in 2020. Although flooding has plagued the watershed for more than a century, it became clear in this updated, strategic planning process that these concerns remain a top agenda item for most SMRC members. As described in the SOTW (2019):

> "*Stormwater management is a core issue in the effort to restore the health of the SMR. Not only is the issue of stormwater the direct cause for one of the most urgent problems impacting communities throughout the watershed, recurrent flooding events, but it also has a direct impact on issues such as water quality, habitat, and access. Improving stormwater management is even more crucial given the impact of climate change. More and more, extraordinary weather events are becoming the norm in Westchester County. Nor'easters, tropical storms, and severe thunderstorms have deluged Westchester with greater frequency and intensity. With intense development throughout the watershed, and specifically along the SMR floodplain, permeable surface is becoming rare, resulting in increasing flow levels in the river and more flooding, bank erosion, low filtration, and the deterioration of sewer utilities.*"

Thus, we aim for this project to support the SMRC and its partners to better assess these rising flood risks in order to begin proactively taking action to mitigate and adapt to them. It builds on research carried out over the last few years by the USL in partnership with GWHV to assess flood vulnerabilities in EJ areas of Southwest Yonkers based on projected increases in rainfall in the future. It expands and modifies that methodology to other areas in the SMR basin, with some limitations, given the much broader geography of the whole watershed and the limits of grant funding.

1. The Saw Mill River Watershed

The history of land use changes in the Saw Mill River Watershed in Westchester County, New York State is marked by a complex interplay between urbanization, industrialization, and subsequent efforts to restore and protect the natural environment. The Saw Mill River is a tributary of the Hudson River and extends 23.5-miles (37.8 km) through southeastern New York, primarily flowing through Westchester County. It begins as a small stream in Chappaqua and winds its way south through several communities before eventually emptying into the Hudson River in Yonkers, NY. The Saw Mill River Watershed partially covers areas of the municipalities of Mount Pleasant, Greenburgh, Yonkers, New Castle, Ardsley, Dobbs Ferry, Elmsford, Hastings-on-Hudson, Irvington, Pleasantville, Sleepy Hollow, and Tarrytown (Figure 1) . A large portion of the watershed is within dense urban or suburban areas (approximately 63%) with only 34% of the land area designated forest, and 1% agricultural lands.

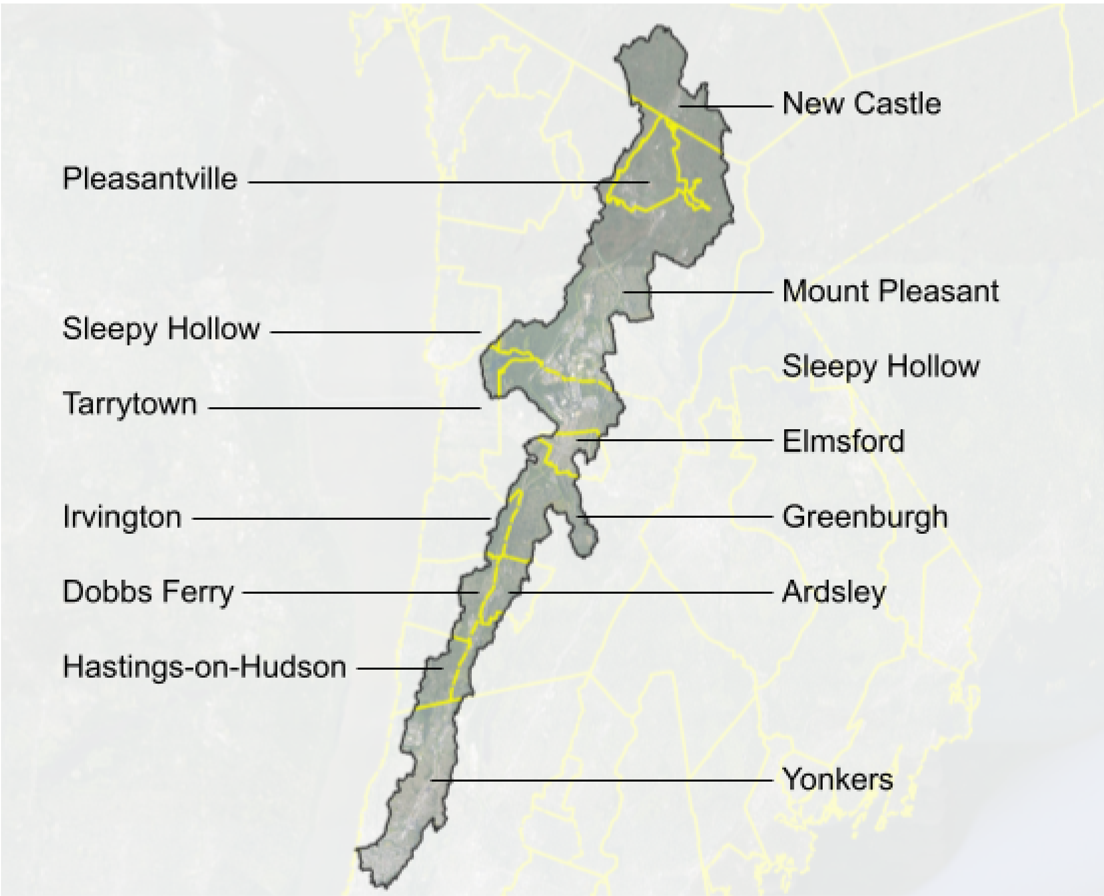


Figure 1: Municipalities that intersect with the outline of the Saw Mill River's Watershed.

Throughout its course, the Saw Mill River has been subject to various environmental challenges, including pollution and urban development. However, there have also been efforts to restore and protect the river's ecological health, such as daylighting sections that were previously buried and implementing green infrastructure to manage stormwater runoff. These initiatives aim to enhance the river's natural flow and improve its water quality for the benefit of the communities along its path. At the same time, concerns about environmental justice and equitable access to clean and healthy environments have been raised in recent years. Initiatives to address environmental disparities and ensure equal participation in environmental decision-making have gained attention. Over the past decade there have been various actions taken to address flooding and environmental hazards in the Saw Mill River Watershed in New York.

2. Land Use and Social Vulnerability

According to the 2020 US Census, there are 177,819 people living in the watershed's boundary. Additionally, there are 37,738 housing units within the Saw Mill River Watershed. The majority of residential parcels are single-family dwellings (79.4%), followed by two-family homes (12.4%) and the remainder multi-family apartments and three-family parcels.

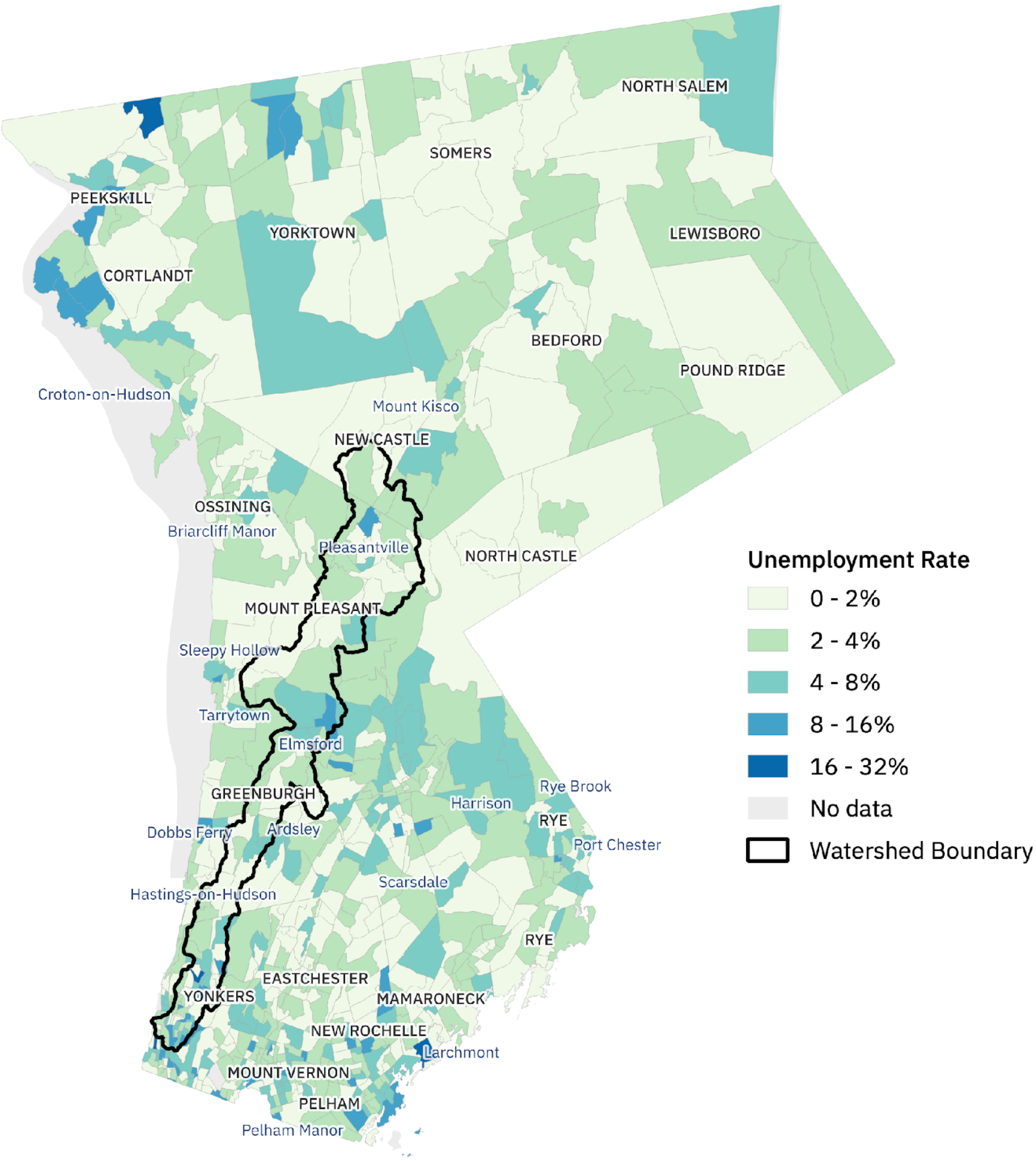
Table 1. Residence Type and Percentage in Saw Mill River Watershed

Type	Dwellings	Percentage
Total residential	20,299	100%
Single-family	16,048	79.06%
Two-family	2,584	12.73%
Three-family	764	3.76%
Multi-family	838	4.13%
Multi-use	14	0.07%
Condominium	27	0.13%
Rural residence	4	0.02%
Estate	14	0.07%
Homes for the aged	6	0.03%

Certain variables are key to investigating social vulnerability to flooding in a watershed. For this study, we focus on a subset of variables included in the Center for Disease Control's Social Vulnerability Index (SVI). Variables include race and ethnicity, income and poverty status, disability, and health insurance coverage. Each variable was examined at the census block group level for the entire county and for the watershed.

Table 2. Social Demographics of Saw Mill River Water and Social Vulnerability Index Variables

Social Demographic	**SVI and Exposure Variables**
45.2% White	Median Per Capita Income: $51,392.5
12.3% Black	8.4% Below Poverty
31.2% Latinx	5.5% w/o Health Insurance
7.6% Asian	27,769 Buildings
0.1% Indigenous	3.0 mi^2 road area
0.05% Islander	


NORTH SALEM
SOMERS
PEEKSKILL
YORKTOWN
LEWISBORO
CORTLANDT
BEDFORD
POUND RIDGE
Croton-on-Hudson
Mount Kisco
NEW CASTLE
OSSINING
Briarcliff Manor
Pleasantville
NORTH CASTLE
MOUNT PLEASANT
Sleepy Hollow
Tarrytown
Elmsford
GREENBURGH
Rye Brook
Harrison
RYE
Dobbs Ferry
Ardsley
Port Chester
Scarsdale
Hastings-on-Hudson
RYE
EASTCHESTER
YONKERS
MAMARONECK
NEW ROCHELLE
Larchmont
MOUNT VERNON
PELHAM
Pelham Manor
Unemployment Rate
0 - 2%
2 - 4%
4 - 8%
8 - 16%
16 - 32%
No data
Watershed Boundary

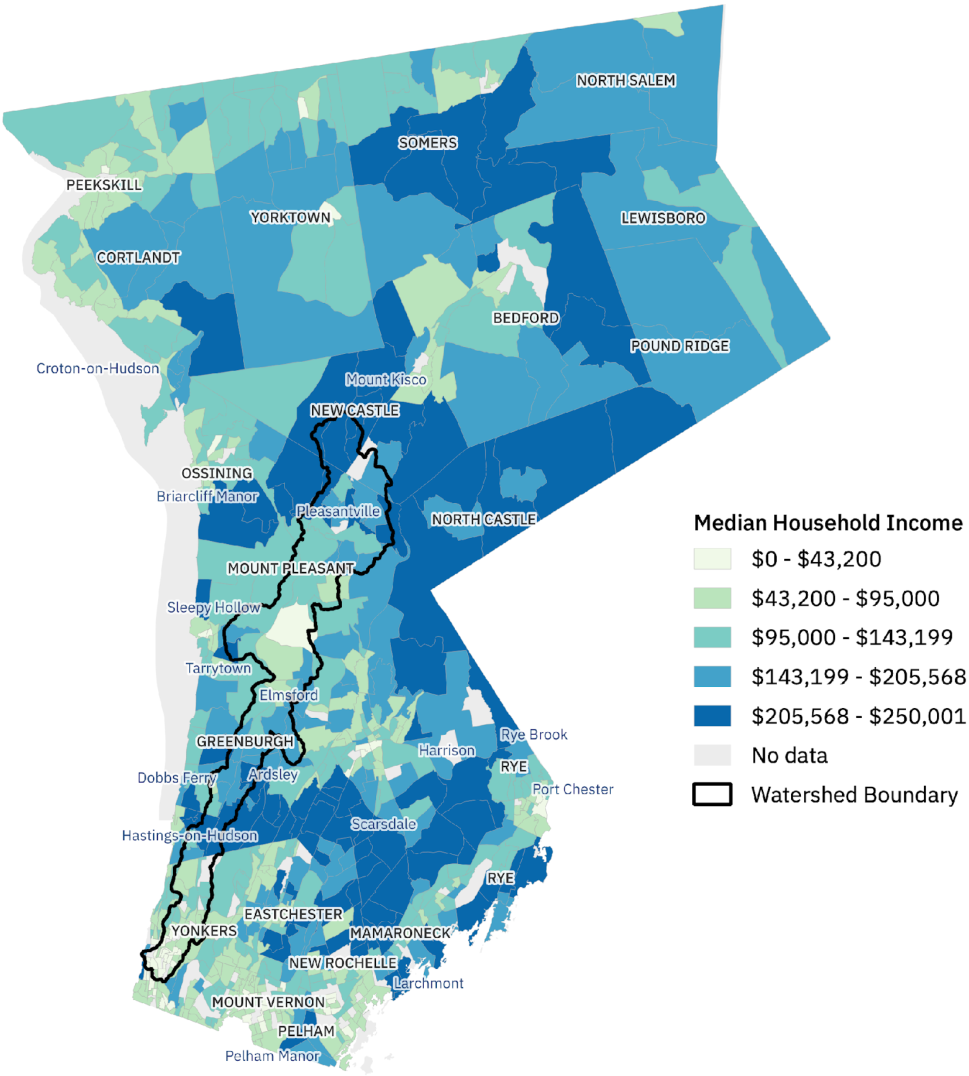


Figure 2. Unemployment Rates (top) and Median Household Income (bottom) for Westchester County with Saw Mill River Watershed Delineated with Black Boundary. Source: 2020 US Census

Using selected SVI indicators on race/ethnicity and income, we can identify what the US Environmental Protection Agency classifies as Potential Environmental Justice Areas (PEJAs) for the watershed region. PEJAs are U.S. Census block groups of 250 to 500 households that meet or exceed minority and poverty rate thresholds[2].

[2] New York State Department of Environmental Conservation. (n.d.). Maps & Geospatial Information System (GIS) Tools for Environmental Justice—NYS Dept. Of Environmental Conservation. Retrieved September 13, 2023, from https://www.dec.ny.gov/public/911.html

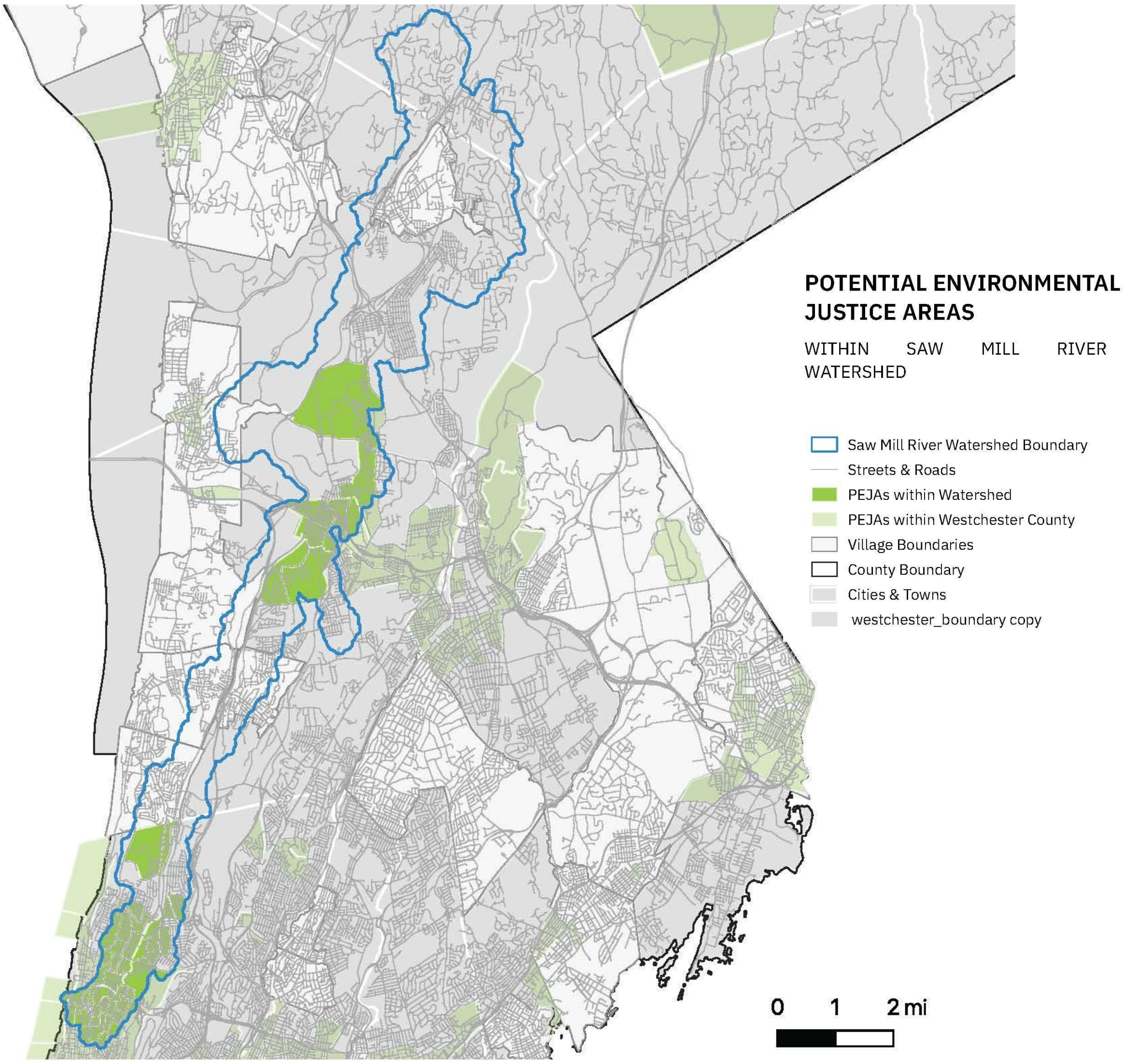


Figure 3. Potential Environmental Justice Areas (PEJAs) for the Saw Mill River Watershed region

In addition to PEJAs, New York State uses various SVI indicators to identify Critical Environmental Areas (CEAs), defined by New York's State Environmental Quality Review (SEQR) regulations as geographic areas with "exceptional or unique character" related to:

- human health
- social, cultural, agricultural, educational values
- ecological, geological, or hydrological sensitivity
- natural settings with important aesthetic qualities.

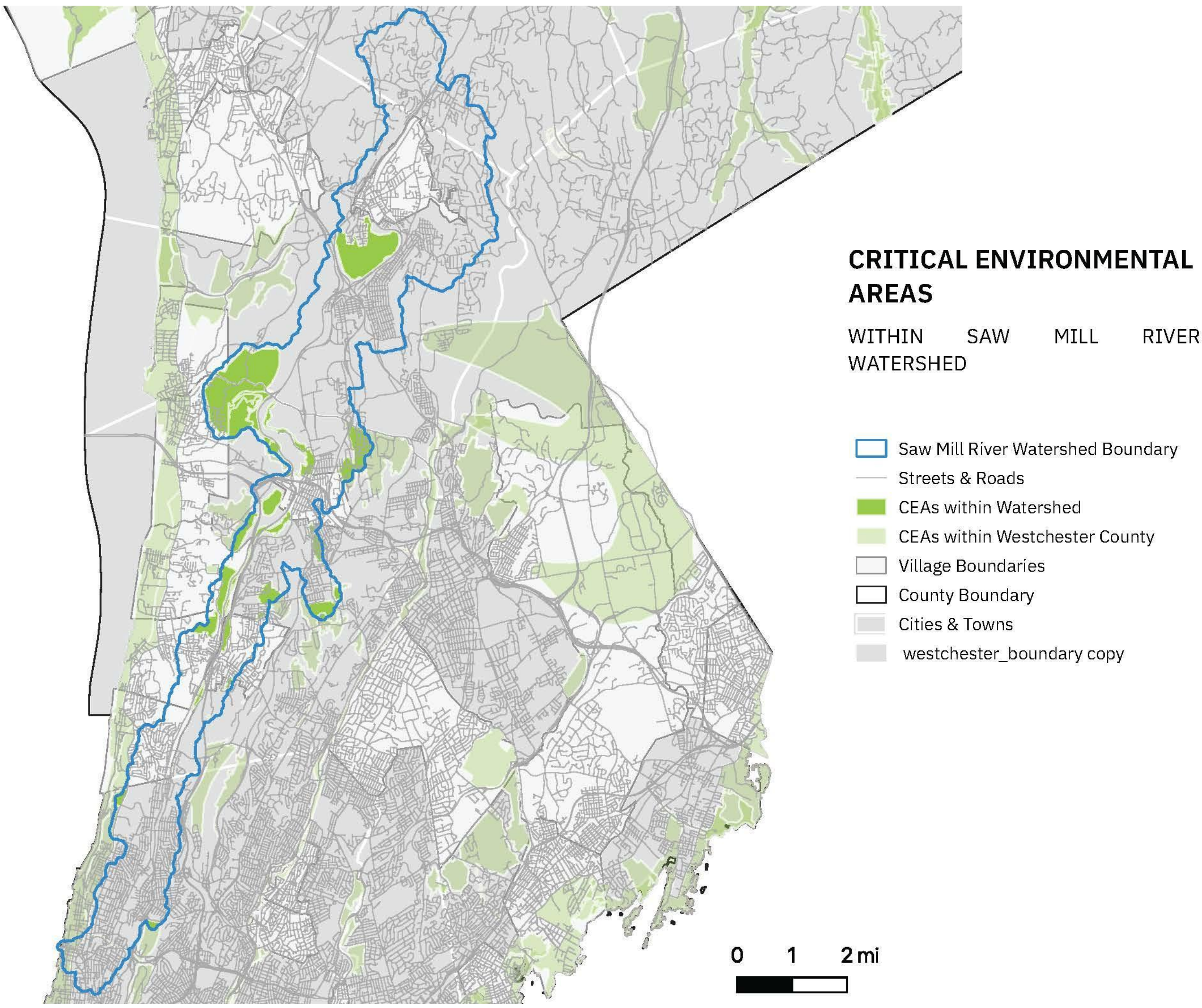


Figure 4. Critical Environmental Areas (PEJAs) for the Saw Mill River Watershed region.

3. Modeling Methodology

To examine flood vulnerability and exposure, the modeling software CityCAT (City Catchment Analysis Tool) was utilized. CityCAT is a fully hydrodynamic flood risk modeling tool that simulates the flow of water in real time by solving the full shallow water equations (Glenis et al. 2018). This tool was conceived specifically for modeling runoff in urban environments, as it is optimized for running simulations at high spatial resolutions and it considers processes specific to green areas such as infiltration and the slow down of surface runoff due to roughness. The CityCAT model was provided by Vassilis Glenis, the model's developer and researcher at Newcastle University.

The resolution of simulations in this project was 5x5 meters (~16.4x16.4 feet), as this is the highest possible in an area the size of the Saw Mill River Watershed without incurring prohibitive simulation costs due to the computational power needed. While this resolution can be considered considerably high, it is not fine enough to incorporate buildings into the model (for which a resolution finer than 2m or 6.6ft is needed). The total area of the simulated boundaries is 21.6 square miles, with a 5x5 meters grid with 2559x5792 cells (14,821,728). While the storms simulated are short (1-hour), the simulations were programmed to run for a period of 12 hours to allow for surface runoff to circulate through the study area.

3.1. Data inputs

The main data inputs that were used in the CityCAT simulations include:

- A model boundary delineating the outline of the Saw Mill River Watershed
- A digital elevations model (DEM) covering the study area
- Soil textures
- Pervious surfaces capable of infiltrating surface runoff
- Storm hyetographs indicating the evolution of precipitation intensity across each storm.

3.1.1. Model boundary

The model boundary is defined as the outer edge of the simulation. The boundary carries a double purpose - defining the area in which precipitation is simulated, and the area in which surface runoff is computed.

In this project, the boundary is defined by the Saw Mill River Watershed, which was delineated using a 5x5m DEM and the tools provided by ArcGIS' Hydrology Toolset. In order to ensure the proper inclusion of the entire watershed in the model, a 100m (~328ft) buffer is used. As a result, surface runoff and flooding are computed in the portions of the municipalities that overlay with the watershed including Mount Pleasant, Greenburgh, Yonkers, New Castle, Ardsley, Dobbs Ferry, Elmsford, Hastings-on-Hudson, Irvington, Pleasantville, Sleepy Hollow, and Tarrytown (see Figure 1 in the report's Introduction). In this simulation, the model's boundary is set as open, meaning that surface runoff is allowed to pass through it, but not return into the modeled area again.

3.1.2. Digital elevations model (DEM)

The digital elevations model represents the topography of the study area and is introduced into the model as a grid with the same resolution as the one in which the simulation will be carried out. In the model, topography is the main driver used to compute the circulation of surface runoff, including its direction and velocity.

The DEM used in the simulation was sourced from the New York State GIS platform, which allows access to the State's high resolution DEM data. The DEM sourced had a resolution of 2x2m (~6.6x6.6ft) and was resampled to 5x5m (16.4x16.4ft) using bilinear interpolation. This interpolation approach is commonly recommended for continuous surfaces.

3.1.3. Pervious surfaces

In the CityCAT model, infiltration is computed in the areas that are defined as pervious. Pervious surfaces are identified through land cover maps that identify categories such as bare soil, grass, shrubs, trees, and wetlands. When a map of pervious surfaces is introduced in the model, CityCAT identifies those cells in the DEM grid that overlap with them. It is in those cells that the process of infiltration will be added. In addition, DEM cells classified as pervious are set with a higher roughness coefficient than those DEM cells considered impervious, meaning that surface runoff is expected to gain less velocity in vegetated than in paved areas. The roughness coefficients used for pervious and impervious surfaces are the ones proposed in Glenis et al. (2018) as default (0.02 for impervious, 0.035 for pervious).

The best publicly available dataset identified as input to map pervious surfaces in this project is the National Land Cover Database (NLCD, 2019 release). This dataset has a resolution of 30x30m (~98.4x98.4ft). This resolution is too coarse to represent small urban green spaces, which tend to fall into a low, medium or high density developed land cover depending on their surrounding built environment. In the context of the project, this means that only larger green areas, normally outside of urban cores, will be identified in the model as pervious.

3.1.4. Soil texture

Soil texture determines the capacity of pervious surfaces to infiltrate surface runoff and the rate at which infiltration takes place. To compute infiltration, CityCAT uses the Green-Ampt equation, which depends on the soil's hydraulic conductivity, porosity and suction head. These factors vary depending on the soil's texture (Table 3).

Table 3: Example values for the infiltration parameters for different soil texture classifications. (Glenis et al. 2018)

Soil	Porosity (n)	Effective porosity (Oe)	Soil suction head (cm)	Hydraulic conductivity (cm/h)
Sandy loam	0.453	0.412	11.01	1.09
Loam	0.463	0.434	8.89	0.34
Silt loam	0.501	0.486	16.68	0.65

Soil texture data is sourced from the USGS' Web Soil Survey (WSS), where the most updated spatial soil data is available (for Westchester County, spatial soil data was last updated in 2019). To access soil textures in the WSS database, we use the guidelines provided by the US Army Corps of Engineers (USACE) to navigate the several tables required. As indicated by the Database's description, soil maps are drawn at scales ranging from 1:12,000 to 1:63,360. As per the USACE guidelines, areas where soil texture data is not available are classified using the Digital Soil Map of the World, a much coarser dataset available at the global scale provided by FAO.

Finally, the computation of infiltration also requires accounting for the soil´s water saturation (how much water is already filling the empty spaces between the soil's solid matter), since it defines its capacity to continue absorbing water. Taking a conservative approach, we set a default soil saturation value of 50% across the study area, except for wetlands, where we set a value of 99%, assuming soil saturation.

3.1.5. Storm hyetograph

The final input to the model is precipitation, which is provided as a hyetograph. A storm hyetograph is a graphical representation of precipitation intensity through time. In this project, we rely on historic precipitation data to generate synthetic storms that are representative of specific durations and return periods. Two storms have been simulated: a 1h-10 year storm and a 1h-100 year storm.

The storms simulated are synthetic, meaning that they are precipitation events created based on historic statistical data that can be used to calculate the magnitude of storms with a specific duration and intensity. For this, we rely on NOAA´s Atlas 14, the US's current authoritative source for assessing extreme precipitation risk. We use the records available at NOAA´s weather station located in Ardsley, NY, since it is the station closest to the watershed studied. Precipitation is simulated homogeneously across the study area, which was deemed appropriate after comparing the precipitation records offered by Atlas 14 for the south and the north of the watershed. Figure 5 shows the two storm hyetographs considered.

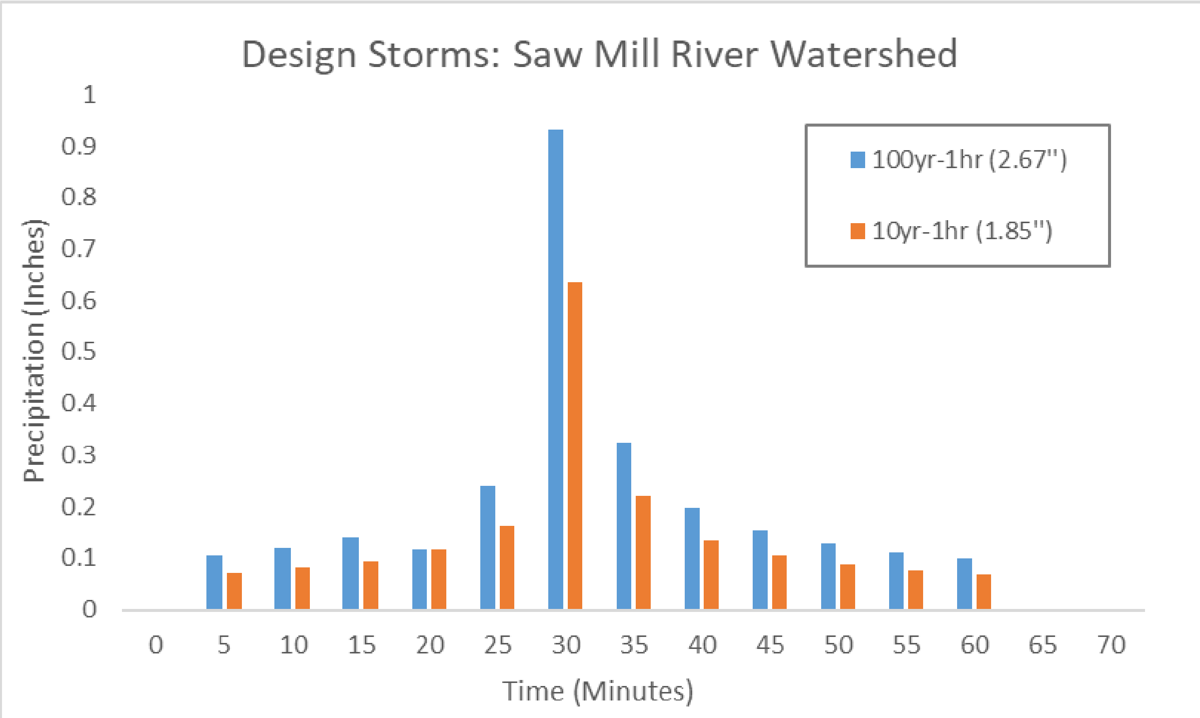


Figure 5. Storm hyetographs for the Saw Mill River Watershed

4. Modeling Results

In this section, we present the results of the flood simulations, as well as impact metrics based on exposure to flooding by homes, buildings, and roads. We present maps of the Saw Mill River Watershed broken down in 4 sub-zones, identified as the Upper Watershed, Greenburgh-Elmsford Area, Rivertowns, and Yonkers (Figure 6).

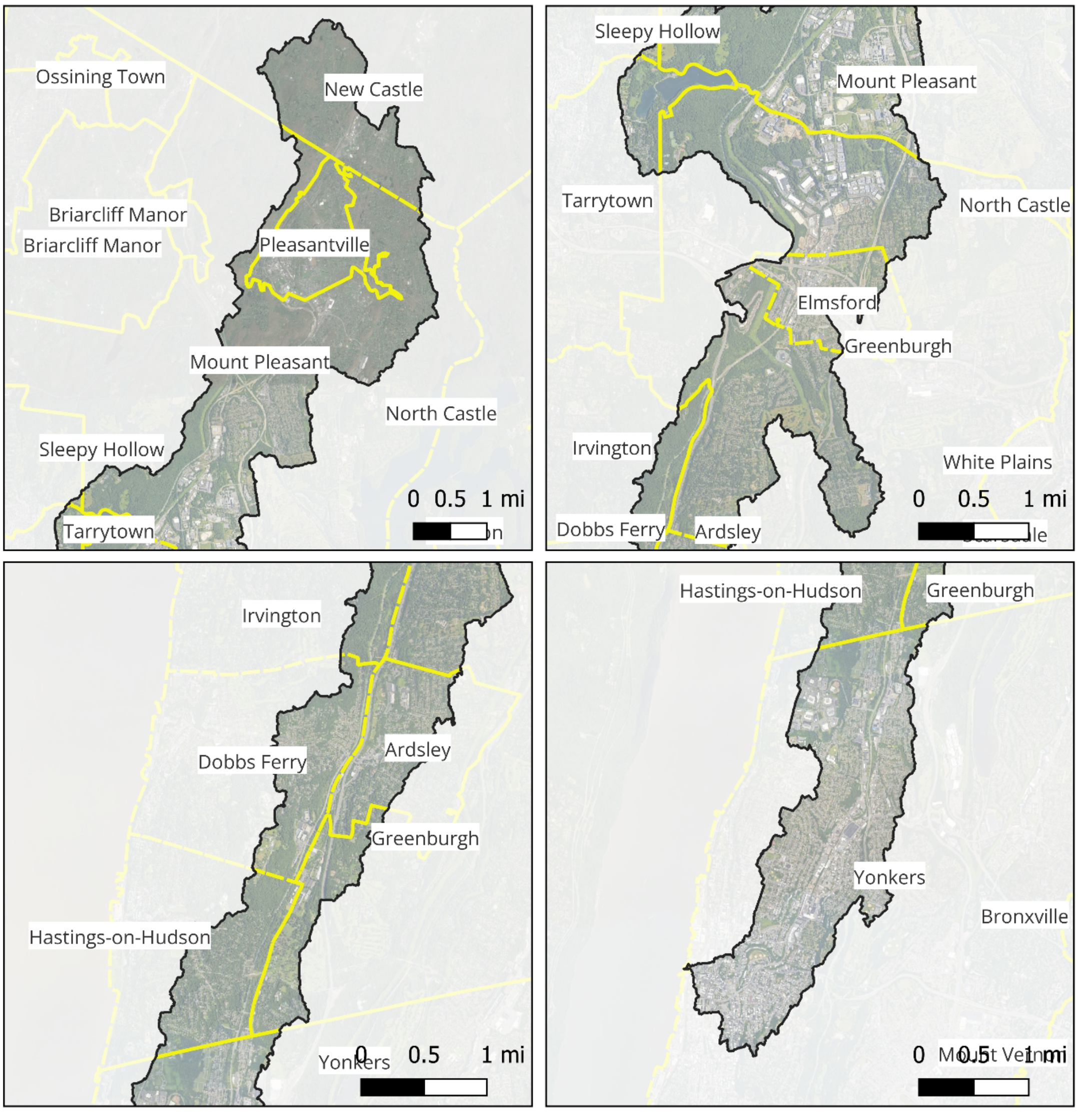


Figure 6: Watershed sub-sections considered to present the results. From left to right and top to bottom: Upper Watershed, Greenburgh-Elmsford Area, Rivertowns, and Yonkers.

The two storms simulated (1 hour, 10-year and 1-hour, 100-year) returned significant flooded areas within the model boundary. Under the 10-year scenario, up to 3.4 square miles of the watershed experience flooding of 4 inches or more. Under the 100-year scenario, the area flooded escalates to 4.2 inches. A visual examination of the two scenarios (Figure 6 and 7) provides three key insights:

1) Flooding tends to appear in the same areas under both scenarios, with slight expansions of flooded locations under the more extreme scenario.
2) Both scenarios show a considerable overlay with the Federal Emergency Management Agency's (FEMA) Special Flood Hazard Area (SFHA), which is delineated based on a 100-year floodplain. FEMA's SFHA mainly identifies locations where flooding reaches depths of one foot or more according to the studies carried out to delineate the floodplain. When comparing FEMA's SFHA with the areas that experience flood depths of 1 foot or more according to the storms modeled in this exercise, we find that our model's outputs overlay with 77.5 % and 89.4 % of FEMA's SFHA under the 10 and the 100-year scenarios, respectively. This metric provides a tentative notion of the degree to which our model matches flood risk previously mapped by FEMA.
3) Several areas throughout the watershed show flooding that is not consistent with FEMA's SFHA. These areas tend to identify minor creeks and depressions that lead to the Saw Mill River. The fact that FEMA does not show these creeks may not necessarily be caused by a false positive, but due to these small areas being overlooked during the mapping exercises carried out by FEMA given that they may not be deemed relevant from a fluvial flooding perspective.

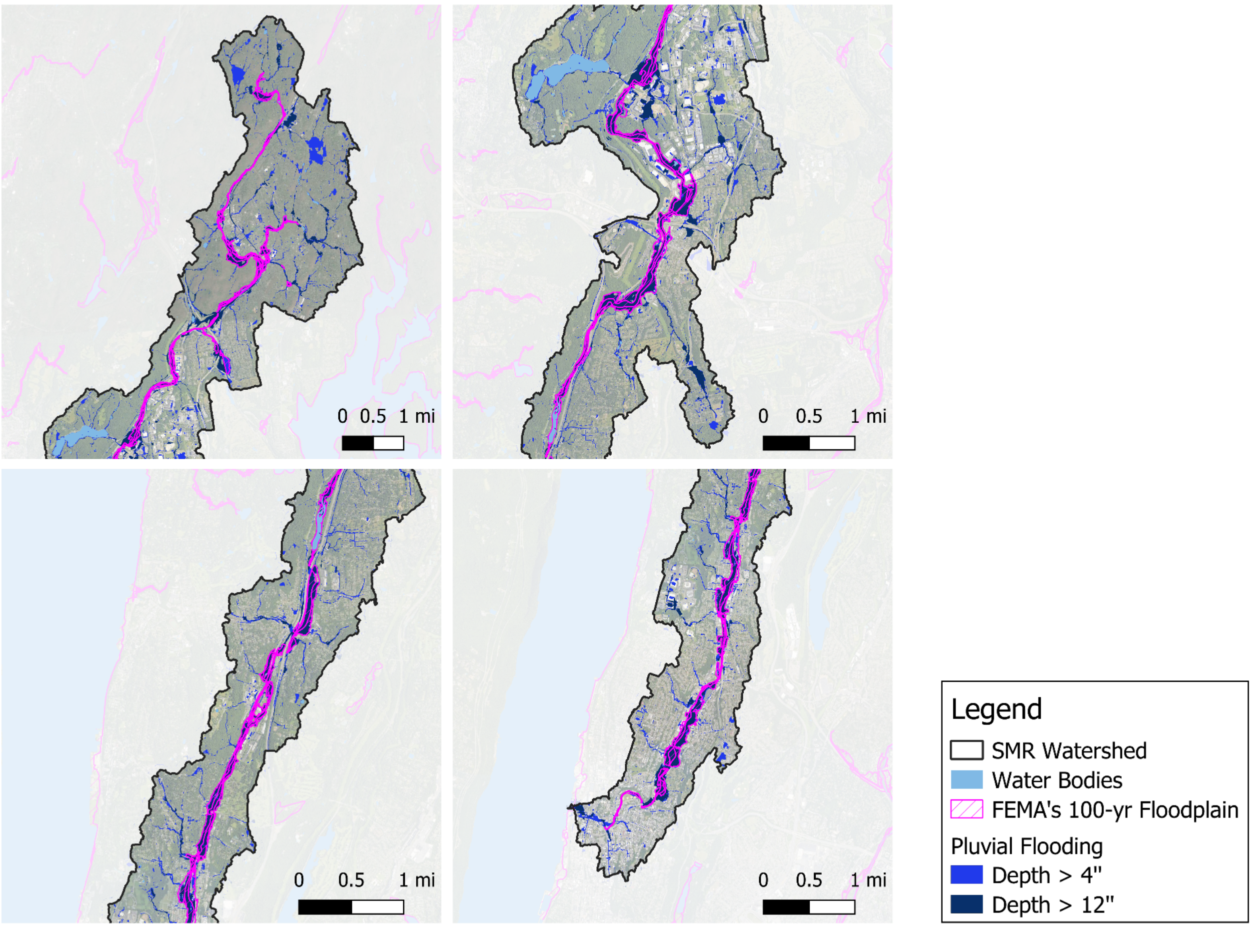


Figure 7. Pluvial flooding in the Saw Mill River Watershed under a 10-year, 1-hour storm.

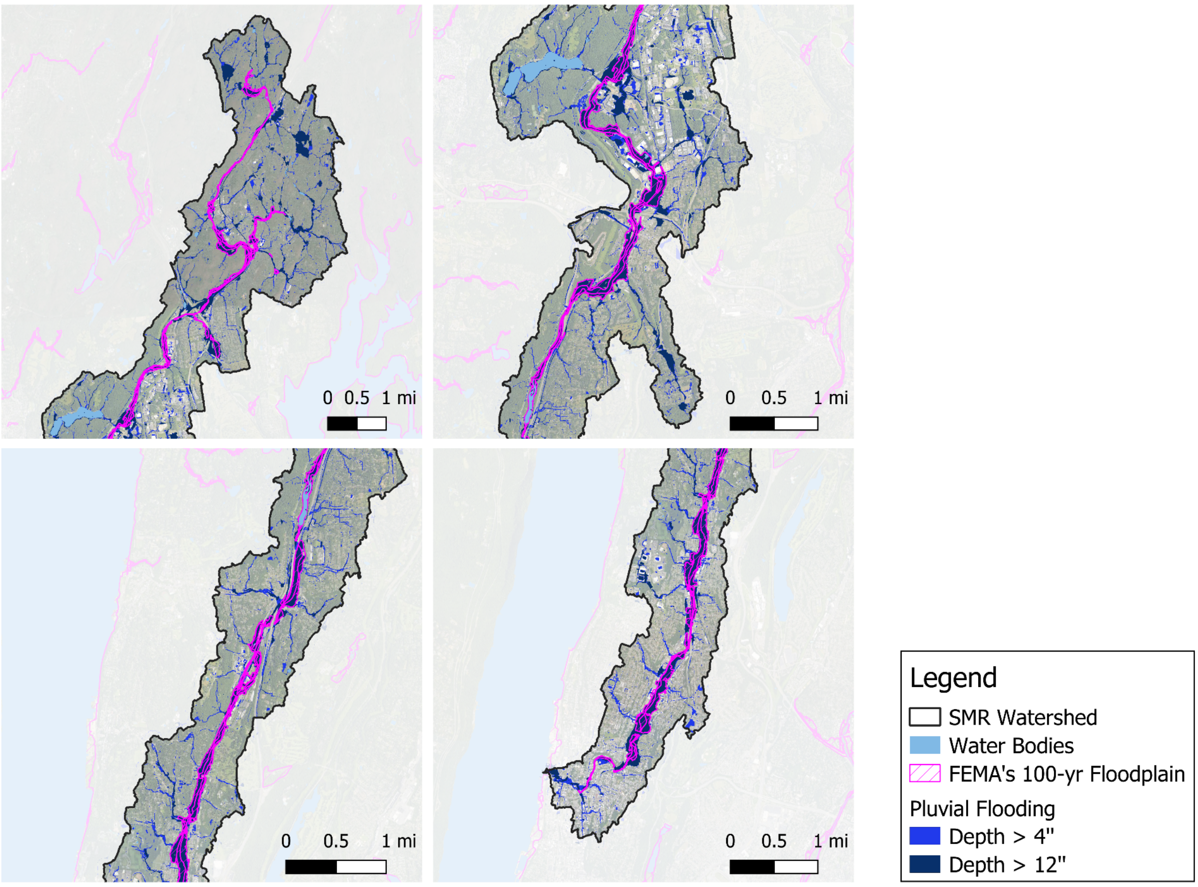


Figure 8. Pluvial flooding in the Saw Mill River Watershed under a 100-year, 1-hour storm.

Table 4 shows summary exposure data according to each of the storms simulated. Based on these results, more than one third of residential parcels and more than half of all buildings are potentially exposed to surface flooding under a moderate scenario. When visualizing these impacts on a map (Figures J, K, and L), exposure hotspots are consistently highlighted in the Greenburgh Area and Yonkers sub-sections.

Table 4. Summary Exposure Data According to Each Storm Simulation for Saw Mill River Watershed Area

Category	Total	Impacted - 10-year	Impacted - 100-year
Residential Parcels (#)	20,299	9,859 (48.6%)	11,699 (57.09%)
Buildings (#)	27,769	10,231 (36.8%)	12,466 (44.9%)
Road area (mi^2)	3.00	0.39 (13.0%)	0.53 (17.8%)

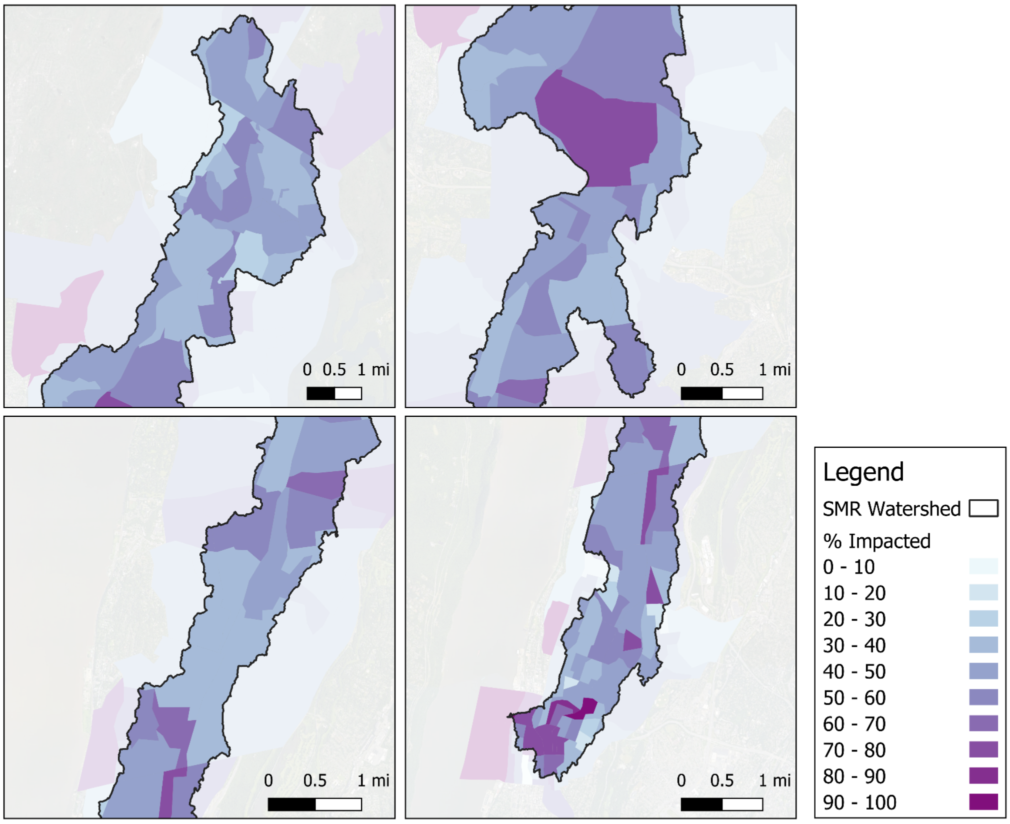


Figure 9. Impacts of flooding to buildings under the 100-year, 1-hour scenario. Buildings were classified as impacted by flooding if their distance to flood depths higher than 4'' were lower than 15m (50 ft).

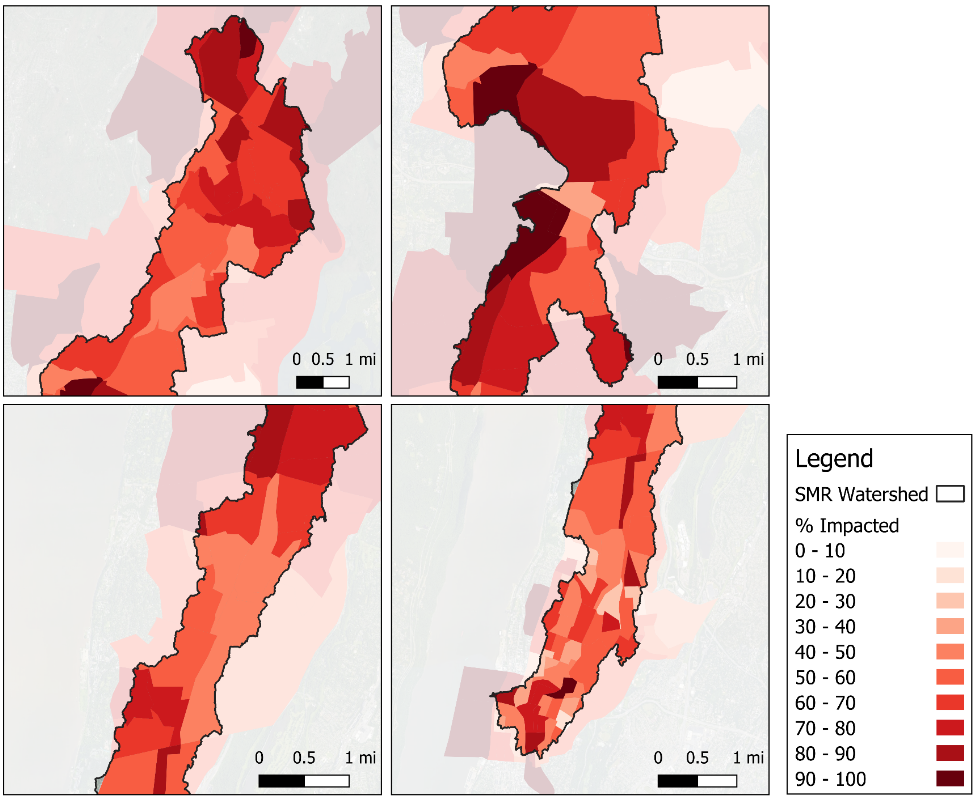


Figure 10. Impacts of flooding to residential parcels under the 100-year, 1-hour scenario. Parcels were classified as impacted by flooding if their distance to flood depths higher than 4'' were lower than 15m (50 ft).

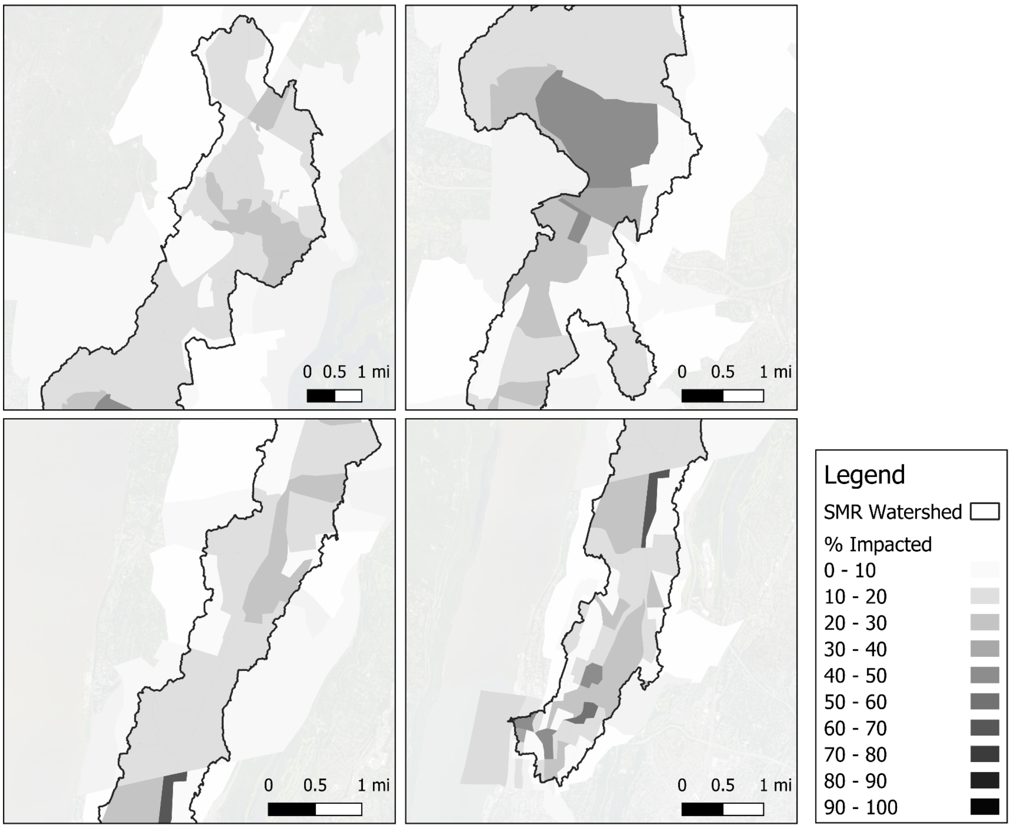


Figure 11. Impacts of flooding to roads under the 100-year, 1-hour scenario. % Impacted refers to the % of the Census Block Group's road area that overlaps with flood depths higher than 4''.

The Greenburgh-Elmsford Area presents a combination of industrial and medium-low density residential land use, while Yonkers is the most densely populated municipality in the watershed. Besides showing significant flooding, these two areas also present the watershed's largest Potential Environmental Justice Areas (Figure A). Hence, these two locations combine high flood exposure and high vulnerability to flooding. A key difference between both locations, however, is the availability of publicly owned land and green spaces. While in Yonkers the dense built environment limits potential interventions to smaller interventions, the Greenburgh-Elmsford Area presents larger areas where flood risk reduction interventions may be possible (Figure B).

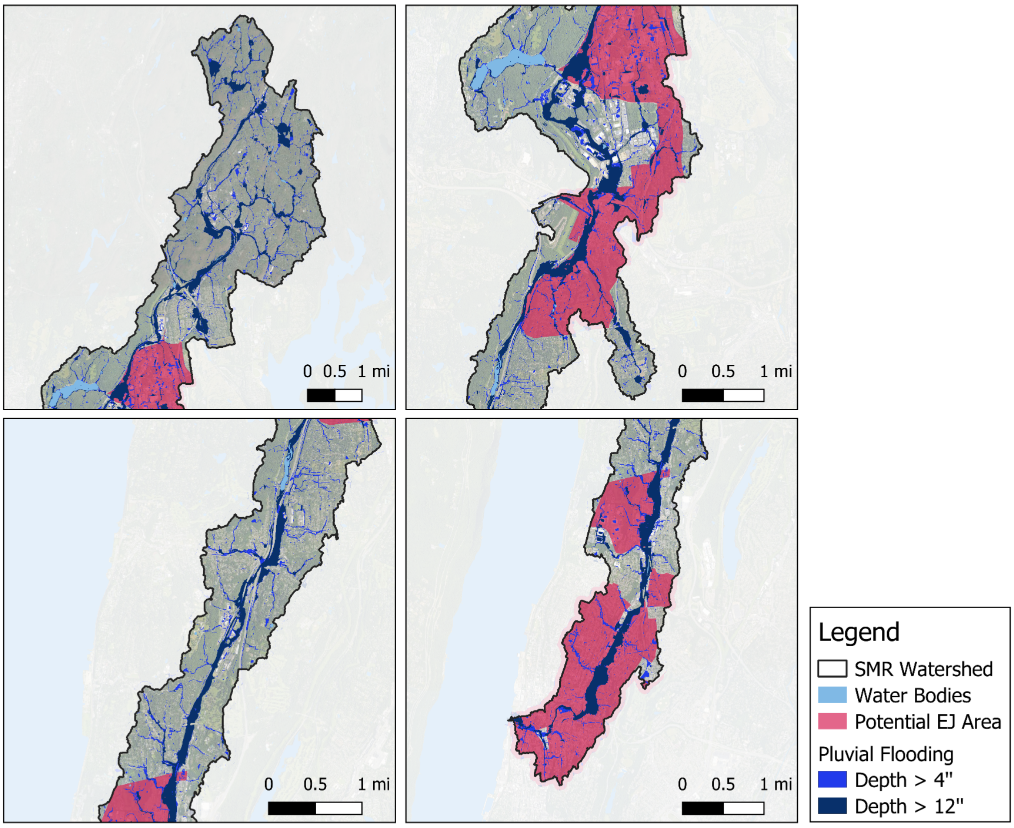


Figure 12. Flooding outputs under the 100-year, 1-hr scenario and Potential Environmental Justice Areas. Environmental Justice areas are locations with a high presence of BIPOC and/or low-income communities.

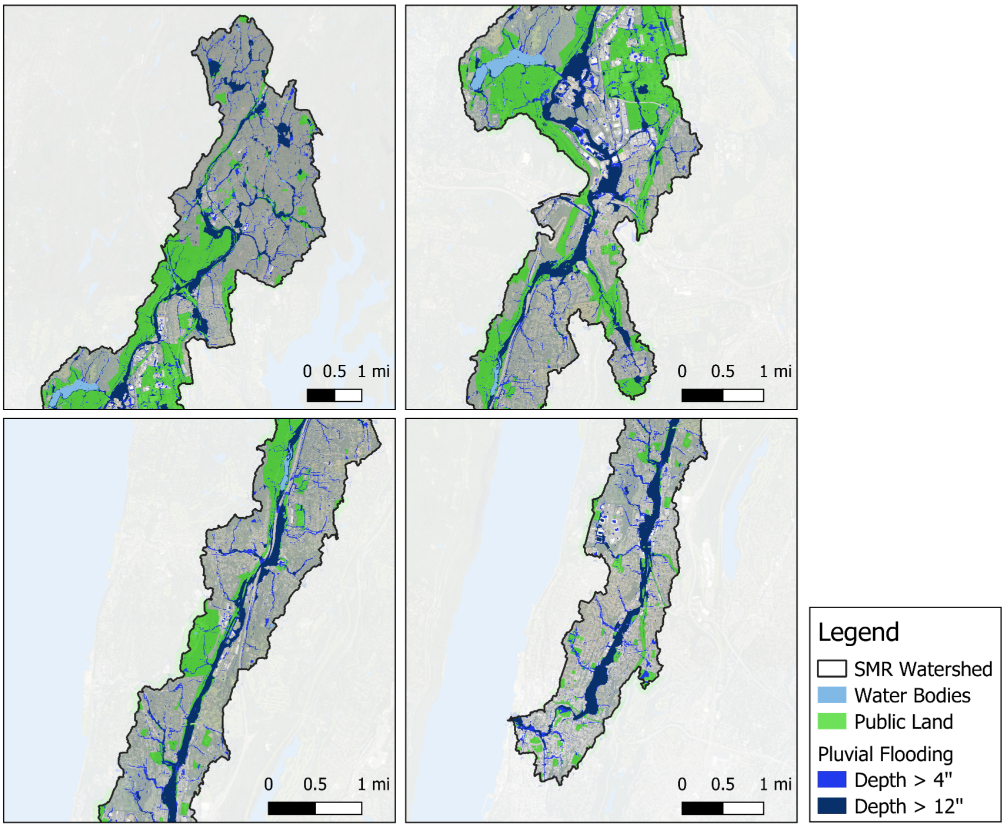


Figure 13. Flooding outputs under the 100-year, 1-hr scenario and Public Land & Open Spaces. Public land corresponds to areas identified by the parcel dataset for Westchester County as one of the following categories: “Institutional and Public Assembly,” “Nature Preserves,” “Public Parks, Parkway Lands,” “Transport, Communication,” and “Water Supply Lands.”

5. Future Research Needs & Limitations

This report presents the results of a flood hazard modeling exercise aiming to develop the first pluvial flood hazard map for the Saw Mill River Watershed. The flood hazard scenarios developed were then used to assess exposure to flooding using high resolution datasets depicting the exact location of buildings, homes, and roads. In addition, this report provides an overlay of the flood hazard maps with Potential Environmental Justice Areas and areas that due to their public ownership or management, and/or their condition as open spaces, hold high potential for hosting Nature-based Solutions aimed at mitigating flood hazards. The results provided highlight several locations where pluvial flooding may occur under moderate and extreme precipitation scenarios. The identification of small tributaries or creeks on the sides of the Saw Mill River is especially important, as these locations are not considered under FEMA's flood hazard mapping programme. The Greenburgh-Elmsford area, for instance, is a good example. Significant flooding has been mapped in this location. Furthermore, the higher built density of this location implies high exposure to flooding by buildings, homes, and roads.

Further research steps are needed to better understand flood risk across the Saw Mill River Watershed and to narrow down the identification of priority locations to assess the potential impacts different interventions may have in mitigating flood risk. First, sub-watersheds of interest could be re-modelled using higher resolution data. For instance, refining local simulations to a resolution of 2m (6ft) or finer would allow for buildings to be accounted for in the simulation if runoff. Second, drainage infrastructure may be added in future modeling efforts to refine the validity of the results. Adding complex sewer networks to pluvial flood risk models requires greater computational resources, time, and data-processing capacity. However, this inclusion may be far more viable at the sub-watershed level. In addition to sewer networks, culverts, bridges, and rivers going underground are major sources of uncertainty that should be solved in future applications. Third, high resolution sub-watershed modeling would enable accounting for potential interventions, even if small in area, to evaluate their capacity to mitigate pluvial flooding.

Finally, both future research and intervention planning steps should be aware of the critical environmental justice considerations linked to flooding. Environmental justice may be understood from two main perspectives: distributional and procedural justice. Distributional justice refers to the uneven distribution of hazards and interventions aimed at mitigating them. Assessing flood risk in the Saw Mill River watershed must account for the heterogeneous distribution of social vulnerability, which is highest in the Yonkers and the Greenburgh-Elmsford regions (Figure 14). Areas within the Saw Mill River Watershed that combine high exposure to flooding and high social vulnerability may be prioritized to implement flood mitigation interventions. Procedural justice refers to the transparency and fairness of the decision-making processes. In this context, we relate procedural justice with ensuring that communities affected by flood risk are invited to participate in the intervention planning process, and that their concerns are consistently attended. In response to the distributional and procedural justice implications of allocating interventions (e.g. green infrastructure), researchers recommend prioritizing the deployment of interventions in communities that explicitly express a need or desire for them, as well as setting clear goals related to the environmental justice implications of the hazard to mitigate and the interventions to deploy (Hoover et al., 2021). More information and recommendations on relevant justice aspects surrounding the implementation of green infrastructure can be found at www.giequity.org.

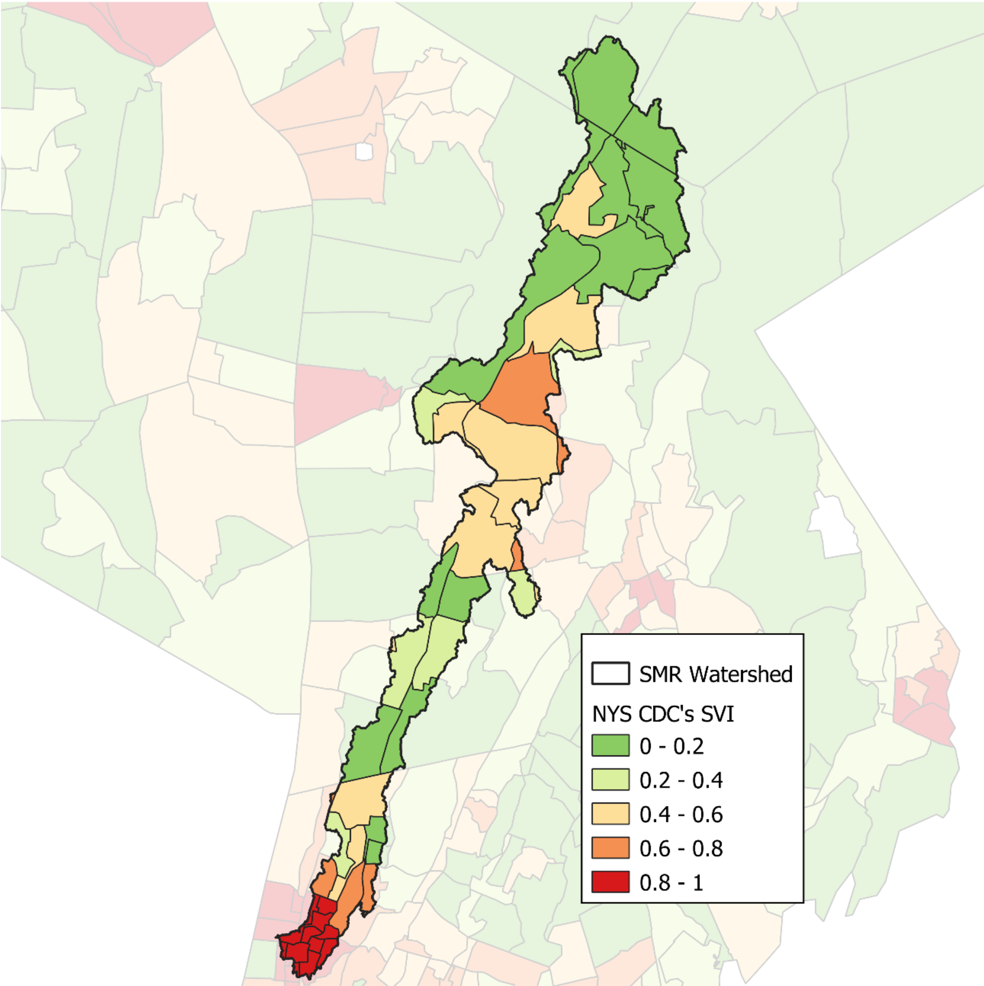


Figure 14: CDC's Social Vulnerability Index in the Saw Mill River Watershed. Higher values imply higher vulnerability based on the indicators considered by the index. Source: ASTDR, 2020.

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