Bronx River Corridor Study and Management Plan for Westchester County, NY – Volume I

Prepared for

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EXECUTIVE SUMMARY

The Westchester County Planning Department is interested in improving channel stability, aquatic habitat, and recreational opportunities along the Bronx River while also reducing flood hazards and erosion hazards. Towards this end, development of the Bronx River Corridor Study and Management Plan has identified the natural conditions and human impacts that control river processes and the resulting morphology, or shape, of the river channel and floodplain.

While the elongated watershed would naturally reduce flood peaks compared to a rounder drainage basin of the same size, the construction of Kensico Dam has greatly reduced flood discharges to the river since its completion in 1915. The subsequent (sub)urbanization later in the 20th century has likely increased peak discharges on tributaries in the lower watershed far above natural levels due to a great increase in impervious surface area, although associated increases in peak discharge on the Bronx River, documented by stream gauge data, are unlikely higher than peak flows prior to completion of Kensico Dam.

The most significant impacts to the Bronx River are due to human activities directly in the river channel and floodplain. Artificial straightening of what was a naturally meandering channel is evident from photographs and maps from the 19th century, a practice that may have begun shortly after European settlement of the region in the 17th century. Much of the straight planform of the river today is the result of another period of channel straightening that occurred during construction of the Bronx River Parkway completed in 1925. Other significant human impacts on the channel and floodplain, some also related to parkway construction, include armoring of the river banks, placement of artificial fill in the river corridor that prevents floodplain access, and construction of numerous dams and bridges across the river that alter the river's profile and channel width, respectively.

Rivers are in a constant state of adjustment that tend towards an equilibrium condition where the amount of change from one point to the next is minimized such that, over time, sharp bends are modified into smooth meanders and steep vertical drops are replaced with smooth profiles with minimal elevation change from point to point. The human impacts on the Bronx River have resulted in river responses reflective of this tendency towards equilibrium, most noticeably with the reformation of meanders along straightened sections of the river that were left unarmored. Where unable to adjust due to armoring or permanent structures such as dams and bridges, the river remains in a perpetual state of instability that leads to habitat degradation and flood hazards and erosion hazards that threaten public safety and infrastructure in the river corridor.

A geomorphic assessment consisting of an analysis of historic maps and aerial photographs as well as the mapping of channel features along the length of the Bronx River in Westchester County documented the location and types of impacts from human modification and the subsequent channel responses. Artificial channel straightening occurred on over 90 percent of the channel's length with meanders reformed subsequent to the straightening on 25 percent of the river's length. Over 30 percent of the total length of riverbanks are armored with either large stone, concrete or stone walls, or gabion baskets, locking in place the straightened condition. However, 17 percent of the total length of the riverbanks is eroding. This erosion occurs primarily where armoring was never placed, but in some areas where aging armor has failed. The 28 mapped areas of erosion proximal to infrastructure were ranked in terms of their potential risk of causing extensive damage into "high", "moderate", and "low" categories based on the distance to the infrastructure, features of the eroding bank (e.g., height, composition/geology), and the value of the potentially threatened infrastructure.

As channel features were being mapped for this report, the river was subdivided into 97 segments, reflecting areas with uniform characteristics such as the level of armoring, degree of channel confinement, and width of mature riparian vegetation along the banks. Each segment was then used to form the basis for corridor planning that prioritized areas with the greatest need for restoration or other type of project based on the segment's current stability, habitat features, and recreational opportunities. In addition to detailing the location of the erosion hazards, the corridor planning also identified flood hazards associated with the Bronx River. Flood hazards were identified by meeting with stakeholders impacted by or tasked with addressing flooding problems, reviewing previous reports detailing flooding problems in the county, and conducting HEC-RAS hydraulic modeling. Flood hazards were identified at 14 locations throughout the Bronx River corridor spaced along the length of the river with two sites ranked as having an extreme risk and four sites having a very high risk of costly damages based on the likelihood and depth of flood inundation as well as the value of the infrastructure that could be impacted.

The segments with the highest need of restoration are primarily those that are confined, armored, and straightened such as channels, which are inherently unstable and prone to rapid erosion, meander reformation, and severe flooding if the armoring fails or floodwaters escape the channel. Such channels often exhibit poor habitat conditions (e.g., low flow complexity, limited cover) and, without an adjacent floodplain, offer little recreational opportunity. Segments with reformed meanders or those that are only partially confined are generally of a lower priority for restoration as they have greater flow complexity at low flow, some floodplain access to reduce hazards during a large flood, and greater space for recreational purposes.

The report provided here represents Volume I of a two-volume set with Volume II to integrate the identified flood hazards and erosion hazards with the segment needs to identify projects that can simultaneously reduce threats to public safety while improving channel stability, aquatic habitat, and recreational opportunities. A prioritization process will link the segments with the greatest needs and hazards with project types (e.g., floodplain restoration, riparian plantings, bank stabilization) most effective at addressing the problems in those segments. Restoration of one segment that increases flood storage, for example, may not only improve habitat within the segment but might also alleviate flood hazards and erosion hazards downstream where more constraints to project implementation may exist. A range of projects of varying size and cost will be developed for each segment with completion of smaller projects at the outset building momentum to implement larger projects that will restore the natural character of the river, where feasible, and increase public engagement with the river flowing through their towns, while reducing hazards that will save costs over time by reducing damages to flood and erosion prone infrastructure along the river.

1.0 INTRODUCTION

The Westchester County Soil and Water Conservation District and Department of Planning have contracted with Field Geology Services, LLC and Tau Engineering to develop a Bronx River Corridor Study and Management Plan (BRCSMP) with the goal of identifying and prioritizing opportunities for reducing flooding and erosion along the Bronx River while simultaneously improving channel stability, aquatic habitat, and recreational use within the river corridor. The term river "corridor" is defined here as the valley bottom area across which the river flows and includes the floodplain as well as areas of artificial fill on the valley bottom that have raised the floodplain surface above the level of floods. The area covered by the BRCSMP covers the 14.1 mile length of the Bronx River and adjacent floodplain corridor in Westchester County from Kensico Dam in Valhalla, NY to the Bronx border in Yonkers, NY (Figure 1). Two tributaries, Grassy Sprain Brook and Laurel Brook, were also investigated given their close association with known areas of concern on the Bronx River itself. (Some figures and tables in this report are embedded within the narrative while most are appended to the end of the report to provide a full page display with figures and tables numbered sequentially from their first mention in the text.)

Volume I of the two-volume plan, presented herein, provides the results of a geomorphic and hazard assessment that have been used to identify the locations where human modifications of the corridor and watershed at large have exacerbated flooding and erosion, degraded aquatic habitat, destabilized the channel, and constrained recreational opportunities. This information was used to prioritize the "need" of various sections of the river for restoration, or other form of intervention, to realize hazard reductions, habitat improvements, and increases in recreational use. The subsequent completion of Volume II of the Plan will provide a prioritized list of various projects of varying magnitude that address specific "needs" (i.e., increased floodplain access, hazard reduction, habitat improvement). Conceptual project designs will be developed for four mainstem sites and one tributary location with the highest needs.

Volume I of the Plan is presented below and consists of: 1) further introductory material detailing the purpose, methods, and outcomes of the BRCSMP; 2) background information on fluvial geomorphology, hydraulic modeling, and the value of both in developing river corridor management plans; 3) a characterization of the Bronx River corridor including information on geology, soils, physiography, climate, and human history; 4) geomorphic assessment results based on an analysis of historical aerial photographs and topographic maps and the mapping of channel features; 5) developing a corridor management planning strategy that states the goals of the BRCSMP and details the methods of site prioritization; and 6) presents initial findings of the corridor management and project prioritization process to be completed in Volume II.

1.1 Achievements of corridor planning

The vision for the BRCSMP is to highlight and develop non-regulatory opportunities to maintain, enhance, protect and restore channel stability, water quality, and habitat within the Bronx River Corridor. These opportunities focus on interventions which ensure public safety, mitigate flooding, conserve and enhance ecosystems, protect public infrastructure, enhance local economies, and increase recreational and tourism opportunities. The BRCSMP was developed with support from Westchester County, will be integrated and consistent with existing local programs and civic organizations' missions associated with watershed management activities, and will promote economically sustainable and vibrant communities throughout the watershed by improving conditions on the river.

1.2 Corridor study and management plan process

The BRCSMP is composed of two Volumes. The first Volume, Volume I, documents watershed stakeholder participation and the analysis of GIS materials, scientific reports, and other regional plans whose findings provide a systematic way of viewing conditions, concerns, opportunities and potential threats within the river corridor. These findings are categorized, prioritized, and ultimately inform the purpose of the BRCSMP (referred to as the "Goal" presented in Section 5.1 below) and short-term and long-term solutions, suggestions, and overall management practices to achieve the Goal. The second Volume, Volume II, presents geographic specific management practices whose implementation will result in incremental improvements in channel stability, aquatic habitat, hazard mitigation, and recreational opportunities. The steps taken to complete Volume I of the BRCSMP were:

1.2a Generate stakeholder data

Stakeholder Data refers to data collected through input gathered at meetings and interactions with representatives of various Westchester County departments and civic organizations. Stakeholder data was categorized into the following topics:

- Stakeholders' views of ongoing challenges within the corridor;
- Existing and desired recreational uses along the river;
- Previous watershed projects designed and completed; and
- Proposed capital improvement plans.

Stakeholder data shaped the overall BRCSMP goal and informed the quantifiable objectives (i.e., the corridor management strategies) that when completed will result in the goal being obtained. Flood water inundation hazard mitigation, erosion hazard mitigation, and aquatic habitat conservation and enhancement are examples of quantifiable objectives. Objective definition, project prioritization, and problem resolution will be discussed in Section 5.0 and Section 6.0 below.

1.2b Organize available GIS data

The initial steps to gather information about the Bronx River corridor included the use of Geographic Information System (GIS), aerial photography, hydraulic software modeling and historic documents which together were referred to as “GIS Data”. GIS Data describes qualities and features of the landscape, historic human activities within the corridor, and public safety hazards. GIS Data comes from a variety of sources such as universities, museums, County archives, and State and Federal Agencies.

Pertinent GIS Data was obtained for the Bronx River corridor from the northern Westchester County boundary along the municipal boundary between North Castle and Mount Please (41.06669°, -73.77356°) and extends to near the southern county boundary in Yonkers where the river flows under Nereid Avenue (40.90078°, -73.86042°). The Bronx River corridor encompassed the adjacent floodplain corridor which is the area within the 500-year return interval floodplain defined by the Federal Emergency Management Agency (FEMA). A 500-year return interval floodplain is defined as the area that statistically has a one in five hundred chance (0.2%) to be covered in floodwater in any given year. The 500-year return interval floodplain is the largest flood event studied by FEMA whose data is easily obtained.

Additional GIS data obtained and organized were: soil types, local geology, local geography, local land uses, land cover, and infrastructure encroachments. GIS mapping exercises were conducted to refine the BRCSMP’s goal, provide a scientific foundation for quantifiable objectives, and justify river corridor implementation strategies.

1.2c Develop the River Corridor Goal and River Corridor Objectives

The Bronx River Corridor Goal and related objectives (see Section 5.1 below) were developed from the Stakeholder Data and available GIS Data. This broad goal reflects the most important river corridor needs in the study area. The goal laid the foundation for specific objectives and implementation strategies. Objectives were developed from Stakeholder Data, available GIS Data, and a geomorphic assessment completed by a team of scientists and engineers who walked the entire length of the Bronx River in Westchester County. The Goal and its supporting objectives are the concrete strategies that can turn the Bronx River Corridor Study and Management Plan into a measurable success.

1.2d Delineate Bronx River Corridor reaches

The Bronx River was subdivided into 20 reaches. A reach is a smaller geographic region or the river where unique features and characteristics could be more easily identified. Reach partitioning allows for specific management practices to improve a specific length of the river corridor resulting in improving the overall health of the river corridor. River corridor needs are more easily defined at the reach scale and increases opportunities to garner funding and support for projects in the future.

1.2e Obtain field data and define segments

The identified reaches were further subdivided into shorter "segments", reflecting the location and occurrence of various human impacts (e.g., channel straightening, bank armoring) and channel responses to those impacts (e.g., bar deposition, redeveloping meanders). Segmenting the stream into smaller sections based on human impacts and channel response serves as the basis for identifying the need for flood mitigation, erosion control, and habitat restoration at various points along the stream. The reaches and segments are of uneven length and the breaks between each occur where there are observable changes resulting from various natural and human conditions. Segment breaks (i.e., where one segment ends and the next begins) are delineated in the field using handheld GPS units. During segment delineation, erosion hazards and other features were mapped and their characteristics measured or observed. An erosion hazard was defined as a location along the river corridor where human infrastructure has a reasonable likelihood of being damaged within the next twenty-five years.

1.2f Organize findings and develop a site prioritization matrix in Volume I

Bronx River Stream Corridor Management Plan Volume I site prioritization are supported by the overall findings outlined in Sections 1.2a-1.2e above. The priority sites were identified, in large part, at stakeholder meetings and through subsequent GIS data analysis, so reflect the local knowledge of stakeholders plus the expertise of riverine scientists and engineers.

1.2g Volume II implementation prioritization and management practices

The Implementation Plan to be found in Volume II is designed to track the progress of the BRCSMP and identify future projects, project partners, and funding sources. These strategies will ensure the BRCSCMP serves as a multi-jurisdictional guidance document for the future management, restoration, resiliency, and enjoyment of the Bronx River corridor and its community members.

2.0 BACKGROUND INFORMATION

The fluvial geomorphic assessment and hydraulic modeling (based on hydrology and hydraulics) underpin this analysis of the Bronx River corridor and will serve as the basis for recommendations to be developed in Volume II. Consequently, a brief primer is provided here of these two practices to give context to the methods, findings, and prioritization presented in the BRCSMP.

2.1 Fluvial geomorphology

Fluvial geomorphology is a branch of geology devoted to understanding how the natural setting and human land use in a watershed determine and alter the morphology or shape (e.g., width, depth, and sinuosity) and stability (e.g., severity of flooding and erosion) of the river channel. A fluvial geomorphic assessment seeks to identify what physical changes have occurred, are ongoing, and will continue in the future along a river in response to past or future natural perturbations (e.g., landslide) and human alterations (e.g., dam construction) in the broader watershed or directly in the channel itself . This information, in turn, can be used to understand and anticipate risks to human infrastructure (potentially threatened by flooding and erosion) and degradation of (or improvements to) aquatic habitat (e.g., loss or creation of pools). A river's adjustment to changing watershed conditions may take thousands of years, as is the case throughout much of New York as the result of deglaciation. In other instances, channel modifications may occur in less than a decade, as is frequently the case with direct human activity in a stream channel such as bridge construction. Understanding how these various perturbations, operating at different time scales, alter the width, depth, planform, and stability of a channel is critical for identifying potential problems in a river system and guiding decisions to reduce hazards and improve aquatic habitat.

The concept of river equilibrium is an underlying principle of fluvial geomorphology that helps determine if a river is unstable and capable of significant adjustments in channel dimensions. Equilibrium is established when the water and sediment delivered from the watershed is conveyed through the river channel with minimal change to its dimensions, although the channel may continue to migrate across its floodplain (representing a change in position but not necessarily dimension). The dimensions of alluvial channels (those flowing through a floodplain formed by the river and thus able to freely adjust its dimensions) are typically sized to contain the dominant discharge (also referred to as the bankfull or channel-forming discharge) that in temperate climates usually equates to a flood with a 1- to 2-yr recurrence interval. Flows larger than the dominant discharge spread out onto the floodplain, thus preventing the additional stream power of bigger floods from altering the channel’s size. As increases in the magnitude of the dominant discharge accompany increases in watershed size, the resulting increases in the width and depth of alluvial channels are surprisingly uniform worldwide (Leopold, 1994) such that certain morphological relationships, like the ratio of channel width to depth, can be used to determine if a channel is near an equilibrium condition regardless of channel size.

Channels that are far from equilibrium are susceptible to significant and rapid changes that are sometimes hazardous to public safety and human infrastructure. A geomorphic assessment compares the expected equilibrium conditions for a river of a given size with those observed on the river under study to reach conclusions on how the river has been altered, the cause of the alterations, and the expected channel adjustments that will occur in the future to reestablish equilibrium. Generally, the best and most sustainable actions to reduce human impacts to channel stability and aquatic habitat on a river are those that restore or move the river towards an equilibrium condition.

2.2 Hydrology and hydraulics

Hydraulic modeling is used to predict river stage (i.e., height) and velocity for a given discharge. River discharge is the product of flow velocity and the area occupied by the flow (velocity multiplied by area) and represents the volume of water (typically measured in cubic feet in the United States with one cubic foot equivalent to 7.5 gallons) passing a certain point in a set amount of time (usually one second is used as the measure of time). The United States Geological Survey operates thousands of stream gauges around the country to calculate discharge where velocity has been measured using a flow meter at several different river levels and the cross sectional area of the river and floodplain has been surveyed (so the amount of area occupied by the flow can be determined for any stage the flow reaches). Since velocity generally remains the same for a given stage at a certain location, the discharge can usually be established, after repeated velocity measurements have been made, by just noting the stage of the river without needing to continue costly and sometimes dangerous velocity measurements.

On large rivers such as the Mississippi River, discharge measurements from an upstream location can be used to predict flood peaks at downstream locations through the use of hydraulic modeling, forming the basis of flood early warning systems. Hydraulic models, by accounting for the gradient (i.e., steepness) of the river, the cross sectional area at numerous locations even where gauges have not been established, and the “roughness” of the river (i.e., obstructions, bends, vegetation, etc. that tend to slow down the flow velocity), can calculate how fast the flow is passing down river and predict the time and elevation at which the river will crest at downstream locations. This information is then utilized to identify communities that will be inundated by the flood, providing critical time to evacuate people and protect property.

Hydraulic modeling is also a valuable tool for understanding why flooding occurs repeatedly in the same areas such as in the Bronx River corridor and is used to determine the potential effectiveness of proposed restoration and flood mitigation strategies. By comparing the existing conditions with the proposed conditions (such as removing a dam), changes in river stage and flow velocity for a given discharge can be established. Although hydraulic models typically consider only the water flowing in the river, and not sediment, the changes to river velocity identified in the models can also help explain the reasons for or anticipate the location of deposition or erosion along the river.

3.0 CHARACTERIZATION OF THE BRONX RIVER CORRIDOR

Both natural conditions and human activities influence the character of the Bronx River and its contributing watershed. A detailed description of the natural and human history has already been provided in other documents such as Partners in Restoration (2010), so the focus here is restricted to those aspects that most closely relate to river morphology, watershed hydrology, and flow hydraulics in the channel.

3.1 Physiography and drainage

Several natural factors control the nature of flooding and the channel's dimensions including the drainage area, relief, gradient, and basin shape. The Bronx River runs north to south in a narrow linear 51 mi^2 drainage basin upstream of the Westchester County-Bronx border (Figure 2; Appendix 1). The form factor (defined as the drainage area divided by the basin length squared – A/L^2) of the watershed is 0.1, reflecting its narrow and elongated character. By comparison, a perfectly circular watershed with the same drainage area would have a basin length of approximately 8.1 mi (compared to 22.6 mi) and a form factor of 0.785 (the highest value possible for this dimensionless hydrological parameter used to assess the character of flooding). In a perfectly circular basin, water draining from different parts of the watershed after a heavy rainstorm would essentially reach the outlet at the same time, creating a high peak of short duration, whereas an elongated basin like the Bronx River will have flow reaching the outlet at vastly different times to create a much lower peak but of longer duration.

Other natural features of the Bronx River watershed further suggest peak flows would be attenuated in the absence of human impacts. The total relief in the watershed is 693 feet with the highpoint of 750 feet in New Castle and an elevation of 57 feet at the Bronx border. The river's average gradient is 0.0039 along the upper half of the river and declines to 0.0021 along the lower half, although the transition in slope is largely gradual with only low natural falls or bedrock controls in some locations (Figure 2). The relatively low relief of the watershed and gentle gradient of the river reduces the potential to generate high peak discharges as compared to more mountainous basins.

A floodplain borders much of the river despite the narrowness of the Bronx River valley. However, the higher uplands naturally constrict the valley in several locations (Figure 4). Natural valley constrictions impede the downstream passage of floodwaters, often causing sediment deposition and channel instability immediately upstream where floodwaters are backed up. Identifying such natural constrictions is, therefore, an important part of a geomorphic assessment attempting to understand the causes for morphological changes along the length of a river.

3.2 Climate and precipitation

The climate of Bronx River watershed is very similar to most of New York and is classified as Humid Continental. The watershed generally experiences seasonable weather patterns characteristic of the northeastern United States. The average summer temperature, as recorded by the National Oceanic and Atmospheric Administration (NOAA) Climate Center at the Westchester County airport is 50.9 degrees Fahrenheit with an average high temperature of 70.7 degree Fahrenheit. Average winter temperature is 30.9 degrees Fahrenheit with an average maximum temperature of 38.2 degrees Fahrenheit. Table 1 reflects the 1981-2010 climate normal temperatures, which are the National Climate Data Center's latest three-decade averages of climatological variables, including temperature and precipitation. Based on the average annual precipitation for this region at the Westchester County Airport Weather Station the 1981-2010 average of precipitation was 49.4 inches. Precipitation is evenly distributed through the year with eastward moving cold fronts bringing the area's most frequent rain showers. Tropical storms will typically move north from the warmer southern coastline and are responsible for larger storms with more rain.

	Precipitation (in)	Min. Temp. (F)	Avg. Temp. (F)	Max. Temp. (F)
Annual	49.4	30.9	50.9	70.7

Table 1. Climate statistics from Westchester County Airport weather station (Station ID CHCND:USW00094745), NCDCs 1981-2010 Averages.

A growing number of climatological models are in agreement that winter and summer temperatures will continue to trend upward. This shows that recent weather patterns of more sporadic rainfall will lead to more frequent short (one to three months) seasonal droughts broken by large intense rainfalls. Greater intensity rainfalls could have a profound impact on the Bronx River and its tributaries, leading to greater channel degradation, instability, bank erosion, and sedimentation.

The average annual rainfall in the Bronx River watershed of 49.4 inches is based on 106 years of rainfall data. The trend over the last century shows an increase in the amount of rain since data recording began. For example, in the early 20th century, the average annual rainfall was between 40 inches and 41 inches compared to the early 21st century with an average annual rainfall between 44 inches and 45 inches (Figure 5).

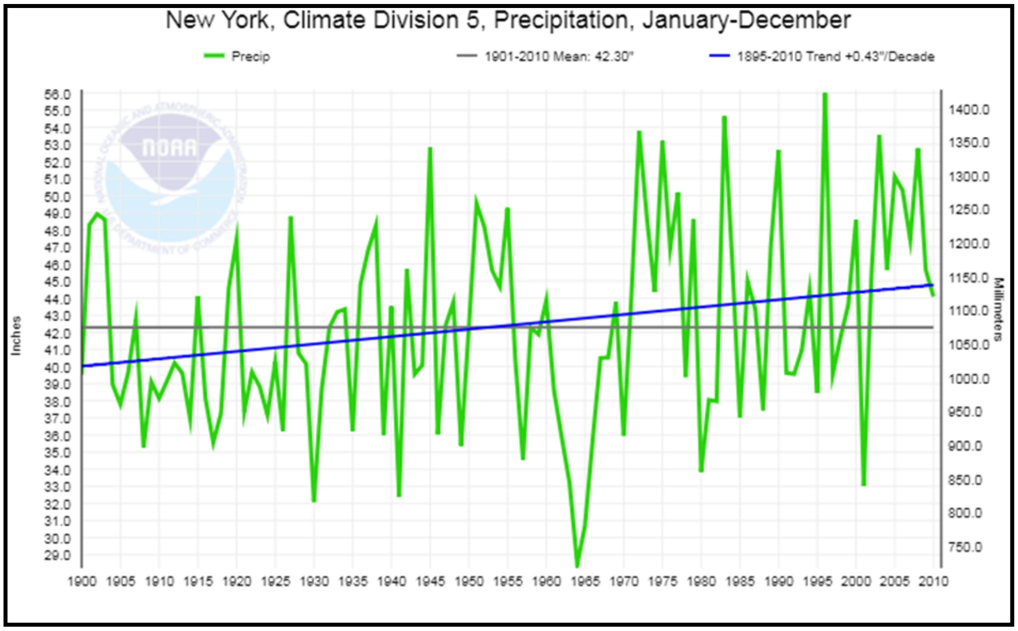


Figure 5. Annual precipitation trends in the Bronx River watershed.

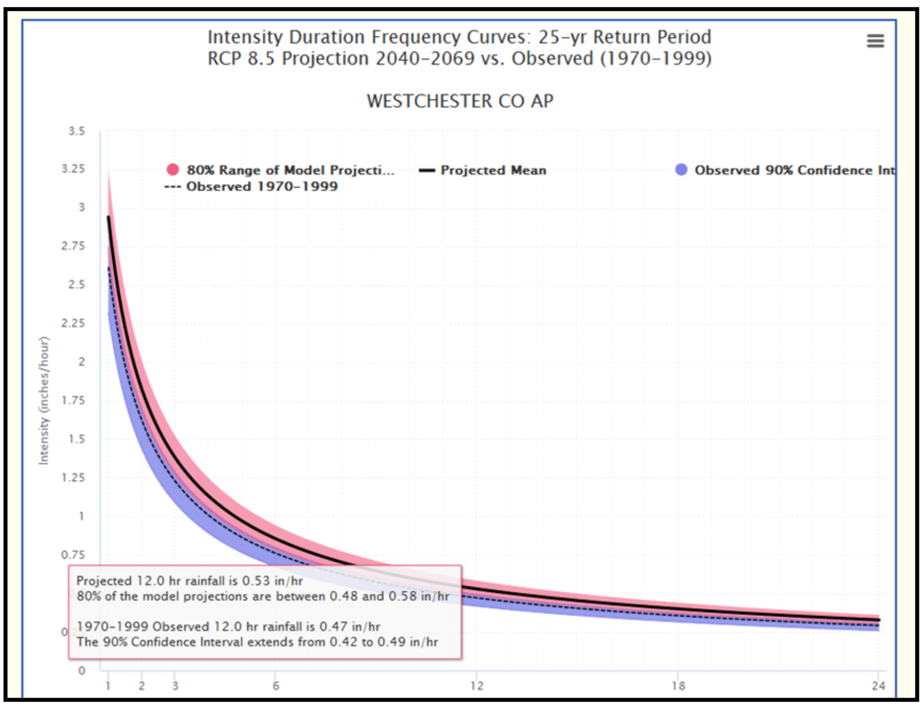


Figure 6. Projected increase in average rainfall intensities.

The types of rainstorms the Bronx River Corridor experiences have also changed over the last several decades, a trend that is expected to continue (Figure 6). The projected mean of rainfall intensity (solid line) is expected to increase over observed rainfall intensity (1970-1999) during larger and infrequent rainfall events. Figure 6 shows the projected average rainfall intensity for a 25-year return interval rainfall event (probability of occurring is 0.05 in any given year) with a duration lasting 1 hour to 24 hours. The amount of rainfall depth occurring during intense rainstorms will increase notably over the next 50 years with higher percentages of the annual rainfall falling during intense storms between short seasonal droughts.

A continuation of the current rainfall trends could also lead to changes in streams and rivers whose physical shape is maintained by a balance between the amount of water flowing through them and the surrounding landscape. The Bronx River and its tributaries have been disturbed by human activities (impervious land cover, dams, etc.) over the last 100 years and could experience significant damage during an intense rail fall event. The ability of the river to return to an equilibrium condition following intense storms will become more difficult as the frequency of damaging rainfall events increases. The result could take the form of increased streambank erosion, greater flood debris risks as more trees and gravel are transported downstream, and reduced water quality.

These climate deviations have the potential to change the appearance of the Bronx River corridor. The greater intensity of the rainfalls could contribute to morphological adjustments of the channels and longer periods of drier weather exposing the river bottoms more frequently and for longer duration during low flow periods. The result of these changes could continue to destabilize stream banks, create warmer water conditions during the summertime, and provide for the colonization of new plant species typically seen today in warmer southern climates.

3.3 Land use and land cover

Land cover is defined as the material that blankets the earth's surface. Land cover includes trees, grass, asphalt, water, bare soils, etc. Land cover is altered by land uses and the distribution of land cover within an area that drains to a stream often governs the stream's health. The collection, conveyance, and retention of water within an area whose rainfall runoff drains to particular locations on a stream (the stream's watershed) are influenced by land cover. Native soils allow rainwater to infiltrate deep into the ground but by covering up native soil with an impenetrable material such as asphalt, the percolation of water into the soil will be reduced. This increases the conveyance speed of runoff into proximal small streams which results in a reduction of water storage in streams, wetlands, and floodplains. A change in land use that results in significant increases in impervious surfaces will result in increased flooding downstream and erosion of the stream's bottom and sides. Stormwater laws seek to mitigate this negative impact of land use change by requiring development of large sites to hold and slowly release the increased runoff from impervious surfaces. These laws are designed to help prevent flooding of downhill neighbors and infrastructure.

Changes in land cover can also contribute to increased transport of contaminants into a river. A region with a lot of impervious areas versus a region with well-buffered water courses and abundant wetlands and grassy areas will transport contaminants and water to the system faster without any significant absorption or filtering before reaching the streams and rivers in the watershed.

Hydromodification is a term that describes what happens to streams when a stream's watershed has undergone a land use transformation resulting in an increase of impermeable surfaces and the corresponding increase of water volume. Studies have shown the magnitude of flow amplification increases generally in proportion to the percentage of impervious surface area. For example, discharge resulting from frequently occurring rainstorm events could be more than ten times higher compared to an unaltered watershed when 20 percent of the watershed is paved (Stein et al., 2012).

Land use cover for the Bronx River watershed was determined using 1999 land satellite imagery with approximately 60 percent of the watershed draining to the Bronx River corridor categorized as developed as shown in the right hand columns of Table 2 and Figure 7. The average impervious percentage of the developed land cover in the watershed is estimated at 35 percent (10.3 mi^2), so roughly 21 percent of the entire watershed is covered with impermeable surfaces. Most of this land change occurred in the middle to late part of the 20th century, therefore significant hydromodification of the Bronx River and its tributaries due to land development began 60 to 80 years ago.

Land Cover	Square Miles	Percent of Watershed		Land Cover	Square Miles	Percent of Watershed
Vegetation	14.0	28.6		Low-Density Residential	15.1	30.7
Water	3.4	7.0		Medium-Density Residential	6.9	14.1
Soil/Exposed Rock	0.5	0.9		High-Density Residential	5.6	11.4
Recreational Grass	1.0	2.0		Commercial/ Industrial	1.7	3.4
Undeveloped	1.0	2.0				

Table 2. Land use cover in the Bronx River watershed (1999 Land Satellite Imagery)

3.4 Human history of the corridor

While the natural character of the watershed exerts important controls on river morphology and behavior, the long history of human alterations along the Bronx River and its watershed has permanently altered the natural hydrology and morphology of the Bronx River in significant ways. Hydrologically, the river's water supply was reduced by 25 percent when the Kensico Dam was completed at the upstream end of the watershed in 1915 (Figure 8; Web citation 1). The upper reaches of the watershed now flow into the upstream reservoir to supply water to New York City. The reservoir, extending to North Castle, NY, is primarily supplied by water diverted over 100 miles from the Catskill Mountains. Despite the diversion of flow into the watershed, the reduction of flow to the Bronx River downstream has likely depressed peak stages during large storm events, although no stream gauge records are available prior to 1915 to directly document the impact.

Records of the USGS stream gauge in Bronxville, NY operating from 1944 to 1999 reveal how (sub)urban development in the watershed has increased peak flows on the Bronx River during this time (Figure 9), although the higher peaks accompanying the increase in impervious surface area are likely still less than the natural peaks that were experienced prior to construction of Kensico Dam. Peak annual flows increased in size from 1944 to 1968 before stabilizing around 1969 when full build-out was achieved (Web citation 2). The extensive development is reflected on land use maps (Figure 7) and soil maps of the watershed downstream of Kensico Dam where urban soils (i.e., soils altered in some manner by human activity) and udorthents (i.e., disturbed soils where the well-developed upper horizons have been removed, filled or graded) predominate (Web citation 3). The original pre-disturbance soils appear largely derived from parent materials composed of fine-grained sediments, so are likely sensitive (i.e., more prone to erosion) to changes in watershed hydrology. The increase in runoff from impervious surfaces has been shown to impact channel morphology and stability when the percentage of impervious surfaces exceeds only 10 percent of the total watershed area (Booth, 1990) whereas 21 percent of the Bronx River watershed is covered in impervious surfaces (see Section 3.3 above). Although the Bronx River may not be as impacted as would be expected given that peak discharges have likely decreased since completion of Kensico Dam, tributaries entering the river downstream of Kensico Dam likely have been impacted as the associated subwatersheds have impervious surface coverage percentages much greater than the basin wide average of 21 percent. Increased channel instability and bank erosion along these tributaries could, in turn, impact the Bronx River, particularly at their confluences.

Numerous human activities within the channel and floodplain have directly impacted the morphology of the Bronx River in significant ways. Floodplain developments have created new valley constrictions (Figure 10) that may impact the river in a similar manner to natural constrictions (Figure 4). The numerous road crossings over the river, where the bridge opening is narrower than the channel, may also create the same backwatering, sediment deposition, and channel migration issues associated with valley constrictions. The current planform of the Bronx River is predominately straight, an artificial condition created largely during the construction of the Bronx River Parkway opened in 1925 (see Section 4.2 below). The unaltered natural planform of the river was highly sinuous as demarcated by some of the town boundaries originally drawn along the once meandering river (Figure 11). In addition to the straightening, a number of check dams (Figure 3) were also constructed at the time the Bronx River Parkway was created to form small ponds along the new roadway. Several other dams were present on the river even earlier as part of numerous mills operating during much of the 18th and 19th centuries that manufactured paper, flour, pottery, and other goods (Web citation 1). Their presence may have dictated the subsequent path of the river and siting of the extant check dams.

Human alterations have impacted the river's planform, gradient, and dimensions both directly (e.g., construction of check dams on river) and indirectly (e.g., changing watershed hydrology). Further details on these and other modifications to the Bronx River, particularly those directly in or adjacent to the channel, and their continuing impact on channel stability and aquatic habitat is the focus of the geomorphic assessment and hazard assessment.

4.0 GEOMORPHIC ASSESSMENT RESULTS

Identifying how human alterations along one part of a river channel or contributing watershed are potentially linked to channel adjustments elsewhere are essential for developing corridor management plans that not only reduce hazards and improve habitat conditions at the site of restoration but also promote equilibrium conditions along the length of the river. This can help prevent a project in one location from simply creating another problem elsewhere. Within this context, a geomorphic assessment of the Bronx River is essential before identifying the best restoration solutions for addressing the flooding, erosion, and habitat degradation problems caused (or exacerbated) by the extensive human modification of the channel and surrounding watershed. The geomorphic assessment presented below consisted of five parts: 1) reach and segment delineation; 2) analysis of channel changes; 3) mapping of channel features; and 4) channel classification. Topographic surveys, an important component of geomorphic assessments, will be conducted as part of Volume II of the Plan once priority areas for restoration are identified (see Section 6.4 below). The topographic surveys will be used to create conceptual restoration designs and to verify the results of the channel features mapping and other aspects of the geomorphic assessment.

4.1 Reach and segment delineation

Since different portions of a river can respond differently to the same natural and human influences, the first task of the Bronx River assessment was to subdivide the river into distinct reaches of varying length that have been sequentially numbered from the downstream end with a "BR" prefix to indicate its location on the Bronx River (Figure 12 and Table 3). Within a given reach, the river has a uniform character and is likely to respond similarly to changing channel or watershed conditions, while the adjoining reaches upstream and downstream are of a different character and may respond in other ways. Reaches that share similar traits are referred to as "like" reaches and an understanding of channel response or effective restoration techniques gained in one reach may apply to other "like" reaches. The break points between different reaches are located at: a) large tributary confluences, b) grade controls (e.g., ledge across the channel), or c) abrupt changes in channel slope or valley confinement. The influence of human factors (e.g., dams, straightening, bank protection) is typically ignored when defining reach breaks, but on the Bronx River, given the extensive human modifications, significant slope breaks (e.g., larger dams) and constrictions (e.g., narrow bridges and culverts) created by human activities were also included (Table 3).

Reaches downstream of valley constrictions (e.g., Reaches BR03 and BR19) occupy more confined valleys where the river channel has a greater likelihood of impinging against the higher valley walls – such valley side slopes are often composed of erodible sediment and not bedrock along the Bronx River. Therefore, the potential for significant and rapid sediment production in these locations in the event of mass failure can affect channel morphology differently than less confined reaches (i.e., in wider portions of the valley) where the channel will predominantly encounter low banks of floodplain sediments (e.g., Reach BR17) and less likely to experience a sudden influx of sediment. Reaches downstream of large tributary confluences (e.g., Reach BR05) often have morphologies different than reaches immediately upstream of the confluence (e.g., Reach BR06), because of the higher discharge and focused input of sediment. The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach breaks themselves. Consequently, the locations of the reach breaks are often points of the greatest channel instability and where the impacts of human modifications elsewhere in the watershed may be most strongly expressed in the form of active bar formation, bank erosion, and channel migration. For example, excess sediment generated by land clearance in a large tributary watershed is often likely to accumulate, potentially miles downstream, at the confluence with the main stem of the river – a reach break – where flow diversion around the developing sand/gravel bar may lead to erosion of the opposite bank. [“Main stem” definition: In hydrology, a main stem (or trunk) is the primary downstream segment of a river, not its tributaries. Water enters the main stem from the river's drainage basin or watershed, the land area through which the main stem and its tributaries flow.] Delineating the reach breaks and characterizing the morphological conditions present within each reach are, therefore, critical for determining whether certain features reflect natural processes or the impacts of human activities.

The identified reaches are later subdivided further into shorter “segments” (Section 6.1 below), reflecting the location and occurrence of various human impacts (e.g., channel straightening, bank armoring) and channel responses to those impacts (e.g., bar deposition, redeveloping meanders). Segmenting the stream into smaller sections based on human impacts and channel response serves as the basis for identifying the need for flood mitigation, erosion control, and habitat restoration at various points along the stream. The reaches and segments are of uneven length and the breaks between each occur where there are observable changes resulting from various natural and human conditions.

The main stem of the Bronx River in Westchester County was subdivided into 20 reaches with five reaches on Grassy Sprain Brook and three on Laurel Brook (Figure 12 and Table 3). The reaches were first identified using topographic maps, aerial photographs, and LiDAR with later verification during the channel features mapping. On the main stem, three of the reach breaks occur at major tributary confluences, three occur at valley expansions, and seven at valley constrictions (Table 12). The 28 reaches in total were later subdivided into 97 segments as described further in Section 6.1 below.

4.2 Analysis of channel changes

Channel changes through time were documented by comparing surveys, early maps, topographic maps, and historical aerial photographs from various years. Previous surveys and early maps were acquired during a visit to the Westchester County Archives and from their online collection, including detailed maps showing the location of the Bronx River in 1914 just prior to construction of the Bronx River Parkway (Web citation

4). The 1914 survey maps were georeferenced in ArcGIS, so comparisons could be made with the existing position of the river (Appendix 2). Historical topographic maps surveyed from 1888 to 1890 are available online for the full length of the river, while only the northern half of the river in Westchester County is available based on a 1932 survey (Web citation 5). A topographic map from the 1980s and aerial photographs back to 1994 are available through Google Earth. All of the maps were visually inspected and compared to identify changes in the channel's position and planform.

The history of channel changes on the Bronx River is marked by an extended history of artificial channel straightening. The earliest maps, although not of sufficient resolution to accurately compare with later maps, demonstrate the Bronx River had a meandering planform prior to the industrialization of the corridor (Figure 13). Despite the construction of the railroad in the Bronx River valley by 1888-90, long meandering sections of the channel remained (Figure 14a). However, the impact of mills and industrialization on river morphology is evident on the historical topographic map surveyed at that time in the form of reservoirs (upstream of dams) and artificially straightened sections of the channel (Figure 14b and 14c). Three hallmark features on topographic maps are useful for identifying where artificially straightening occurred: 1) missing meander loops along sections of otherwise meandering river; 2) a channel "hugging" the edge of the valley despite a wider floodplain across which the river could flow; and 3) the presence of old abandoned meanders (i.e., oxbows) demarcating the position and planform of the former channel (Field, 2017). Ground photographs of the Bronx River from 1913 further corroborate the straightening as well as document the numerous buildings that once existed along the river's edge at that time (Figure 15).

Evidence of additional straightening on the Bronx River in the 20th century is documented by comparing maps and aerial photographs from different time periods. In preparation of Bronx River Parkway construction, detailed survey maps of the river were created in 1914 showing some portions that are meandering with the hallmarks of straightening evident elsewhere (Figure 16). The river's overall sinuosity in 1914 was 1.20, but is only 1.07 today (Table 4 and Appendix 2), indicating that extensive additional straightening occurred after 1914. (Sinuosity is defined as the ratio between channel length and the straight line valley length with a sinuosity of 1.0 representing a completely straight channel with no meanders.) The additional straightening occurred prior to 1932 (survey date of the 1938 topographic map) and is assumed to be the result of construction of the Bronx River Parkway opened in 1925. Nearly 94 percent of the channel's length is considered to have been artificially straightened at some point (Table 5) with some areas likely straightened multiple times since European settlement of the valley nearly 400 years ago (Figure 17).

Artificially straightened channels are inherently unstable, so the subsequent natural reformation of meanders is a common process on rivers throughout the northeastern United States (Field, 2007). The Bronx River is no exception as several new meanders have formed along previously straightened reaches of the Bronx River (Figure 18 and reflected in those reaches whose length increased since 1914 as shown in Table 4). About 25 percent of the river's length has reformed meanders since the extensive straightening undertaken during the Bronx River Parkway construction and earlier (Table 5). While uncertain given the poor map resolution, the Bronx River was likely extensively straightened prior to the survey of 1888-90 with the meandering pattern seen on that historic topographic map representing an earlier period of meander reformation prior to parkway construction. Given that nearly 400 years have passed since European settlement of the valley, multiple cycles of artificial straightening and subsequent natural meander reformation have potentially occurred.

Meander reformation begins when flow in the straightened channel is deflected by sediment deposited at tributary confluences (and other locations) or at blockages created by trees falling into the channel. Ultimately, to reach an equilibrium condition, rivers minimize the amount of change that occurs from one location to the next, so a sharp right-angle bend in a river where all the change in flow direction occurs at one point will be transformed into a smooth meander bend where only a minimal amount of change in flow direction occurs at any given point along the meander's length. Such changes can only occur where the river is free to adjust its bed and banks, so armored reaches often remain locked in a straightened configuration until such time the armor begins to fail, the forces exerted on the banks exceed a threshold necessary to mobilize the armor, or the river's flow escapes the channel with sufficient force to carve an entirely new channel/meander across the floodplain. As a result, the meander reformation process can occur unexpectedly and rapidly during a single flood event along sections of channel that have not experienced any significant change for decades. Meander reformation has likely already occurred on the Bronx River where the banks were unprotected or the channel was otherwise prone to adjustment (e.g., low banks where floodwaters could escape more easily onto the floodplain with force). Areas that remain straight are inherently at risk of rapid meander reformation with the intendant erosion and flooding hazards associated with that process. Identifying the condition of armored banks and other characteristics of the present channel through channel features mapping can help discern where the risk of future meander reformation is greatest.

4.3 Channel features mapping

Several channel features were mapped continuously along the Bronx River in order to: 1) identify locations of channel instability and sensitivity; 2) characterize physical habitat conditions; and 3) document the impacts of past human activities on channel morphology and evolution (e.g., channel armoring and dam construction). The mapped features include: 1) bank stability (e.g., eroding areas); 2) grade controls (e.g., dams, waterfalls); 3) past management activities (e.g., bank armoring, channel straightening); 4) bar types (e.g., point bars, mid-channel bars); and 5) habitat features (e.g., woody material, log jams, deep pools). The mapping for most features was completed using a hand-held ArcPad computer with an embedded Trimble GPS and loaded with 2016 digital orthophotos as a base map. Bank stability was mapped with different equipment (Trimble 7X series) and the results also utilized in the erosion hazard assessment (see Section 5.4a below). Straightening, re-meandering, and the presence of mature riparian vegetation were mapped while viewing digital orthophotographs on a computer and later verified in the field. The beginning and end points of features mapped in the field (e.g., an eroding bank) were recorded, so GIS shapefiles could be created and analyzed. For example, the channel instabilities resulting from straightening more than 90 percent of the Bronx River (see Section 4.2 above) are manifest in the 52 percent of the channel banks that are either eroding or armored (Table 5). Channel features mapping was also conducted on Grassy Sprain Brook and Laurel Brook and the results are discussed separately in Section 4.3f below. The channel features mapping data were used to characterize several identified channel types (see Section 4.4 below) and to quantify the "needs" of each delineated segment (see Section 6.1 below).

The ArcView GIS shapefiles of the mapped features detail the character of the channel bed and banks for all points along the Bronx River in Westchester County (Appendix 2). The GIS shapefiles can be used to compare the location and distribution of multiple mapped features (see discussion below). Based on an analysis of the GIS shapefiles, a statistical summary was produced to reveal the percentage of stream length along which certain conditions are found (e.g., percentage of eroding banks) or numbers of certain features observed (e.g., log jams) (Table 5). In addition to channel straightening, the channel features mapping reveals the extent and impact of other human alterations of the Bronx River channel and floodplain including bank armoring, dams and impoundments, stream crossings, and artificial fill on the floodplain. The channel features mapping also enables characterization of the habitat quality that can then be compared to the distribution of various human impacts to assess the potential causes of habitat degradation.

4.3a Bank armoring

Armoring has been placed on more than 50,000 feet (nearly 10 miles) of riverbank, representing 34 percent of the total bank length along the Bronx River in Westchester County (Table 5); armoring is found on both banks simultaneously along 21.8 percent of the river's length (Table 5). Several different armoring and bank protection techniques have been used on the Bronx River, including the use of large riprap stone, walls made of concrete or stacked stone, gabion baskets, or boulder groins/deflectors (Figure 19). Typically, armoring is placed on river banks that are actively eroding as was the case for a recent bank stabilization/restoration project just downstream of Harney Road (Figure 19d). However, much of the armoring on the Bronx River may have been placed during the straightening of the river during parkway construction in anticipation of instability and in an effort to maintain the straightened course along which the parkway was built.

Where a river is extensively armored as is the case on the Bronx River, adjacent unarmored areas are prone to aggressive bank erosion and bed scour. This is well illustrated just downstream of Tuckahoe where armoring is continuous on both sides for a long distance through town with a large deep scour pool developed and surrounded by eroding banks immediately after the armor ends (Figure 20). In many places along the Bronx River the armoring was completed decades ago with the armor now failing in places, allowing erosion to attack the exposed bank (Figure 21). Three and a half percent of the armored banks are classified as failing for a total of 1,785 feet or 1.2

percent of the total length of the riverbanks. A short section of failed armor amidst a long section of intact armor is particularly prone to severe erosion as the river's capacity for erosion (i.e., sediment transport) is focused in a small area. Failed armor represents a potentially severe hazard as the rate and amount of bank recession at that one place will be much greater than along an unprotected bank. On unarmored banks, only a little bit of erosion occurs at any one place as the river's capacity for erosion is evenly distributed along the entire bank length in a reflection of a river's tendency towards an equilibrium condition. As the armor on the Bronx River continues to age and begins failing in new areas, the potential for severe and damaging erosion could increase if left unattended.

4.3b Dams and impoundments

A total of 8 dams are extant on the Bronx River in Westchester County (Figure 3 and Appendix 2). Several of the extant dams are small check dams built with the Bronx River Parkway to create small ponds designed to increase the aesthetic appeal of the new roadway (Web citation 1). Although fine sediment held in suspension can pass over a dam with the river's flow, coarser sediment transported along the bed of the channel is blocked and deposited upstream of the dams. The largely sediment-free water that passes downstream as a result of the upstream deposition often results in bank erosion or incision of the channel bed with armor often later placed on the banks to prevent further erosion. These channel adjustments associated with dams have been well documented throughout the United States (Brandt, 2000; Kondolf, 1997; Williams and Wolman, 1984) and are well illustrated upstream and downstream of the check dam at Harney Road (Figure 22). Similar features can be seen at some of the other dams (Appendix 2) but are sometimes muted by other features such as bedrock that has limited scour downstream of the check dam in Scarsdale (Figure 3) or could be related, at least partially, to other activities besides the dam as is the case with the extensive bank armoring in Tuckahoe where a dam is also present (Figure 20). While some open water is still present behind some dams, the ponds are now predominately choked with sediment and characterized by shallow stagnant water and emergent (often invasive) vegetation. While the dams are generally small, they also impact flow in the channel with areas prone to flood inundation on the valley bottom are sometimes located upstream of the dams (see Section 6.2 below).

4.3c Stream crossings

The Bronx River is crossed by 62 bridges and one culvert in Westchester County with an average of 4.5 crossings/mile (Table 5). While the dimensions of the bridge openings were not measured during the channel features mapping, many were observed to be narrower than the channel. In such cases, the crossings can act similar to dams during large flows. Since flow in a channel (and floodplain at high flow) cannot instantaneously transition through a narrower bridge/culvert opening, backwatering occurs upstream and results in deposition as flow velocity declines in the temporarily ponded area. Flow velocities increase through the narrower constricting structure, enhancing the scouring effect of the sediment-starved flows downstream. While not all bridges are narrower than the channel, numerous examples of upstream deposition are observed (Figure 23a) with fewer examples of downstream scour (Figure 23b) in large part due to the extensive armoring of the channel. The presence of several bridges per mile along the river results in frequent disruption of natural river processes that limits the ability of the river to achieve an equilibrium condition and inhibits ecological continuity and connectivity.

4.3d Artificial fill on the floodplain

Human impacts on channel morphology are not always the result of activities in the channel itself as is the case with channel straightening, bank armoring, dams, and stream crossings as described above. Many places along the Bronx River have had artificial fill placed on the floodplain, resulting in channel adjustments despite no direct activity in the channel. Although the location of fill was not a mapped channel feature, its presence was noted in the field and on maps (Figure 10) with the degree of morphological impact related to the degree to which the channel and floodplain have been constrained. Where the artificial fill occupies only a limited portion of the floodplain, as at the Metro-North Commuter Railroad in North White Plains (Figure 10), the impacts on channel morphology are limited (Figure 24a) with no excessive erosion or bank armoring compared to adjacent reaches. In contrast, approximately half of the entire floodplain has been filled across from Scout Field in Bronxville. The fill extends all the way to the edge of the river channel with the right bank and adjoining surface now much higher than the left bank, resulting in frequent flooding problems at the ball field and bike path along the river on the lower left bank and floodplain. In addition to increased inundation, the increased flow velocities associated with constraining half of the natural floodplain may also be contributing to the higher levels of erosion in the area and the resulting need to construct a bank stabilization project incorporating armor and boulder groins (Figure 24b).

A long straightened reach through Mount Vernon is constrained by artificial fill both on the left and right bank such that the channel can no longer access a floodplain on either side as the raised banks on both sides of the channel cannot be overtopped even during the largest floods. Bank conditions in the channel were hard to observe due to significant growth of invasive species but armor appears where visible and is likely present along the entire length of the channel given the railroad and parkway running along either edge of the channel. Bank erosion due to the constraining artificial fill is, therefore, not observed but the habitat conditions in the channel seem to have been impacted as illustrated by the absence of wood in this section (which can be easily flushed by the high velocities generated by the constrained flow) (Figure 24c). The above examples illustrate why human activities occurring outside the channel must be considered when attempting to identify the causes for bank instabilities and habitat degradation in the channel.

4.3e Habitat features

To link human impacts to habitat degradation in the channel, the channel features mapping made observations related to the physical habitat conditions in the channel and adjacent corridor. In general, the extensive human impacts observed on the Bronx River and discussed above lead to degraded aquatic habitat. Artificial straightening (due to the shortened length) and floodplain fill (by constricting the flow) energize the channel such that important habitat features like pools, bars, and wood are washed out of the channel. The river banks are often destabilized as well, leading to channel widening and, as a result, shallower flows that result in warmer (more stressful) water temperatures during low flow summertime conditions. Straightening also leads to largely unidirectional flow oriented down river whereas meandering streams have complex multi-directional flow patterns down the channel, across the channel, and up and down through the water column. Flow complexity creates heterogeneous habitats that are closely spaced, so organisms can find the variety of habitats required for survival in close proximity. Flow complexity also leads to the segregation of particles of different size, so rather than having fine sediment embedded in gravels, typical of straightened channels, fine sediments and organics are separated from gravels such that habitat is created for macroinvertebrate colonization and trout spawning, respectively.

Given the severity of human alterations on the Bronx River, the impacts to aquatic habitat are, not surprisingly, evident in the channel features mapping. More than 500 large isolated pieces of wood or debris jams (largely composed of large wood) are found along the river (Table 5). The total count equates to 36 pieces or jams of wood per mile whereas 175-225 pieces/mile are believed to have occurred naturally on northeastern rivers (McKinley et al., no date). The limited amount of wood able to be retained in the straightened and constrained channels that characterize the Bronx River reduces the potential to create and sustain cover habitat, flow complexity, and sites for macroinvertebrate colonization (among other habitat attributes associated with wood in the channel). The length of all depositional features combined is less than 14 percent of the river's mapped length (Table 5) with long lengths of the river containing no depositional features at all (Figure 25). On a naturally meandering stream, point bars on either bank might typically be found along 50 percent or more of the river's length. In contrast, straightened and constrained channels are able to efficiently transport sediment through long stretches of the channel with deposition concentrated only in areas where the velocity and transport capacity of the flow is reduced such as at impoundments and undersized bridges. The lack of depositional features along most of the river's length (and concentration of sediment to small areas) reduces flow complexity, limits particle size segregation, and contrasts with a river in equilibrium where sediment, and its associated habitats, would be evenly distributed along the channel's length.

Despite the extensive human impacts to the Bronx River, positive habitat attributes are also present. The number of deep pools mapped on the Bronx River totals 283, or 20 per mile (Table 5), a value higher than might be expected on a naturally meandering stream with similar dimensions. Pools are typically spaced at a distance equal to 5 to 7 times the channel's bankfull width on unaltered streams (Leopold, 1994). ["Bankfull" definition: The water level, or stage, at which a stream or river is at the top of its banks and any further rise would result in water moving into the floodplain.] Taking 78 feet as the channel's bankfull width for an undisturbed condition on the Bronx River (Field and Fowler, 2015), the historically meandering river that existed prior to European settlement of the region may have had less than 14 pools/mile. The higher frequency of pools today should be considered a result of (rather than in spite of) the human impacts to the channel with deep pools frequently observed downstream of dams, bridges, and long armored reaches. However, pools alone do not equate to high quality aquatic habitat and are best complemented with other habitats (e.g., riffles) in close proximity. Another positive habitat attribute on the Bronx River includes the mature riparian buffer that is present on 21.8 miles, or 78 percent, of the total bank length mapped (Table 5) with the tall trees providing shading to reduce summertime warming of the channel and a source of wood recruitment to the channel (Figure 26). Given the concerns of flooding along the river, much of this recruited wood may ultimately be cut and removed from the channel, so sustainable habitat improvements along the river may require removing human conflicts from the corridor, where possible, to allow wood and other habitat features to remain undisturbed.

4.3f Tributary mapping

The channel features mapping of two tributaries, Grassy Sprain Brook and Laurel Brook, reveal many of the same human impacts observed on the main stem of the Bronx River. The lower 1.7 miles of Grassy Sprain Brook that were mapped are 100 percent straightened, nearly 60 percent armored or eroding, and depositional features were found along only 6.3 percent of the mapped length (Figure 27a and Table 5). Despite those impacts, the density of wood per mile is higher than on the main stem (as wood may be more easily retained on a narrower channel), but still much lower than a natural unaltered channel in the northeast (McKinley et al., no date). The frequency of pools is approximately the same as might be expected on a natural river system, although their occurrence, as on the main stem, seems more closely related to the impacts of bridges and armoring. The alterations along Grassy Sprain Brook are likely increasing sediment delivery downstream and contributing to the bank instabilities that led to the 2018 construction of a bioengineering project at the confluence with the Bronx River (Figure 27b).

Laurel Brook is much smaller than Grassy Sprain Brook and other tributaries, but was chosen for mapping since its confluence is located in the area of Scout Field where flooding and erosion are frequent problems. Although the upper reaches of Laurel Brook are incised into river terrace sediments, the upper brook as well as the lower reaches are straightened, armored, and further constrained by a sewer line running along the channel (Figure 28). Given the rapidly declining slope, considerable sediment is accumulating in the mapped lower portion of the channel and at the confluence with the Bronx River (Table 5). While sedimentation at the confluence may not be the primary cause of channel instability and frequent inundation at Scout Field, deposition at the brook's mouth could certainly be a contributing factor.

Manhattan Brook and Fulton Brook in Greenburgh and White Plains, north of the Westchester County Center, were also considered for mapping, but great lengths of those tributaries are piped underground through long culverts so do not lend themselves to the mapping of geomorphic features. The lack of data collection from these areas, however, should not be construed as a lack of human impact. Similar to the two mapped tributaries, greater sediment transport capacity on these (and other) tributaries, given the channel constraints and high levels of impervious surface in their contributing watersheds, may explain the presence of erosion at their confluences with the Bronx River (Appendix 2).

4.4 Channel types

In addition to the specific channel features mapped, short geomorphic segments (see Section 6.1 below) were identified during the course of the mapping. After completing the mapping of a given segment, additional observations were made (e.g., presence of floodplain fill, invasive vegetation) to better characterize the conditions of each segment. Although each segment has unique characteristics, many share similar traits with other "like" segments. Recognition of these similarities between segments led to the creation of five channel types that collectively embody the range of conditions observed on the Bronx River and mapped tributaries (Figure 29, Table 6, and Appendix 3). By classifying the segments into five channel types, the causes for flooding, channel instability, and habitat degradation identified in one segment may provide clues to the cause of similar impacts in other segments of the same channel type. Similarly, successful restoration efforts in one segment may also prove effective in other segments similarly classified, while other channel types may require different restoration strategies for addressing what are likely to be different types of flooding, erosion, and habitat degradation problems. The geomorphic segments were created in the field prior to the identification of the channel types, so, in a few minor instances, two channel types may be present within a single segment with the type more dominant selected to represent the segment. The channel types are briefly described below, detailed and illustrated in Appendix 3, and utilized in the restoration planning process (see Section 6.1 below and ultimately Volume II).

The 5 channel types are: 1) confined bedrock-controlled channels; 2) partially confined channels; 3) artificially confined, armored, and straightened channels; 4) channels with reformed meanders; and 5) impounded channels. Although limited in extent, ***confined bedrock-controlled channels*** are those where both banks are constrained by high banks that contain large floods since no floodplain can be accessed. Confinement can be the result of bedrock on just one bank, as is the case immediately downstream of the check dam in Scarsdale (Figure 3). Where present, bedrock is usually found only on the channel bed and at the base of the constraining bank, but its presence is still significant as channel adjustments are unlikely where bedrock outcrops. ***Partially confined channels*** are segments confined on only one bank with floodplain access available on the other bank. The partial confinement may be due to the river flowing against a natural landform (e.g., river terrace) as along the left bank downstream of Scarsdale or artificial fill as at Scout Field (Figure 24b).

Artificially confined, armored, and straightened channels have maintained an artificially straightened condition due to either complete or partial armoring on both banks and also lack floodplain access as a result of confinement. The confinement in this channel type is the result of artificial constraints and generally prevents any overbank flow even during the largest floods (e.g., section through Mount Vernon highlighted in Figure 24c), although in some instances the banks may be low enough where overtopping in large floods is possible (but not as frequent if the natural floodplain level was still present) (Figure 20). The total length of artificially straightened channels indicated in Table 5 does not match the length of artificially armored and straightened channels in Table 6 as some straightened channels may only be partially confined (and designated as partially confined channels), while others may be classified as channels with reformed meanders (and designated as having been straightened in Table 5).

Channels with reformed meanders are previously straightened channels where meanders are in the process of reforming or have completely reformed. The antecedent straightened channels were likely not armored when the reformation of meanders occurred (or meander reformation occurred after such armor failed), but in many instances armor has been placed on the banks subsequent to the meander reformation (Figure 22b). Since nearly the entire length of the Bronx River has been artificially straightened, none of the existing meanders are believed to have been present prior to European settlement of the region and are thus all reformed from a straightened condition, although in some instances that reformation may have occurred prior to, and its planform left undisturbed by, construction of the Bronx River Parkway in the early 20^{th} century (e.g., Segment 10G).

Impounded channels are those segments upstream of dams or weirs where the flow is impeded enough for velocities to be so significantly reduced that significant deposition of fine sediment is occurring and large bars have formed. As a result of the deposition, flow depths are generally much shallower than in other channel types (Figure 22a). For larger dams, the impoundment level is high enough to overtop the banks of the channel and create a wide pond across the floodplain (e.g., just upstream of Tuckahoe), while in other areas, such as upstream of Harney Road, the impoundment is largely contained within the channel margins and the impoundment more narrow and linear.

5.0 CORRIDOR MANAGEMENT PLAN STRATEGY

The geomorphic assessment results are focused on how human impacts have altered channel morphology, river processes, and aquatic habitat. These alterations, in turn, also have the potential to impact public safety and human infrastructure through severe flood inundation and bank erosion. In developing strategies for corridor management and restoration, these potential risks must also be considered in addition to how proposed activities may improve river condition and habitat. Projects that can both reduce hazards while improving river condition and habitat will be of a higher priority than projects that improve conditions on the river but exacerbate hazards or projects that reduce hazards but worsen river stability and habitat degradation. In identifying and prioritizing such projects, a clear statement of the BRCSMP goals and objectives are required and identification of risks to public safety and human infrastructure detailed. After stating the project's goals and objectives, the methods and strategies used to prioritize the location of future restoration projects for improving river stability and aquatic habitat are outlined below followed by a similar discussion of the methods and strategies used to identify priority sites for flood and erosion hazard mitigation. Section 6.0 below will present the initial results and findings of these prioritization approaches with Volume II to detail the process of selecting the location and types of projects that will ideally simultaneously improve river stability and aquatic habitat while mitigating flood and erosion hazards.

5.1 Bronx River corridor wide goal and objectives

The single goal of the BRCSMP was defined as the achievement to protect people, communities, local economies, river processes, water quality, and wildlife within the river corridor as a foundation for initiatives that provide for sustainable communities and environmental protection. To achieve this single goal, eight supporting objectives described below have been identified:

1. Reduce sedimentation and erosion hazards

Debris in stream channels and along the banks of steams are often one of the primary causes of catastrophic flooding, water quality impacts, and severe erosion. Debris, from the perspective of hazards, is anything that can become mobilized during the course of a storm event (e.g., sediment, logs, lumber, trash) and excessive erosion can lead to an increase in sediment production and debris recruitment. Debris can cause channels to infill or stream crossings to become blocked, increasing the likelihood of flooding, erosion, infrastructure damage, and habitat degradation. Through best management practices and stream restoration projects, erosion hazards and the amount of debris moving through the system can be minimized. Establishment of an equilibrium condition on the river will enable mobilization of the natural sediment load through the river system and prevent the excessive sediment build up that now occurs on certain sections of the Bronx River.

2. **Improve water quality**

Chemical, physical, and biological characteristics of water can negatively affect many aspects of communities along the river corridor and those further downstream. Improving water quality is often mentioned by regulators and politicians, but funding is often limited for achieving these improvements. Through scientific measures, benchmarks can be established to measure water quality improvements. Water quality can be improved by reducing turbidity, nutrients, and pathogens in the water. All other objectives listed here that provide for more natural stream conditions will help in this effort. Water quality can also be improved by reducing human-made floatable debris that is often swept off adjacent land during rain storms and into storm drains that eventually outlet into streams and rivers. Floatable debris breaks down into smaller pieces (microplastics) which make their way into the ecosystem where the smallest of animals consume them and then move up the food chain. Floatable debris reduction can be accomplished through educational campaigns such as the storm drain stenciling program "drains to river" campaign. Physical infrastructure such as debris booms can also be utilized to capture floating debris, including plastics, in a stream and river. These booms should be sited in stream segments that are geomorphically stable and not proximally located downstream of a notable debris (e.g., trees and rocks) source.

3. **Reduce threats to public infrastructure from flood inundation hazards**

The most costly river-related impacts to the local taxpayer are damages or closure to public infrastructure during flood events. Public roadways along with the local sewer and water systems are the primary essential services provided by local governments. Damage to this infrastructure has far reaching impacts and costs. Without these public facilities, local businesses are shut down, residents are stranded, and life comes to a halt. Protecting this infrastructure is essential if a community is to remain sustainable. Only through better engineering, a sound understanding of the geomorphology of the system, and a robust plan to address the most critical threats to public infrastructure can the threat and costs from future flood events be reduced.

4. **Reduce threat to public and private properties from flood inundation hazards**

Homes, businesses, and agricultural operations within the U.S. Federal Emergency Management Agency's (FEMA) mapped Special Flood Hazard Area are at risk of flood damage and can negatively impact living conditions, economic growth, and property values. These areas are recognized by FEMA as having an increased risk from flood damage, so mitigation projects are, therefore, more costly to develop and implement. Homes in these areas often require flood insurance as a security for a mortgage, making them difficult to sell, refinance, and ultimately afford. This has implications on the property owner as well as the local tax base. If mitigating impacts through acceptable flood prevention measures as defined by FEMA prove too costly, removing critical public facilities as well as homes from these areas whenever and wherever possible may be the most sustainable and cost-effective approach to hazard reduction and may also create essential space for restoring natural river processes and channel stability.

5. **Improve aquatic habitat**

American Shad (*Alosa sapidissima*) is one of many fish species known to inhabit sections of the Bronx River. Fish populations can be under duress for a variety of reasons including a lack of habitat, limited food sources, and barriers to fish passage that disconnect habitat and lead to less genetic diversity. Turbidity caused by suspended sediment is an impediment to sustaining healthy fish populations. Insufficient riparian buffers are also a notable contributor to warm water temperatures, another stressor to cold-water species. Through improvements to stream channel stability and riparian vegetation, fish habitat can be preserved and sustained for future generations.

6. **Reconnect disconnected floodplains**

Floodplains are a critical feature in stream health and flood hazard mitigation. Floodplains allow floodwaters to spill into them, spreading flood volumes over a wider space. This increases flood storage, reduces downstream peak discharges, and lessens the resulting flood damages. Floodplains can also store fine sediment and debris, thereby improving water quality in streams after a flood. Floodplain storage capacity allows for better clean-up of debris as well as sediment following a flood, so impacts further downstream are reduced. Floodplains are often cutoff from the stream by physical structures (roads, railroads, fill, etc.) as is the case in the Bronx River corridor (see Section 4.0 above). Floodplain disconnection can also occur through channel incision. Incision results in a drop in the streambed elevation over time, increasing the height between the channel bed and floodplain. Channels that have undergone severe incision can no longer access their floodplains. The results of the geomorphic assessment can be used to identify areas where floodplain connectivity can be restored or flood benches can be developed to increase flood storage.

7. **Reduce invasive species migration**

Invasive plant species have impacted large swaths of the Bronx River corridor causing native stream side plant species to be choked out and altering the make-up of vegetation that feeds the streams ecosystem. Additionally, invasive species often have shallow root systems that reduce the amount of protection from erosion compared to the natural riverbank plant species that have traditionally grown in the region. Where well established, eradication of the invasive species may not be feasible; however, a proactive approach to reduce the impacts of invasive species elsewhere and slow the spread of these species is necessary for stream health.

8. **Restore natural river processes where possible**

Reestablishment of a natural equilibrium condition on the entire length of the Bronx River is unlikely given the extent of human impacts in the channel, corridor, and wider watershed. However, taking advantage of opportunities to restore natural processes where possible can reduce flow velocities, sediment loading, and the potential for rapid erosion and channel migration, not only at the site of restoration but in downstream locations as well. For example, storing sediment evenly along a restored reach results in less sediment moving downstream that might accumulate upstream of a narrow bridge. The restoration of natural processes can reduce risks to infrastructure, improve aquatic habitat, and increase the aesthetic appeal of and recreational opportunities on the river.

5.2 Geomorphic restoration planning and prioritization strategy

Section 4.0 above provides a general understanding of the geomorphic conditions present on the river and the natural conditions and human impacts that led to their development. However, the geomorphic assessment data must be analyzed at a more granular level in order to prioritize areas where restoration projects and other interventions would provide the most benefit and to select the most appropriate strategies to address the problems identified in those priority areas. To achieve a more detailed analysis of the geomorphic and hydraulic assessment, the 28 reaches (Table 3) were further subdivided into shorter segments based on the assessment data (see Sections 5.2a and 6.1 below) and form the basis for developing and evaluating self-mitigating restoration options that will reduce flood and erosion hazards, improve aquatic habitat, and increase recreational opportunities along the river. As described in Section 5.2b below, the priority segments for undertaking restoration are established by identifying the “needs” of each segment. Volume II will identify the most appropriate restoration approaches to address the needs of the various segments and will develop project concepts of various sizes and complexities based on those needs. Some potential projects might address all the needs of a particular segment but may prove too expensive and, therefore, impractical to implement in the short term but could be phased in over time. Others may be easier to implement, although unlikely to address all of a segment’s needs. Through this restoration planning approach, some high priority segments can potentially have the most acute needs addressed quickly, allowing time for more comprehensive projects to develop that could address multiple needs over multiple segments in a more comprehensive and sustainable way.

5.2a Restoration planning methodology

Delineating short river segments along the river with uniform morphological conditions facilitates the selection of appropriate restoration options and their extent, because a single restoration design can usually be applied to the entire length of a given segment. This process is referred to as segment delineation. Each segment has a uniform morphological character that is distinct from the immediately adjacent segments upstream and downstream but may be similar to other segments elsewhere. The segments represent subdivisions of the geomorphic reaches; each segment is identified first by the reach number and then by a sequentially-alphabetized letter starting from the downstream end of the reach. For example, the third segment from the downstream end of Reach 3 is designated as Segment 3C. Four short reaches were not segmented due to uniform morphology throughout and were treated as single segments in the restoration planning process with only the reach number used without a letter designation added. The results of the segment delineation process are presented in Section 6.1 below.

5.2b Restoration prioritization strategy

The need for restoration within each identified segment was quantified by ranking the degree to which the segments possessed 12 conditions embodying geomorphic, hydraulic, habitat, and recreational conditions or attributes associated with a natural river in geomorphic equilibrium. The resulting scores reflect the “needs” to be fulfilled in a segment before an ideal equilibrium condition is achieved where excellent aquatic and riparian habitat is present, floods can access and spread across the floodplain on a nearly annual basis (i.e., bankfull condition), and recreational opportunities are available for human residents and visitors. The ideal condition, in this case, is from the perspective of the river (and whether natural river processes are unencumbered and sustainable) and may be in conflict with human ideals where inundation of the floodplain, for example, may be considered in a negative light given the potential for infrastructure damages. Ranking the segments in this manner is not meant to indicate that a return to natural pre-historical conditions is a priority but merely provides a means of establishing to what degree human impacts have altered natural river processes and the difficulties, obstacles, and expense that might be faced in trying, if only partially, to reestablish natural river processes and the quality aquatic habitat such processes create and sustain.

A rating scale (ranging from 0 to 5) was developed for each of the 12 conditions to reflect the geomorphic, habitat, and recreational needs of a given segment with a higher score reflecting a greater need for geomorphic stability, habitat enhancement, and recreational opportunities. The GIS shapefiles completed as part of the channel features mapping (Appendix 2) form the basis for assigning a score to some of the 12 “needs” categories (e.g., wood, erosion, armoring), while the scores for other categories were assigned directly in the field after completing mapping of a segment (e.g., particle size segregation) or, in part, from remote sensing data (e.g., canopy). A high score generally indicates that habitat quality and geomorphic stability are poor, so the “need” to improve the conditions is high. For example, a high score for Condition 7 indicates that the segment has little capacity for self-adjustment (e.g., to reform meanders along a straightened reach) or limited ability to improve habitat on its own under the existing conditions. The 12 conditions utilized are outlined below with the scoring rubric used to assign the “needs” score. All of the individual scores for the 12 conditions and the overall total for each segment are presented in Section 6.1 below.

Condition 1 - Floodplain access (FPACC)

0 = floodplain access on both sides of channel
3 = floodplain access on one side
5 = no floodplain access

Condition 2 - Meander development (Meander)

0 = well-developed meanders, high sinuosity
3 = meanders developing, cutbanks eroding, low sinuosity
5 = no meander development, straightened channel

Condition 3 - Particle size segregation (PartSeg)

0 = presence of large boulders (for cover and pool habitat), fine sediment and organic matter deposited on floodplain and channel margin (for greater soil fertility and macroinvertebrate taxa richness), coarser sediment in channel (for oxygenation), presence of active bars (for spawning along edges)
3 = 2 out of 4 present
5 = no boulders, no active bars, highly embedded substrate

Condition 4 - Flow complexity (Flows)

0 = presence of multiple flow conditions across the channel or in close proximity (i.e., fast deep flowing water near fast shallow, slow deep and slow shallow flows), characterized by deep pools (for cover and overwintering habitat), shallow riffles or steps (for feeding and oxygenation), and side channels (for nursery habitat)
3 = missing 2 out of 4 flow types
5 = almost entirely fast shallow flow (i.e., continuous riffle; plane-bed morphology) with limited pools and side channels

Condition 5 – Quality of pools (Pools)

0 = well developed deep pools (for cover, refuge, and overwintering habitat)
3 = shallow pools only
5 = no pools

Condition 6 - Wood in channel (Wood)

0 = plentiful wood in channel (for creating cover, increasing flow complexity, carving pools, and trapping other organic matter, fine sediment, and spawning gravels)
3 = multiple pieces of wood in channel but not plentiful
5 = no wood in channel

Condition 7 - Capacity for adjustment (CAPADJ)

0 = stream transporting bedload, capable of transporting bank material and adjusting planform morphology (for creating flow complexity), truly alluvial
3 = not capable of transporting bank material on one side due to armoring or high confining bank
5 = constrained on both sides with no capacity to transport bank materials and adjust planform due to armoring and/or high confining bank

Condition 8 – Canopy

0 = mature vegetation growing along approximately 75 percent of the channel banks (for shading and recruitment of organic matter to the channel), well-developed riparian zone with native vegetation and little to no invasives, intervention would yield little possible improvement in channel shading
3 = mature vegetation along approximately 25 percent of the channel banks, decent riparian zone could be improved and low to moderate levels of invasives present
5 = no mature vegetation on channel banks, poorly developed riparian zone providing very little shade with moderate to high levels of invasives present

Condition 9 – Bank erosion (Eroding)

0 = no bank erosion present (stable banks reduce fine sediment inputs to the river, support healthy riparian vegetation growth, and provide cover habitat)
3 = 20-30 percent of the banks are eroding

5 = more than 50 percent of the banks are eroding

Condition 10 – Bank armoring (Armor)

0 = no bank armor present (allows for channel adjustment to achieve geomorphic stability and create flow complexity)
3 = 20-30 percent of the banks are armored
5 = more than 50 percent of the banks are armored

Condition 11 – Graded profile (GRAPRO)

0 = Smooth concave up profile with no sharp breaks (changes in elevation and slope from one point to the next along a river in equilibrium is minimized)
3 = Presence of a low weir or pipe crossing resulting in low vertical drop in profile of less than or equal to 2 feet – score applied to segment upstream and downstream as such structures are typically at the segment break
5 = Presence of a check dam or other vertical drop in profile of 5 feet or more – score applied to segment upstream and downstream as such structures are typically at the segment break

Condition 12 – Recreational opportunities (Rec)

0 = Bike path present and other recreational access or opportunities as well (e.g., fishing)
3 = Only one opportunity present (in most instances just the bike path)
5 = No bike path present or other recreational facilities

Note: "Needs" scores of 1, 2, or 4 may also be used in scoring the 12 conditions when the specified values or general conditions fall in between the options described above.

5.3 Flood hazard mitigation planning and prioritization strategy

5.3a Flood hazard identification methodology

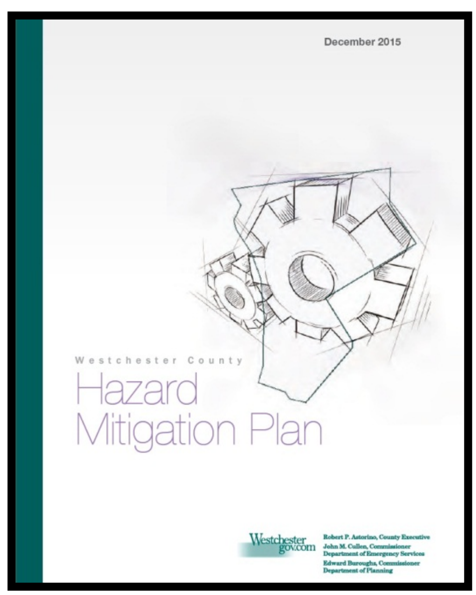
Flood hazard locations for the BRCSMP were identified by collecting existing electronic and hard copy data from local, county, state, and federal governments along the Bronx River corridor. This data allowed for a series of hydraulic modeling runs to be completed that calculated flood water depths for various discharges and documented potential flood hazards. This process was referred to as the "hydraulic analysis".

The existing hydraulic model runs were conducted using the computer programs HEC-RAS (version 4.1.0, RAS) and ArcGIS (version 9.3). HEC-RAS is a software program developed by the U.S. Army Corps of Engineers and is the industry standard for calculating water depth and water velocity for various discharges. HEC-RAS model outputs are used to develop the FEMA Flood Insurance Rate Maps (FIRMs). All of the Bronx River within Westchester County had been modeled previously using the HEC-RAS program and the results were used to create FEMA's floodplain maps for the municipalities within the study area. This model is referred to as the effective FEMA model and was obtained, replicated as part of this study, and the replication compared to the published FEMA Flood Insurance Study to ensure accuracy. This vetted model is referred to as the duplicated FEMA model. The duplicated FEMA model was run for floods with the following return intervals: 10-year, 50-year, 100-year, and 500-year. Outputs were then digitized to form a water surface elevation raster file.

Buildings and road digital files were also obtained and duplicated in the ArcGIS program. Road elevations and a lowest adjacent grade around buildings within flood prone areas (referred to as the Special Flood Hazard Areas within FEMA's 100-year floodplain) were obtained from a topographic survey completed in 2009 using Light Detection and Ranging (LiDAR) methods. The topography raster was subtracted from each water surface elevation raster to calculate water depths at these locations during the four flood intervals.

Next, a stakeholder group was consulted to create of list of flood-hazard locations important to the community. The stakeholder group consisted of representatives from the Westchester County Department of Public Works, County Planning Department, County Parks Department, and community elected officials. This meeting took place at the Westchester County Planning Department office in the fall of 2018. The group identified several flood prone locations of interest that were subsequently digitized and georeferenced. The stakeholder group also included the Westchester Parks Foundation and the Bronx River Alliance who took part in conference calls after the fall 2018 stakeholder group meeting to discuss their activities within the Bronx River corridor and what flood hazards and other Bronx River issues were of importance to citizens. The inundation flood hazards of greatest concern to the stakeholder group are locations where flood waters submerge important areas of the communities such as buildings or highly traveled roads.

The stakeholder group also recommended the BRCSMP review two publicly available documents to understand flooding hazards in the Bronx River corridor that have been previously identified.



The first document, published by Westchester County, was the county's "Hazard Mitigation Plan" released in December 2015. This document followed FEMA guidelines to document and characterize human-made and natural hazards occurring within the community. Chapter 5.4.3 "Flood" was reviewed to understand what critical facilities may be prone to flooding in the corridor.

The second applicable document for flooding in the corridor was the "Stormwater Reconnaissance Plan for the Bronx River Basin Watershed". This document, published through a collaborative effort with the County Department of Planning and the County Department of Public Works and Transportation was released in April 2013. This

Plan was developed using community driven input from municipal officials or municipal representatives (supervisors, engineers, etc.) to identify and characterize flooding problems in the Bronx River watershed. The plan also assigned an evaluation score to each flooding problem using community input.

5.3b Flood hazard mitigation prioritization strategy

Floodwater inundation poses a threat to public safety. To understand the public safety threat severity, the term "risk" was used in the BRCSMP. For this plan, risk was defined as the product of the likelihood of a flood hazard to occur and the consequence severity of the flood hazard. The likelihood of a flood hazard occurring was the probability an area would be covered with flood water. The flood's return interval (i.e., 10-year, 50-year, 100-year and 500-year) represents the likelihood, or probability, a flood event of that size would occur in any given year: 0.1 (10%), 0.02 (2%), 0.01 (1%) and 0.002 (0.2%) respectively.

If an area of interest first became inundated during a 10-year, 50-year, or 100-year flood event a "High", "Moderate" or "Low" likelihood of occurrence score was assigned, respectively. The 500-year flood is an important flood and was used to calculate annualized flood damage (discussed in more detail in Volume II) but was considered too infrequent for calculating risk. A numerical value of five (5), three (3) and one (1) was then assigned to "High", "Moderate" or "Low" likelihoods of occurrence, respectively. This numerical value was one part of the equation to calculate risk.

The consequence severity level was assigned based on what the flood waters were inundating or surrounding. Buildings surrounded by floodwaters slow first responder time to emergencies and once floodwaters enter a building, additional problems arise. Mechanics (electricity, heating) if inundated with floodwater stop working and could be shut down for several days, which in winter could cause water pipes to freeze. Water that saturates walls can cause health concerns of mold and rot. For these reasons, inundation of buildings is very undesirable. Therefore, if the hydraulic modeling results show flood water elevations higher than a building's lowest adjacent grade, then a flooding hazard exists and the severity consequence score of "high" was assigned.

To evaluate the severity of potential flood damage to these buildings, a simple mathematical calculation was completed. Water surface elevations at the studied flood events were extracted from the hydraulic modeling software program (HEC-RAS) using ArcGIS in the form of raster electronic files which are composed of square cells (9.8 feet by 9.8 feet). A raster file was created from the digital elevation model of the ground around the buildings and subtracted from the water surface elevation raster for each studied flood event. The resultant, was a third raster which represents water depth for each flood event. This raster is used to create a "water depth grid" map, which is a useful tool to predict water damage in an understandable format. Building outlines are added to the exhibit to allow the reader to easily determine the water depth around a building of interest. Data can be presented in tabular and graphical formats to compare the potential flood damage severity at each flood hazard.

Buildings vary in their function (i.e., a single family home serves a different purpose than a building which shelters a sewage pumping facility). Therefore, determining the type of building that is inundated is important. In Westchester County's Hazard Mitigation Plan, important buildings, referred to as "critical facilities", are buildings that if damaged or destroyed would have a notable and severe short term impact to the community. Critical facilities include fire departments, shelters for displaced community members, and water treatment plants. Building type is an important prioritization metric that is used in the prioritization of segments and projects discussed in more detail in Volume II. Flood water depths modeled for the four recurrence-interval events studied was also an important prioritization metric because deeper flood waters typically cause more flood damage than shallower flood water depths. Water depth was an even more important prioritization metric if a building was inundated during a 10-year return interval flood (the smallest studied flood discharge), since buildings surrounded by relatively deep water during the 10-year return interval flood are also likely flooded at a more frequently occurring flood event, resulting in higher annualized flood damage. Annualized flood damage is calculated as part of the prioritization process to determine the importance of flood mitigation in each segment and how effective proposed projects will be in mitigating floods of different magnitudes.

Floodwaters also pose a threat to public safety when overtopping a road. The National Weather Service's "Turn Around, Don't Drown" program is a public safety message warning drivers and pedestrians not to enter flood inundated streets. A mere six inches of water can sweep an adult off their feet or lift a car off the road (Web citation 6). Therefore, when flood waters inundate a road, a flood hazard exists. Flood water inundation of roads was assigned a "moderate" consequence severity level or "low" consequence severity level.

The average daily traffic count (the amount of cars traveling on a road) is often used to understand traffic volume on each road. One, if not the most heavily traveled road in the Bronx River corridor is the Bronx River Parkway. During a traffic count study in October 2010, roughly 30,000 cars traveled on the parkway in the Town of Greenburgh and a similar study in August of 2010 measured roughly 13,000 cars on Ardsley Road in the Hamlet of Greenburgh. When a road is closed due to flooding, the detour will push traffic onto arterial streets, straining already clogged streets and resulting in longer response times for first responders. Such road closures also negatively impact commuters and other aspects of daily life.

Therefore, when a road with a relatively high average daily traffic count is closed due to flooding, the severity of the flood hazard is higher than a road with a notably lower average daily traffic count. A “moderate” consequence severity level was reserved for flooding of the Bronx River Parkway. All other road inundations were assigned a “low” consequence severity level.

A severity consequence level of “high” score was assigned a numerical value of five (5). A “moderate” score was assigned a three (3) and a “low” score was assigned a value of one (1). To establish flood hazard importance in the Bronx River corridor, the numerical value for likelihood of occurrence was multiplied by the severity consequence numerical value. The flood hazard with the highest product is the hazard that potentially causes the most damage and, therefore, represents the highest priority for mitigation. All flood hazards were ranked based on their product result and adjusted based on prioritization metrics such as floodwater depth, building type, etc. The findings of the flood hazard prioritization process are found in Section 6.2 below.

5.4 Erosion hazard mitigation planning and prioritization strategy

5.4a Erosion hazard identification methodology

During the geomorphic assessment field visit to conduct channel features mapping (fall of 2018), eroding banks were observed, mapped, and measured. An actively eroding bank was defined as a river or stream bank whose observed average slope was steeper than the surrounding stream bank material (Figure 30) and evidence was found of colluvium (eroded material derived from higher on the bank) accumulating at the base of the bank or in the stream. To be mapped as actively eroding, the erosion had to extend for at least 10 feet with an average bank height of 1.0 feet. These metrics applied to eroding banks at river mile 0.0 (the most upstream end of the Bronx River) downstream to approximately river mile 5.0. For each 5.0 river miles further downstream, the average vertical height requirements to meet the eroding bank definition increased by a half foot. At the most downstream end of the Bronx River, the average vertical height of an eroding bank was required to be 2.0 ft.

Active Eroding Bank, note near vertical stream bank slope

Historic Eroding Bank, note gradual stream bank slope along the stream bank toe

Figure 30. Photos of active eroding banks and historic eroding banks

The beginning and end of each eroding bank was mapped using a handheld GPS device (Trimble 7X series, average horizontal accuracy 1 foot +/-). Additional characteristics of the eroding bank were entered into a digital database on the GPS unit. Table 7 presents the other qualities that were observed or measured. The purpose of capturing these qualities was to document and measure eroding bank characteristics that may prove useful in future planning efforts. For example, knowledge of eroding banks undermining large trees would be important if flood debris mitigation was the focus of a particular management effort. Another example would be if water quality pollution prevention was an important management strategy then bank stabilization of relatively large eroding banks containing a high percentage of silts and clay might be a high priority.

During bank stability mapping, the distance between the top of an eroding bank and any adjacent infrastructure was observed and measured. Infrastructure included roads, recreational pathways, and observable utilities. The distance between the top of an eroding bank and the infrastructure is important in determining the likelihood that the eroding bank will ultimately reach, undermine, and damage the infrastructure.

5.4b Erosion hazard mitigation prioritization strategy

The definition of risk in the BRCSMP is the product of the likelihood of an event occurring and consequence severity level of said event. For erosion hazards, the distance between the top of bank and the proximal infrastructure was used as the surrogate for the likelihood of an event occurring.

Distances between the top of the eroding bank and infrastructure were grouped into three distance categories: 0 to 5 feet, 5 to 10 feet, and greater than 10 feet. Infrastructure within 0 to 5 feet from the eroding bank are likely to be damaged over the course of a few years of “normal” flooding conditions or be damaged during a single large flooding event. If this distance was observed, then the likelihood of a hazard event occurring was assigned a “high” score. Infrastructure located 10 feet or more away would most likely not be damaged after 10 to 20 years of “normal” flooding conditions or several large flooding events, therefore the likelihood of a hazard event occurring was assigned a “low” score. Infrastructure located within 5 to 10 feet was assigned a “moderate” likelihood of suffering erosion damages.

A “high” likelihood of the event occurring was assigned a numerical value of five (5), “moderate” was assigned a three (3) and “low” was assigned a value of one (1).

The consequence severity of an erosion hazard event was a function of the importance of the proximal infrastructure. For the BRCSMP, the Bronx River Parkway or observable utilities (natural gas, sewer, water) were deemed critical infrastructure to protect from erosion damage, therefore a “high” consequence severity score was assigned. Arterial roads because of their relatively lower traffic count were assigned a “moderate” consequence severity score. Other infrastructure such as the recreational pathway was assigned a “low” consequence severity score. To maintain consistency with the prioritization approach used for flood hazard mitigation, a “high” severity consequence was assigned a numerical value of five (5), a “moderate” score was assigned a value of three (3), and a “low” was assigned a value of one (1).

To establish erosion hazard importance in the Bronx River corridor, the numerical value for likelihood of occurrence of each eroding bank located proximal to a piece of infrastructure was multiplied by the severity consequence numerical value. The erosion hazard with the highest product is the hazard that potentially causes the most damage and therefore would be the highest priority to mitigate. All erosion hazards were ranked based on their product result. The findings of the erosion hazard prioritization process are found in Section 6.3 below.

6.0 CORRIDOR MANAGEMENT PLAN IMPLEMENTATION

The results and findings of the prioritization processes described in Section 5.0 above are presented below.

6.1 Restoration findings

As discussed in Section 5.2a above, a useful approach to restoration planning is to delineate a river into smaller segments based on the uniform morphological conditions found along short lengths of river channel. Segment delineation provides an approach that allows a single restoration approach to be applied to the entire length of a given segment.

Ninety-seven segments were delineated and characterized in the field during the channel features mapping (see Section 4.3 above) by assigning segment breaks at locations where one or more channel features changed significantly (Figure 31). Examples of where segment breaks were made include bridge and culvert stream crossings that constrict the channel, weirs and low profile grade controls (with dams already marking reach breaks), significant changes in bank stability and armoring, variations in the nature of the riparian buffer (e.g., levels of invasive species) or land use, differences in channel confinement and channel corridor encroachments, increases or decreases in sinuosity, changes in channel substrate size, and other variations in the geomorphic character of the channel or adjacent corridor that were noted in the field. Segment breaks were imported into and reviewed in ArcMap and, in some cases, adjusted based on the channel features mapping and remote sensing data in order to best represent the discrete changes in the geomorphic character and features of the channel and corridor used to establish the segments. Further information on the types, distribution, and exact location of features within each segment can be gleaned from the GIS data (Appendix 2).

As discussed in Chapter 5.2b, restoration needs for each segment were quantified by ranking the degree to which the segments possessed 12 conditions embodying geomorphic, hydraulic, habitat, and recreational conditions (Table 8). The total combined needs scores (of the 12 conditions) provide a quantitative means of identifying those segments with the widest range of needs over multiple categories. For example, Segment 8c has the greatest combined needs score of 52 out of a possible 60 along the Bronx River with a higher combined score (of 56) found only on Grassy Sprain Brook (Segment GS_1B). Both of these segments are classified as artificially confined, armored, and straightened channels. In fact, the segments with the eight highest combined needs scores on the Bronx River are all artificially confined, armored, and straightened channels as are the seven highest scores on Grassy Sprain Brook and the highest score on Laurel Brook (the only segment so classified on Laurel Brook). The predominance of the highest scores for this channel type reflects the significant human impacts that have altered the geomorphic and habitat conditions and, in many respects, have also limited recreational opportunities. The channels with reformed meanders and partially confined channels tend to have the lowest needs scores as some positive geomorphic qualities have been retained (e.g., floodplain access) or have been naturally restored (e.g., reformed meanders with greater flow complexity) (Table 9).

A high needs score in different segments can result from a different combination of conditions, so a high combined needs score itself does not provide any indication of the best restoration strategies to use to address the given needs, but the needs scores do provide a means for prioritizing the segments in which restoration, in whatever form, may provide the greatest benefit. The needs scores of individual components can also be useful. Opportunities targeting certain activities or issues may be of interest to certain stakeholders or funding agencies, so having individual component scores can be helpful for prioritizing more narrowly targeted activities. For example, a group interested in engaging students in riparian plantings could focus on those segments with the highest canopy needs score of 5 even though other segments may have much higher combined needs scores (e.g., Segment 17a, a partially confined channel with a relatively low needs score of 34).

6.2 Flood hazard findings

This section presents hydraulic analysis results to document the general scope and breadth of flood hazards in the Bronx River corridor. This data will be further refined in Volume II for use in the prioritization of segments and prioritization of implementation strategies.

6.2a Hydraulic model duplication results

As discussed in Section 5.3 above, hydraulic modeling was completed using a software program (HEC-RAS) created by the U.S. Army Corps of Engineers. This program was used in FEMA's Flood Insurance Study (FIS) for Westchester County (#36119CV001A, effective date 9/28/2007) and to develop the Flood Insurance Rate Maps (FIRMs) for the county. Obtaining, duplicating, and running the hydraulic model used in FEMA's FIS and FIRMS maintains consistency with the governing agency who oversees floodplain, hazard mitigation grants, and flood insurance rates. To ensure consistency with results from the FEMA recognized hydraulic model (referred to as the effective model), the results from the hydraulic model used here for the BRCSMP (referred to as the duplicate model) were compared to the effective model's results.

Using the same model is also important since using a FEMA recognized hydraulic model will help Bronx River corridor managers apply for FEMA flood hazard mitigation grants. The managers can demonstrate the benefits gained from proposed flood hazard mitigation projects if they can compare model results with the FEMA recognized hydraulic model.

Where the results were reasonably close, then the duplicate model was considered consistent with the effective model. The range of differences between the duplicate model and the effective model is (-)0.06 feet to 0.03 feet and the average difference between the six evaluated cross sections is less than 0.01 feet as seen in Table 10.

Therefore, the duplicate model was deemed overall a satisfactory replication of the FEMA effective model. The locations of the cross sections used in the comparison of the two models are shown in Figure 32.

Comparison Number	Name of FEMA Cross Section in FIS	Cross Section ID in Duplicate HEC RAS	Water Surface Elevation at 100-year Flood in FIS (feet)	Water Surface Elevation at 100-year Flood in Duplicate HEC RAS (feet)	Difference in Water Surface Elevation (feet)
1	AQ	70093.09 (Inter)	193.45	193.48	+0.03
2	AO	60093	184.5	184.53	+0.03
3	AL	45586.04 (Inter)	156.6	156.54	-0.06
4	AI	30054.9 (Inter)	106.4	106.43	+0.03
5	U	14540	80.0	80.0	0.00
6	G	4914.97 (inter)	71	71.02	+0.02

Table 10. Comparison of duplicate modeling results to FEMA effective modeling results.

6.2b Stakeholder group flood hazards

The stakeholder group meeting in fall 2018 decided that any section of the Bronx River Parkway being closed due to flooding should be rated a "high" priority importance for the BRCSMP. Additional "high" priority locations were the apartment complex near the confluence of Grassy Sprain Brook and the Bronx River (40.940374, -76.840689) and near the intersection of Garret Ave and Yonkers Ave (40.949464, -73.833264) in Tuckahoe.

6.2c Previously documented flood hazards

A review of publicly available documentation regarding flooding described the Scarsdale High School as a critical facility proximal to the Bronx River corridor (Westchester County's "Hazard Mitigation Plan", 2015). The high school which is the most proximal critical facility to the corridor that is within a FEMA delineated floodplain is located 0.75 mi upstream on an unnamed tributary. Due to its distance from the corridor, the high school was not included in this analysis of flood hazards.

The "Stormwater Reconnaissance Plan for the Bronx River Watershed" (Reconnaissance Plan) documented dozens of flood problems, which were reviewed as part of the BRCSMP. The causes of flooding in the Reconnaissance Plan were diverse, while this study focused on flooding problems caused by direct surface water overflow from the

Bronx River or its tributaries within the Bronx River corridor. Included in this study were instances where flooding due to stormwater backing up in stormwater pipes as a result of elevated surface waters on the Bronx River. Other flooding problems caused by insufficient stormwater pipe capacity, blocked pipes, or areas occurring outside the corridor were not included as flood hazards but should be addressed per the recommendations in the Reconnaissance Plan.

Four flood hazards identified in the Reconnaissance Plan were included in this study (Table 11). These, as well as all other, flood hazard locations are presented graphically in Figure 33 through Figure 36. Note, the flood hazard priority importance presented in Table 11 comes from community input as described in Section 5.3 above.

Identification	Municipality	Geographic Location	Proximal Roads	Cause of Flooding	Flood Hazard Priority
BRX-1	Bronxville	40.938592, -73.835910	Paxton Ave. Parkway Rd.	Surface Water Flooding	High
TUC-1	Tuckahoe	40.949354, -73.833112	Yonkers Ave. Garrett St.	Surface Water Flooding	High
WHP-1	White Plains	41.049915, -73.772549	Haarlem Ave. Holland Ave.	Floodwater Backup Stormwater Pipe	Medium
Yon-1	Yonkers	40.940304, -73.840783	Brooklands Complex, Cedar Knolls Neighborhood	Surface Water Flooding	High

Table 11. Flood hazards identified from the Stormwater Reconnaissance Plan for the Bronx River basin watershed.

6.2d Hydraulic analysis flood hazards

Fourteen flood hazards were mapped following the procedures described in Section 5.3 above and are distributed throughout the Bronx River corridor as seen in Figure 37. Flood hazards were assigned an identification number starting from the downstream end of the Bronx River corridor. The likelihood of a flood hazard occurring (the flood's return interval) multiplied by the flood hazard consequence severity level resulted in the flood hazard's risk level. Risk was parsed into "high", "moderate" and "low" levels. As discussed in Section 5.3 above, other characteristics may be added to further scrutinize flood hazards in greater detail. For example, a building with deeper flood water suffers more damage than a building with shallower depths. Using these additional characteristics, risk was parsed into several categories: "Extremely High", "Very High", "High" and "Moderate". Table 12 presents the quantity of flood hazard sites in each category.

Flood Hazard Priority	Quantity	Flood Hazard Priority	Quantity
Extremely High	2	High	3
Very High	4	Moderate	5

Table 12. Number of sites in each flood hazard category.

Figure 37 displays where the flood hazards were mapped within the Bronx River corridor. The most flood hazard types were associated with road inundation (n=5) whose road and flood characteristics (average daily traffic count, flood water depth, etc.) varied. The second highest number of flood hazards within the corridor were buildings within a flood prone area (the 100-year return interval flood boundary, which governs FEMA flood insurance rates). Of note, the 10-year return interval flood elevations (the smallest flood studied) were higher than the lowest adjacent grade near the buildings at two locations. These two locations were rated as “extremely high” priority flood hazards.

The following sections break down each flood hazard priority into descriptive characteristics including geospatial location, municipality, nearby roads, and flood water inundation depth and frequency. Figures 33 through Figure 36 are exhibits of flood hazards at a finer scale.

"Extremely high" priority flood hazards

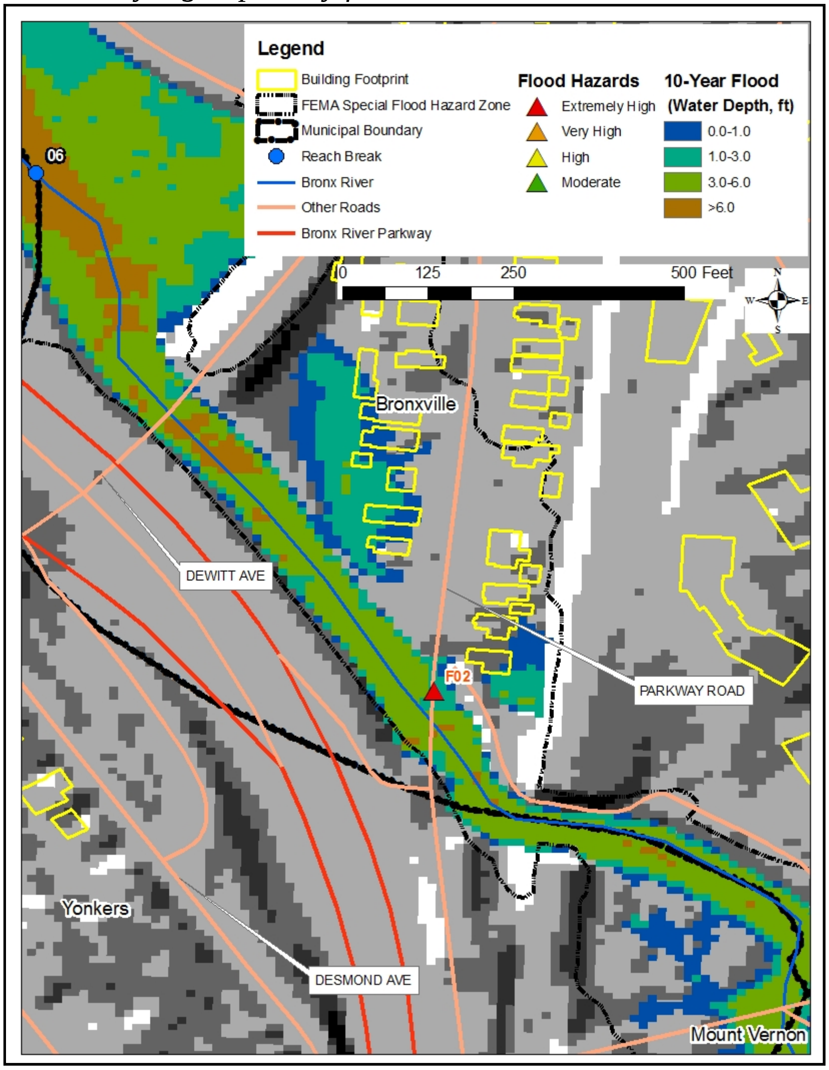


Figure 38. Example of extremely high priority flood hazard.

As discussed in Section 5.3b, if a building was surrounded by floodwaters, it was scored a "high" consequence severity level. A building damaged by floodwaters during a 10-year flood event would have a higher annualized flood damage than a similar building that is only damaged during a 100-year flood event. Therefore if the likelihood of a building being surrounded by floodwaters occurs during the 10-yr recurrence interval, the resulting flood hazard was given an "extremely high" priority. In Figure 38, several buildings west of Parkway Road are surrounded by flooding waters (between 1.0 feet to 3.0 feet deep) during the smallest return interval flood studied (the 10-year return interval flood). Figure 38 is an example of a water depth grid map which presents information that can be used by Bronx River corridor managers to understand potential flood damage by using flood water depth as a prediction tool. At flood hazard "F02", between six to eight buildings may be inundated with 1.0 feet to 3.0 feet of water. There are two "extremely high" priority flood hazards (Table 12).

"Very high" priority flood hazards

A "very high" priority flood hazard is different than an "extremely high" flood hazard because the buildings in a "very high" flood hazard are surrounded by flood waters during a larger, less frequent flood than the 10-year return interval flood. In "very high" priority flood hazard, building damage due to floodwaters was scored a "high" consequence severity level while the likelihood of the two studied larger flood events, the 50-year return interval flood and the 100-year return interval flood, were assigned a "moderate" and "low" likelihood of occurring, respectively. Figure 39 presents an example of a very high priority flood hazard (Flood Hazard F14). Figure 39 also shows the Bronx River Parkway as being inundated by floodwaters. As discussed in Section 5.3b this is a notable condition since a closure of the parkway due to flooding would likely last for hours until floodwaters recede and damage inspections can be completed. The closure will force a large portion of the vehicles which travel on the parkway (approximately 30,000 vehicles/day) onto arterial streets where the extra vehicle load may endanger pedestrian safety. Four very high priority flood hazards were found in the Bronx River corridor (Table 13).

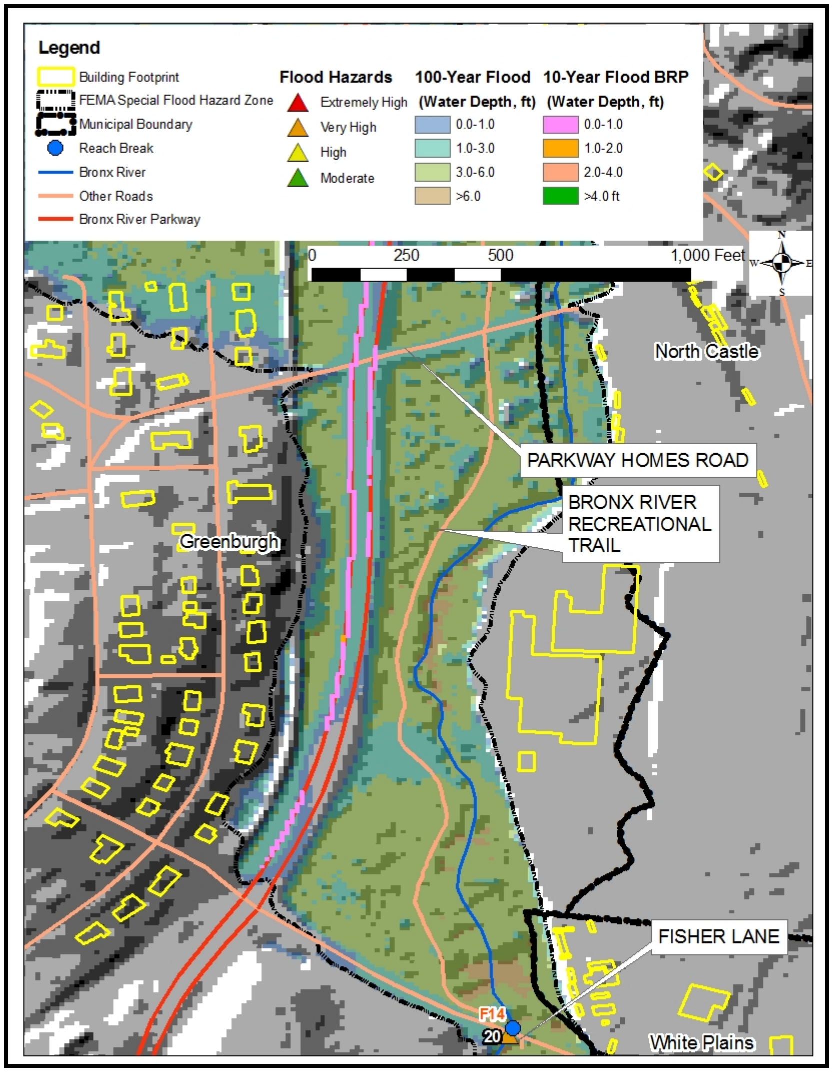


Figure 39. Example of a very high priority flood hazard.

"High" priority flood hazards

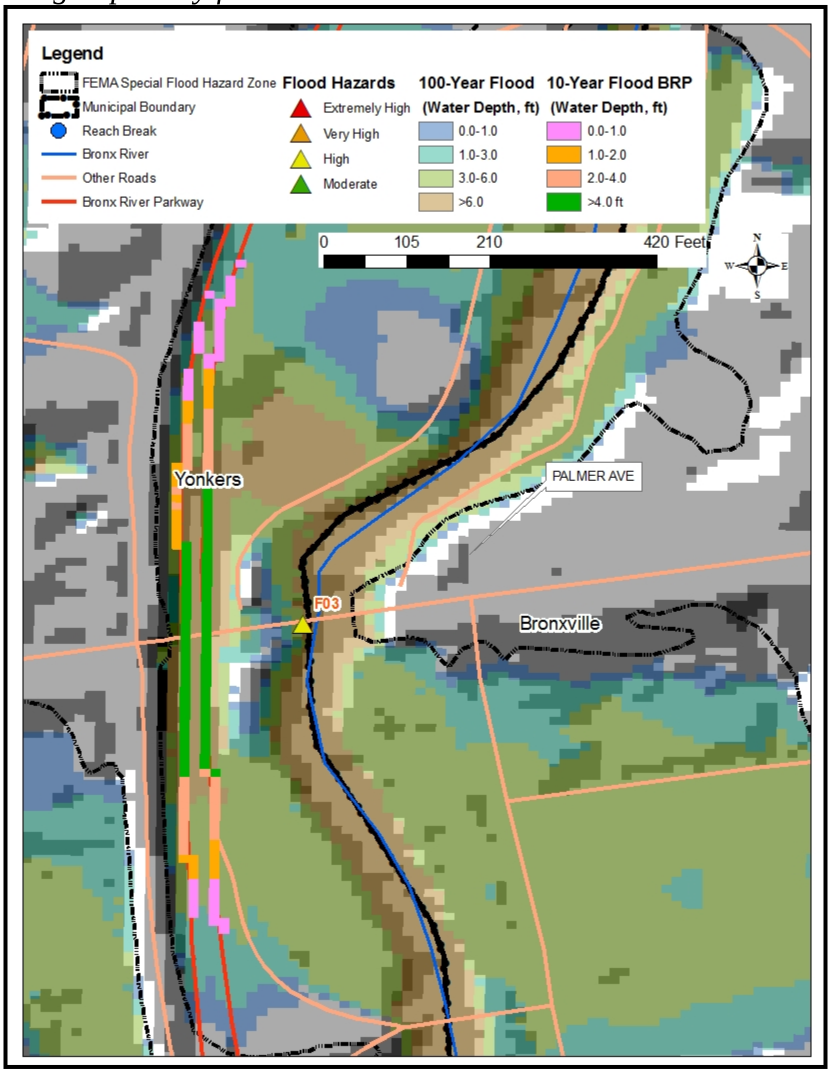


Figure 40. Example of a high priority flood hazard.

High priority flood hazards contain sections of the Bronx River Parkway that are inundated during the smallest studied flood event, the 10-year return interval flood. As discussed in Section 5.3b, the consequence severity level under this condition was assigned a "moderate" score. The likelihood of the flood event occurring was assigned a "high" score since flood inundation occurs at the smallest studied flood event, the 10-year return interval flood. To assist Bronx River corridor managers, a greater level of detail was used to understand if the parkway flooded more frequently than the 10-year return interval flood. If a section of parkway is inundated with two (2) feet of flood water or more during the 10-year return interval flood, that section is likely to flood more frequently than the 10-year return interval flood, possibly on an annual basis. For this reason, parkway sections with greater than 2 feet of floodwater depth during the 10-year flood were assigned as "high" priority flood hazards. Figure 40 shows flood hazard "F03" marking a parkway section, approximately 800 feet in length, near the intersection with Palmer Avenue, inundated with four feet or more of water during the 10-year flood. Three high priority flood hazards were identified in the Bronx River corridor (Table 14).

Moderate priority flood hazards

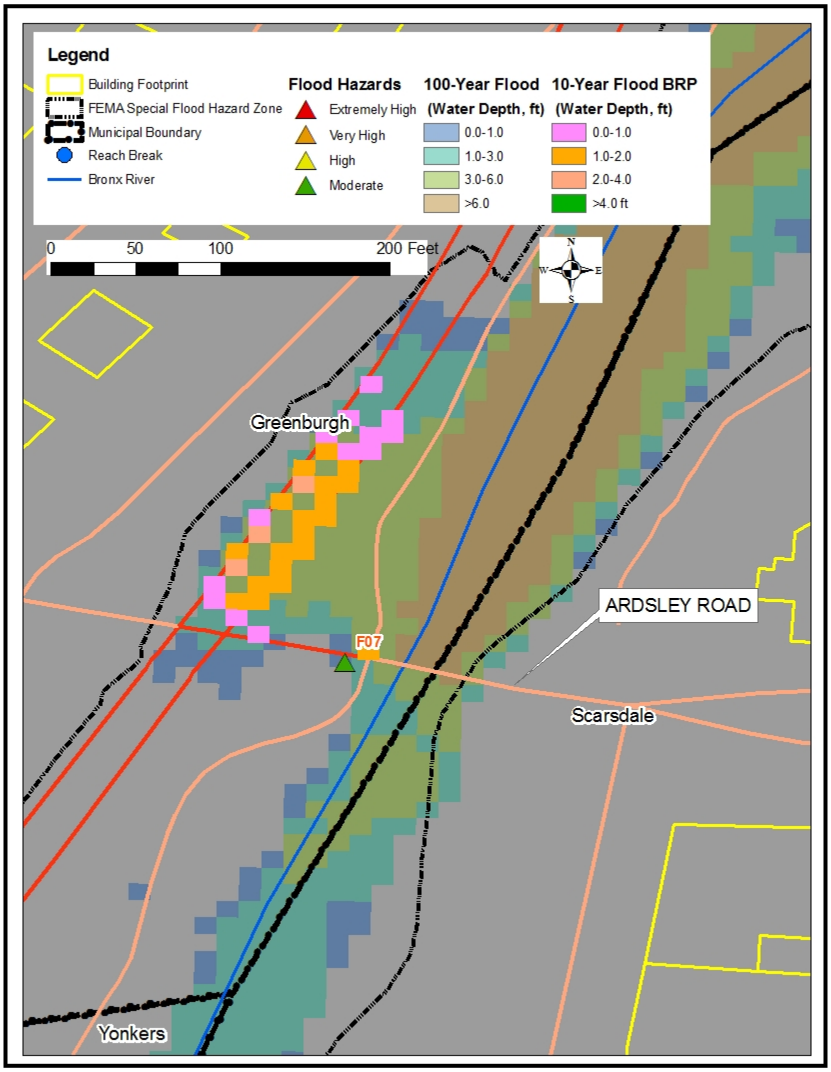


Figure 41. Example of a moderate priority flood hazard.

"Moderate" priority flood hazards differ from "high" priority flood hazards by the flood water depth over the Bronx River Parkway during the smallest studied flood event, the 10-year return interval flood. If the modeled floodwater depth is less than 2 feet, then flooding of the parkway is less frequent and therefore the flood hazard was rated only as a "moderate" priority. These sections potentially have shorter closure times because they would drain faster and require less clean-up. Figure 41 presents a moderate priority flood hazard (F07) along the parkway where relatively shallow flood waters inundate the parkway during the 10-year return interval flood. Figure 41 also depicts the water depth grid map during the 100-year return interval flood for comparison of the water depths (between 3.0 feet and 6.0 feet) during this larger, less frequently occurring flood. Five moderate priority flood hazards were identified in the Bronx River corridor (Table 15).

6.2e Flood hazard summary

Flood hazards were located throughout the Bronx River corridor. Hydraulic analysis results identified several buildings located within the 10-year floodplain (i.e., surrounded by water during the 10-year return interval flood). As discussed in Section 5.3b, building type is an important characteristic for Bronx River corridor managers to understand when deciding how to prioritize flood hazard mitigation sites. For example, a critical facility such as a water treatment plant is more important to protect than an outbuilding (non-residence) against flood water damage. In addition to the buildings located within the 10-year floodplain, several others were located within FEMA's special flood hazard area, a flood prone area equivalent to the 100-year floodplain. More importantly, water depths during the 10-year return interval flood were several feet deep for several of the identified flood hazards and suggests flood inundation may occur more frequently, perhaps multiple times a year. This is an important piece of information since annualized flood damages are higher with increasing floodwaters depths and are often used to financially justify the cost for a flood hazard mitigation project. Floodwaters during the 10-year return interval flood overtop the parkway at several locations in the Bronx River corridor, forcing the parkway to shut down and causing deleterious impacts to the community. Since the parkway has a relatively high average daily traffic count (approximately 30,000 vehicles per day), the annualized flood damage cost (which uses vehicles per day in its calculations) is likely very high.

6.3 Erosion hazard findings

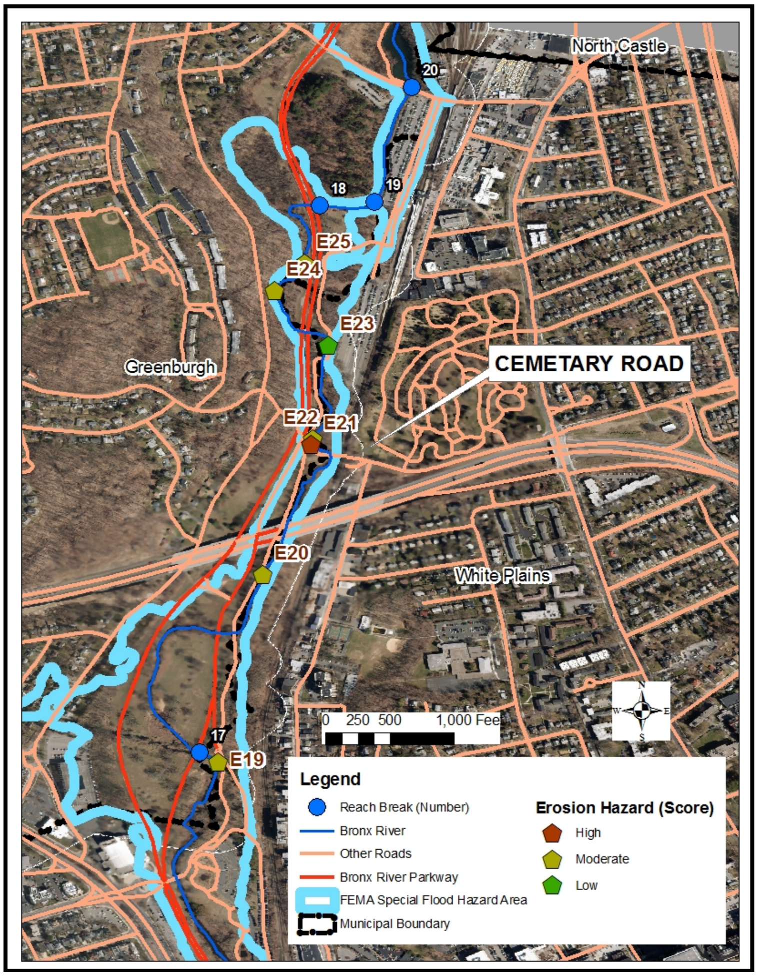


Figure 43. Example of erosion hazards.

A total of 28.2 miles of stream bank along the Bronx River were inspected for erosion hazards. Of that length, 4.9 miles, or 17 percent, were mapped as actively eroding. Eroding banks were found throughout the Bronx River corridor, but long gaps were present where no erosion was found, in part due to the extensive bank armoring recorded as part of the channel features mapping (see Section 4.3 above). If the total length of armoring is combined with the length of erosion, more than 50 percent of the banks on the Bronx River are either actively eroding or protected from erosion.

Twenty eight erosion hazards were mapped on the Bronx River, but none were identified on the two mapped tributaries. Table 13 presents the number of “high”, “moderate” and “low” priority erosion hazards based on the ranking described in Section 5.4b above. Erosion hazard locations are distributed throughout the Bronx River corridor (Figure 42) with a notable gap in erosion hazards near the White Plains and Scarsdale municipal boundary line due to the lack of proximal infrastructure near the river. Figure 43 above shows an erosion hazard within three feet of Cemetary Road.

Erosion Hazard Priority	Quantity
High	4
Moderate	16
Low	8

Table 13. Quantity of erosion hazard sites in each hazard category in the Bronx River corridor.

6.4 Volume II introduction

Volume I has detailed the numerous ways that the Bronx River has been impacted by human activities in the channel, on the floodplain, and throughout the surrounding watershed. The responses of the river to these alterations (e.g., reformation of meanders, frequent inundation of low lying areas), in turn, have the potential to impact public safety and infrastructure at several locations within the corridor. Identifying and prioritizing approaches to address these impacts will be the focus of Volume II. Given the severity of human impacts, effective solutions that will lead to improved river stability, enhanced aquatic and riparian habitat, reductions in flooding and erosion, and increased recreational opportunities will likely require bold and potentially expensive initiatives for which public support will be essential. Consequently, achieving the goal and objectives of the BRCSMP (see Section 5.1 above) will require a mix of engineering projects to make physical changes on the ground and educational initiatives to inform local residents of the long-term benefits of such projects in terms of cost savings from reduced hazards and improved quality of life associated with a more natural river system at their doorstep.

Towards this end, the next steps of the BRCSMP to be presented in Volume II include:

- Linking the identified flood hazards and erosion hazards to the geomorphic segments, so project prioritization and development can simultaneously consider both the river's "needs" and threats to public safety and infrastructure;
- Identifying those segments with the highest priority for project implementation considering both river "needs" and potential hazards (i.e., those segments with both the highest needs scores and highest hazard rankings);
- Incorporating additional metrics (i.e., water quality, debris management, recreational opportunities, etc.) into the prioritization process to assist in the selection of segments for restoration or other types of projects;
- Ranking different classes of projects (e.g., floodplain restoration, riparian plantings, bank stabilization) in their effectiveness in addressing the river needs, hazards, and other metrics in each segment;
- Creating a list of appropriate projects for each segment reflecting varying costs and complexities, so managers can set long-term planning goals while still being able to quickly respond in the short term to implementation opportunities as they arise;
- Detailing funding mechanisms, strategic partnerships, and general implementation constraints that should be evaluated prior to final selection and development of conceptual solutions in prioritized segments;
- Topographic surveying of five sites on the Bronx River and one on a tributary site to: 1) verify Volume I results, 2) further characterize human impacts and resulting river responses, and 3) provide baseline data and base maps for development of conceptual project designs in high priority segments; and

- Developing project conceptual designs for five high priority segments that include plan and cross section views of project implementation proposals, implementation cost estimates, and brief narratives regarding implementation benefits (i.e., needs addressed and hazards reduced) and potential constraints (i.e., costs, regulatory, public support).

With completion of Volume II, the Westchester County Planning Department and other stakeholders will have a blueprint for resolving riverine issues along the entire length of the river within the County. By detailing both small-scale and large-scale projects in Volume II, minor issues (e.g., the need for park benches in a segment with limited recreational opportunity) can be taken up first to create the public engagement necessary to tackle large projects over multiple segments that address several problems at once (e.g., removing floodplain constraints to improve channel stability and aquatic habitat while potentially reducing identified flood hazards downstream through increased flood storage). Through the completion of multiple projects over time, a noticeable improvement in channel stability, enhancement of aquatic and riparian habitat, reduction in flood and erosion hazards, and increase in recreational opportunities will be realized.

7.0 CONCLUSIONS

The Bronx River's current form (i.e., sinuosity, dimensions, grade) are primarily the result of human impacts in the channel (straightening, bank armoring) and floodplain (artificial fill), although natural constraints (narrow floodplain, valley constrictions) also exert some influence on the distribution of channel instabilities, degraded aquatic habitat conditions, and flood hazards and erosion hazards. Over 90 percent of the river in Westchester County as well as long lengths of the two studied tributaries were artificially straightened by 1925 (Table 5), perhaps multiple times since European settlement of the watershed in the 1600s. Bank armor in the form of large stone, concrete and stone walls, and gabion baskets cover 34 percent of the river banks, perhaps exacerbating the erosion observed on 26 percent of the river's banks that remain unarmored. The erosion is related in many cases to the process of meander reformation that, when completed, creates positive aquatic habitat features such as increased flow complexity and improved particle size segregation. Riverine habitat is particularly poor along river segments that remain locked in a straightened condition due to armoring and confinement (47 percent of the river's length) or where dams have impounded the channel (14 percent of the river) (Table 6).

Meander reformation and other causes of erosion (e.g., downstream of check dams) presents a potential near-term hazard to infrastructure located within 10 feet of the river bank. Of the 28 erosion sites identified as potentially threatening infrastructure, four sites are considered a high risk and 16 sites are a moderate risk to cause costly damages. Human impacts along the river and the resulting channel adjustments they engender may also exacerbate flood hazards in the corridor. The heaviest density of flood hazards are located in three sections of the Bronx River (Figure 37): 1) Reach 16 through Reach 18 where four moderate priority flood hazards (F09, F11, F12, and F13) and two very high priority flood hazards (F10 and F14) were identified using the hydraulic modeling approach discussed in Section 5.3, 2) Reach 5 to the middle of Reach 7 with two extremely high priority flood hazards (YON-1, F02), one very high priority flood hazard (BRX-1), and one high priority flood hazard (F03), and 3) Reach 8 to the middle of Reach 9 with one extremely high priority flood hazard (F05) and two very high priority flood hazards (F04, TUC-1).

In Volume II, a roadmap will be prepared for Bronx River managers to make informed decisions on where to begin implementing projects that simultaneously achieve river stability, improve aquatic and riparian habitat, reduce flood hazards and erosion hazards, and increase recreational opportunities along the river. These decisions will be guided by the findings of the geomorphic assessment and erosion hazard and flood hazard assessment that will establish the efficacy of various potential projects aimed at addressing river instability and degraded aquatic habitat while also mitigating hazards to public safety and infrastructure. The river's potential to improve channel stability and aquatic habitat on its own is reflected in the process of meander reformation, but the river's ability to self-adjust remains extremely constrained by human alterations of the channel (e.g., dams, stream crossings, armoring) and its watershed (e.g., diversion of flow at Kensico Dam reduces the potential of the river to produce large floods capable of effecting channel changes). Consequently, the corridor planning process initiated in Volume 1 has prioritized areas with the greatest need for addressing river stability, habitat, and hazard issues with restoration projects targeted to improve conditions in those areas to be identified, prioritized, and developed in Volume II.

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FIGURES

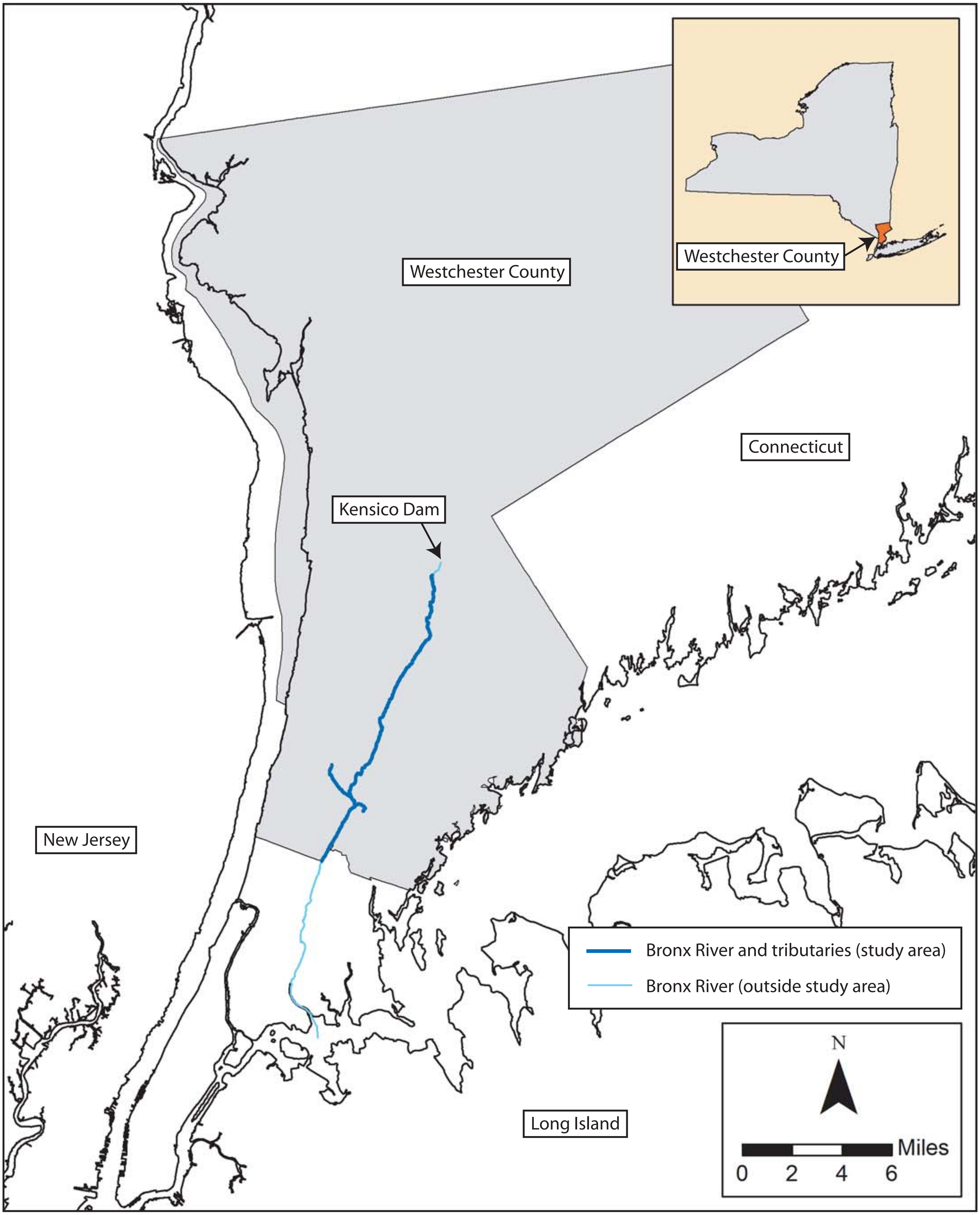


Figure 1. Location of Bronx River corridor in Westchester County, N.Y.

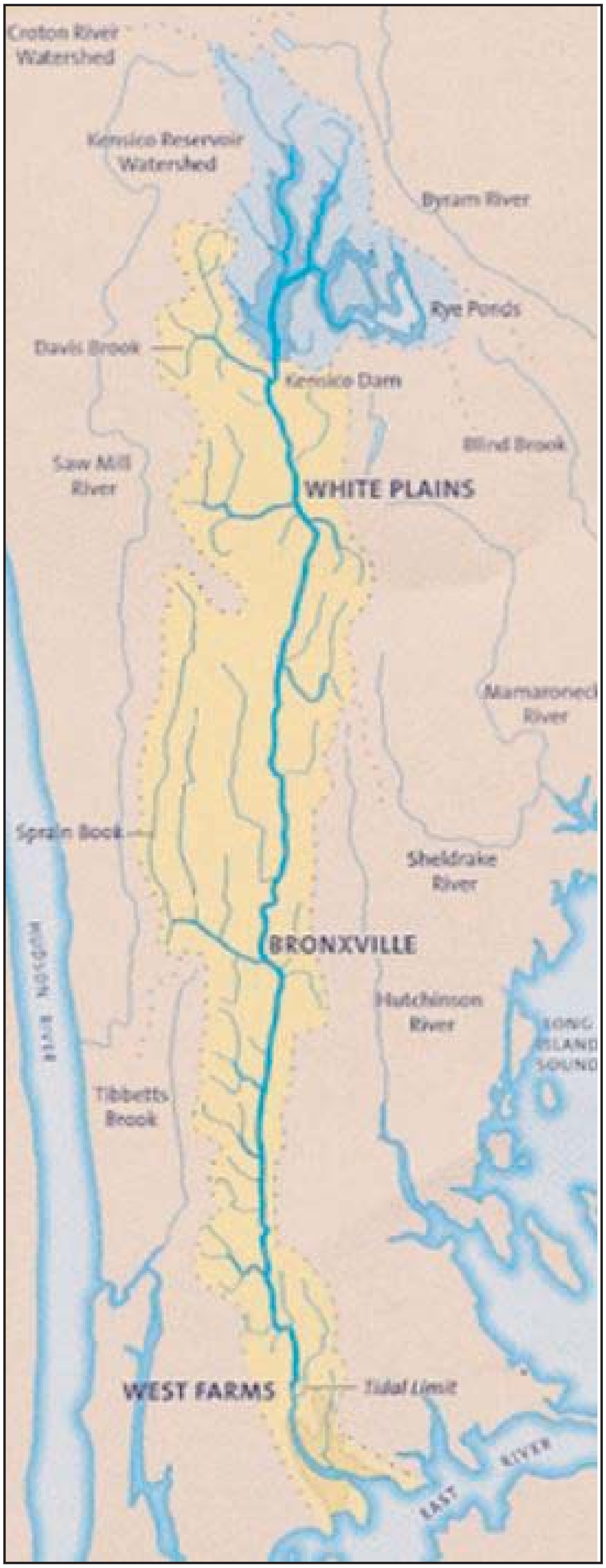


Figure 2. The Bronx River runs north to south in an elongated watershed.

Figure 3. Low natural falls in Scarsdale, N.Y. atop of which was built a low head check dam.

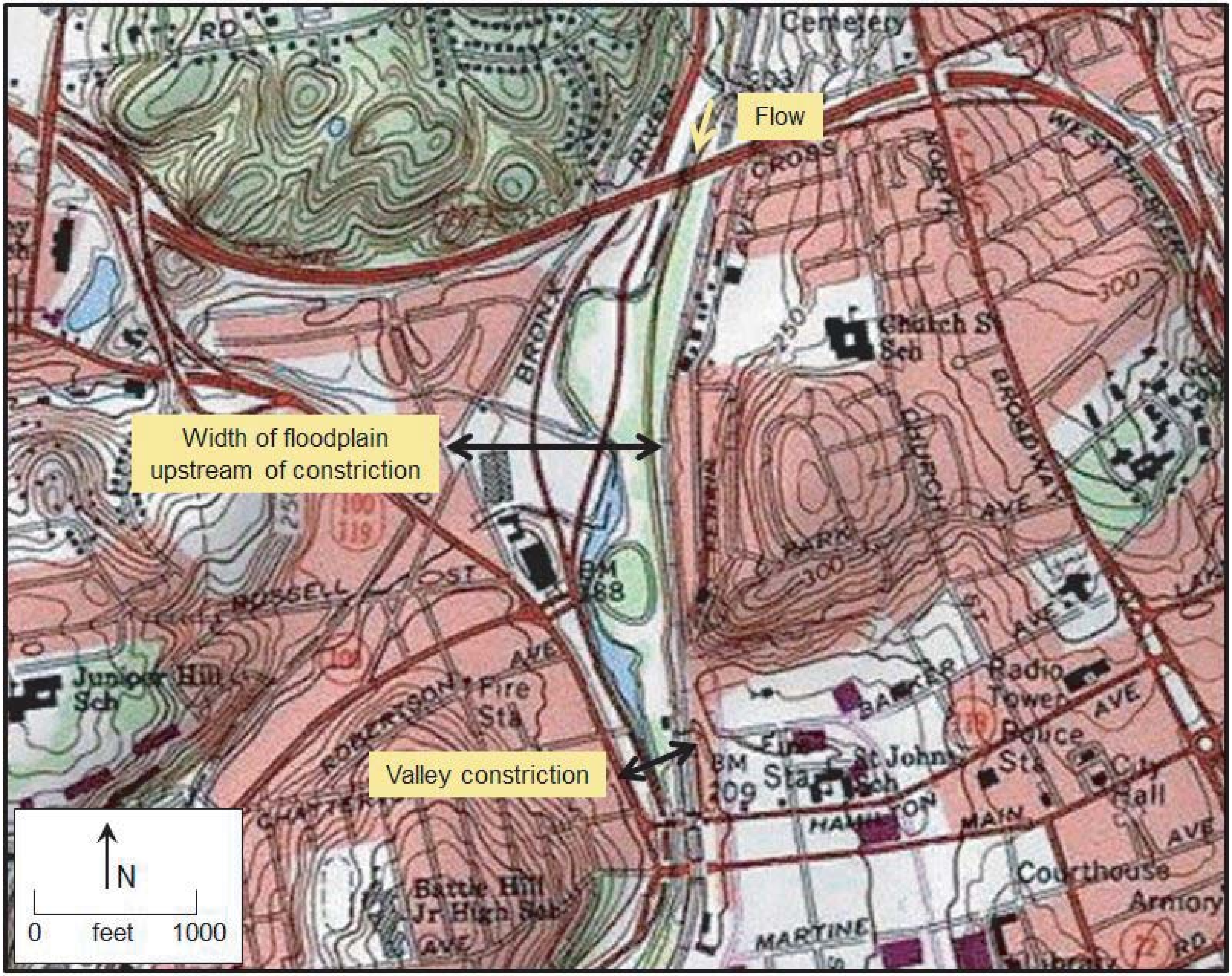


Figure 4. Natural valley constriction along Bronx River in White Plains, N.Y.

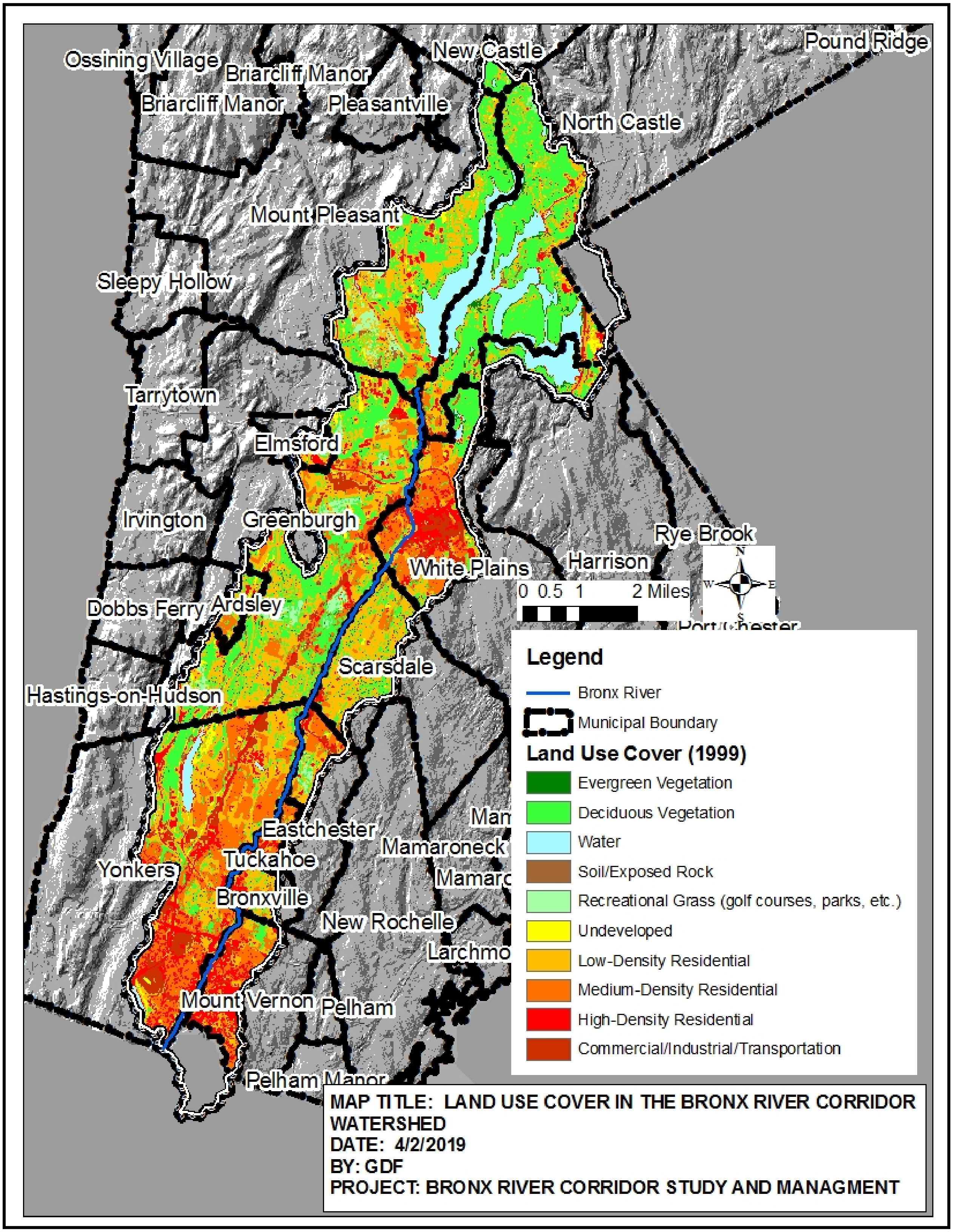


Figure 7. Land Use Cover in the Bronx River Corridor Watershed

Figure 8. Kensico Dam at upstream end of Bronx River in Valhalla, N.Y.

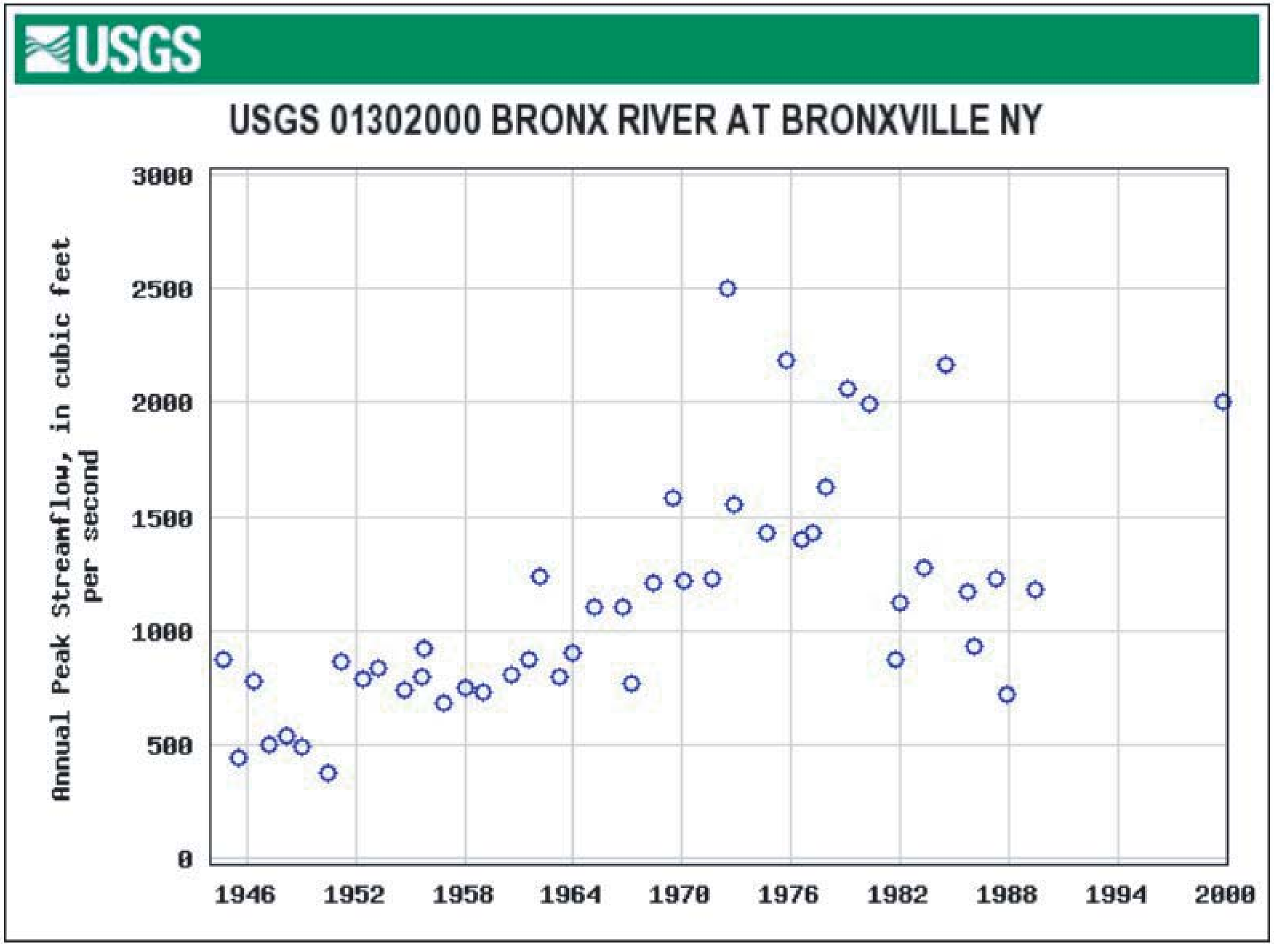


Figure 9. USGS gauge record from Bronxville, N.Y.

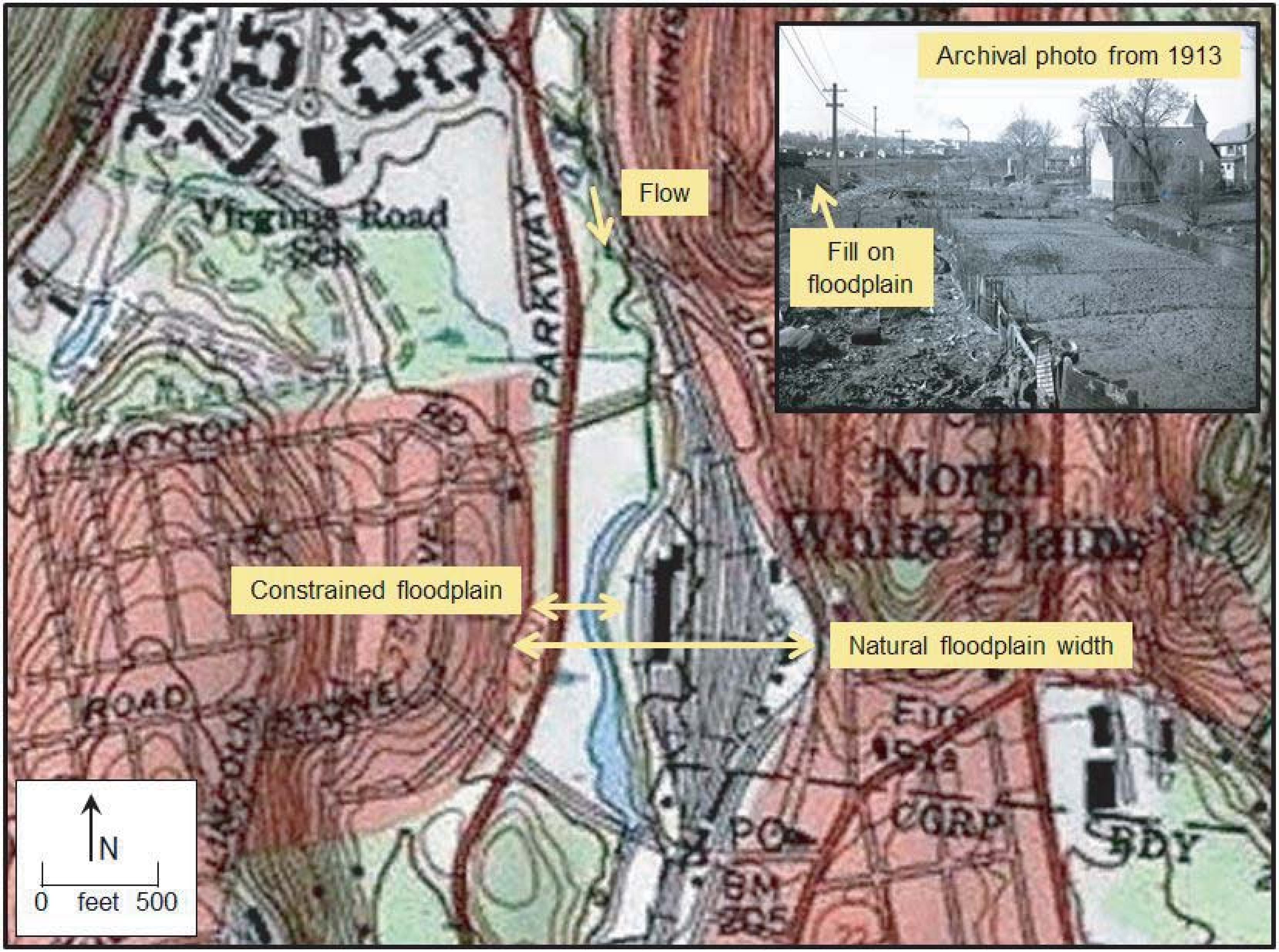


Figure 10. The rail lines at the Metro-North Commuter Railroad in North White Plains are built on the floodplain and artificially constrict the valley.

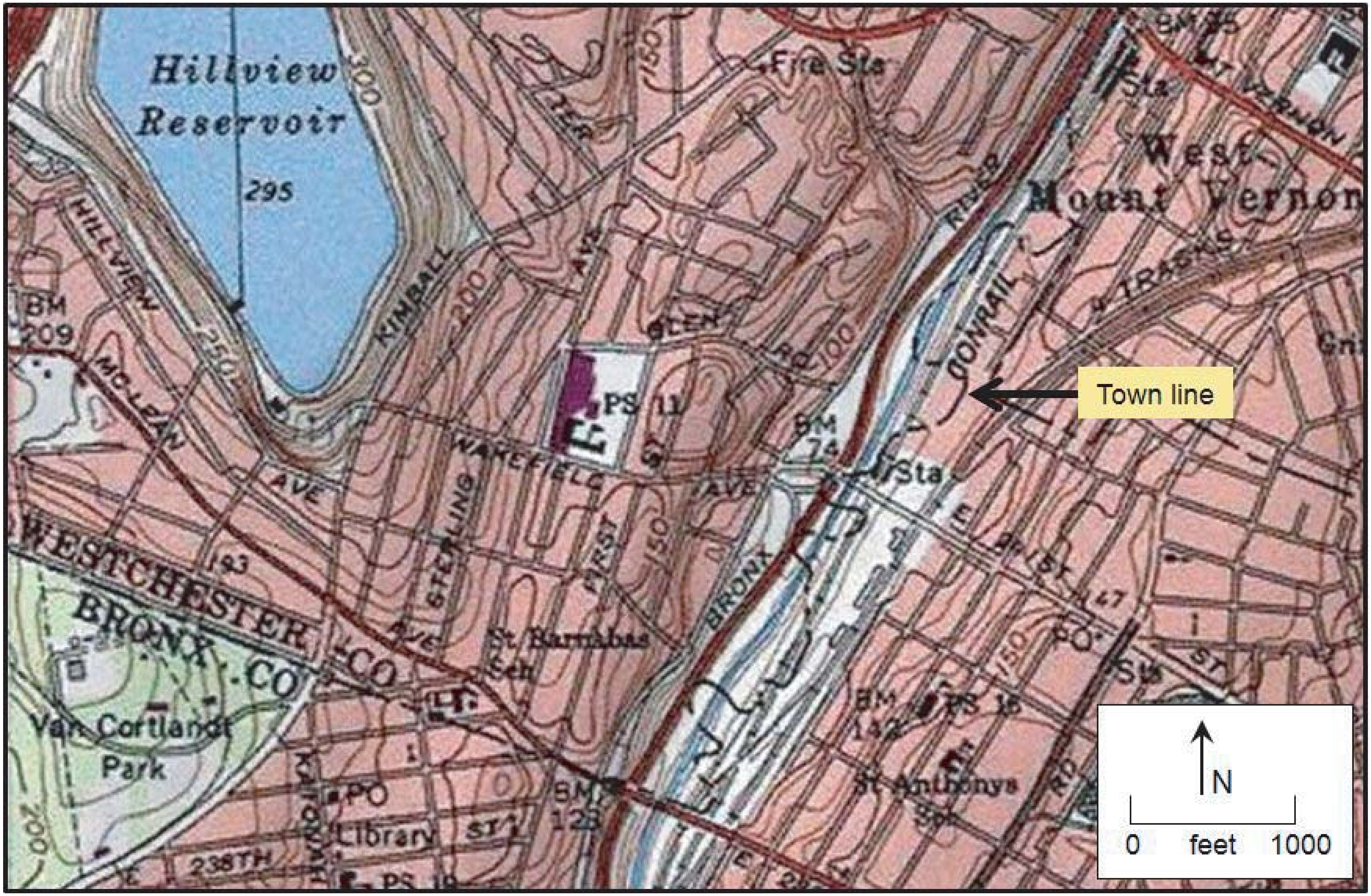


Figure 11. The sinuous border of Mt. Vernon, settled in 1664, followed what was then the meandering path of the Bronx River.

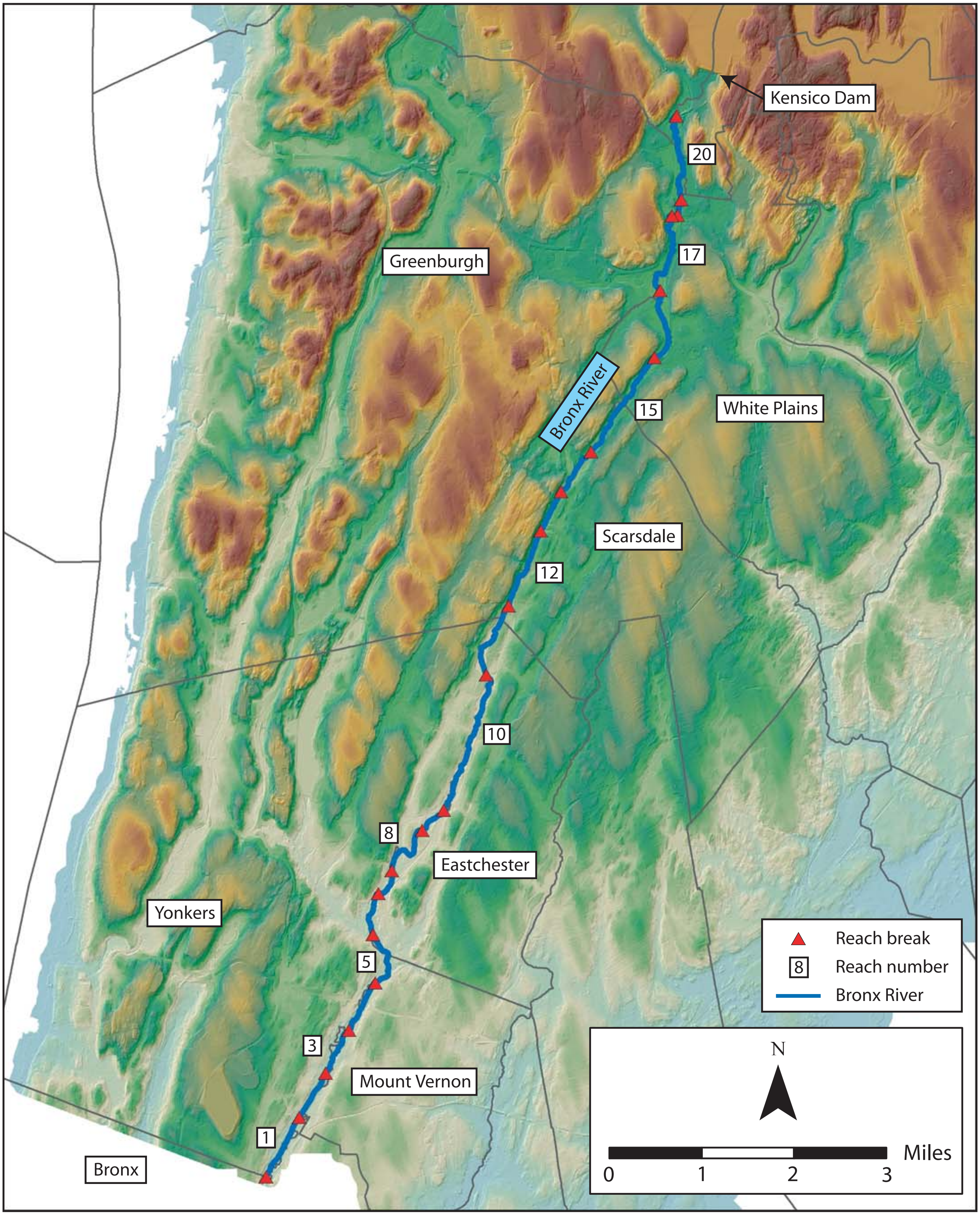


Figure 12. Geomorphic reaches on the Bronx River and the two assessed tributaries.

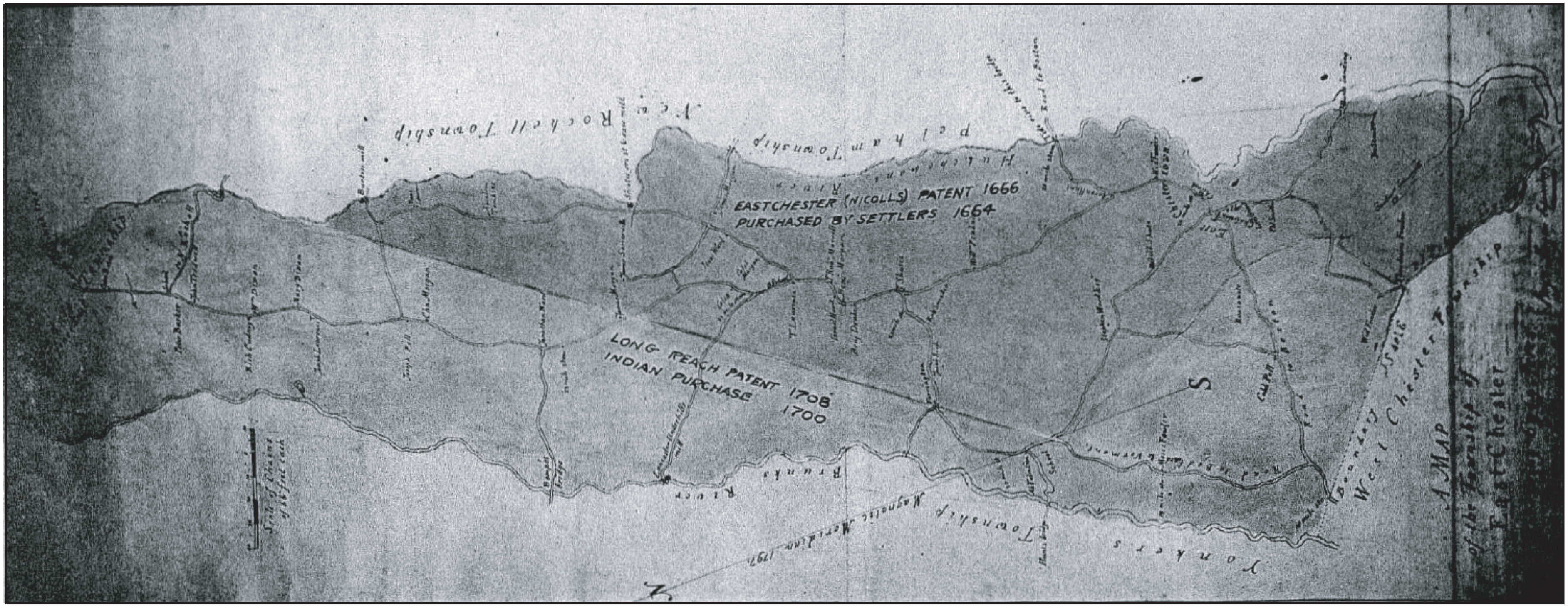


Figure 13. Map of Eastchester, N.Y. from 1708 showing meandering planform of Bronx River (at bottom of page). From Westchester County Archives.

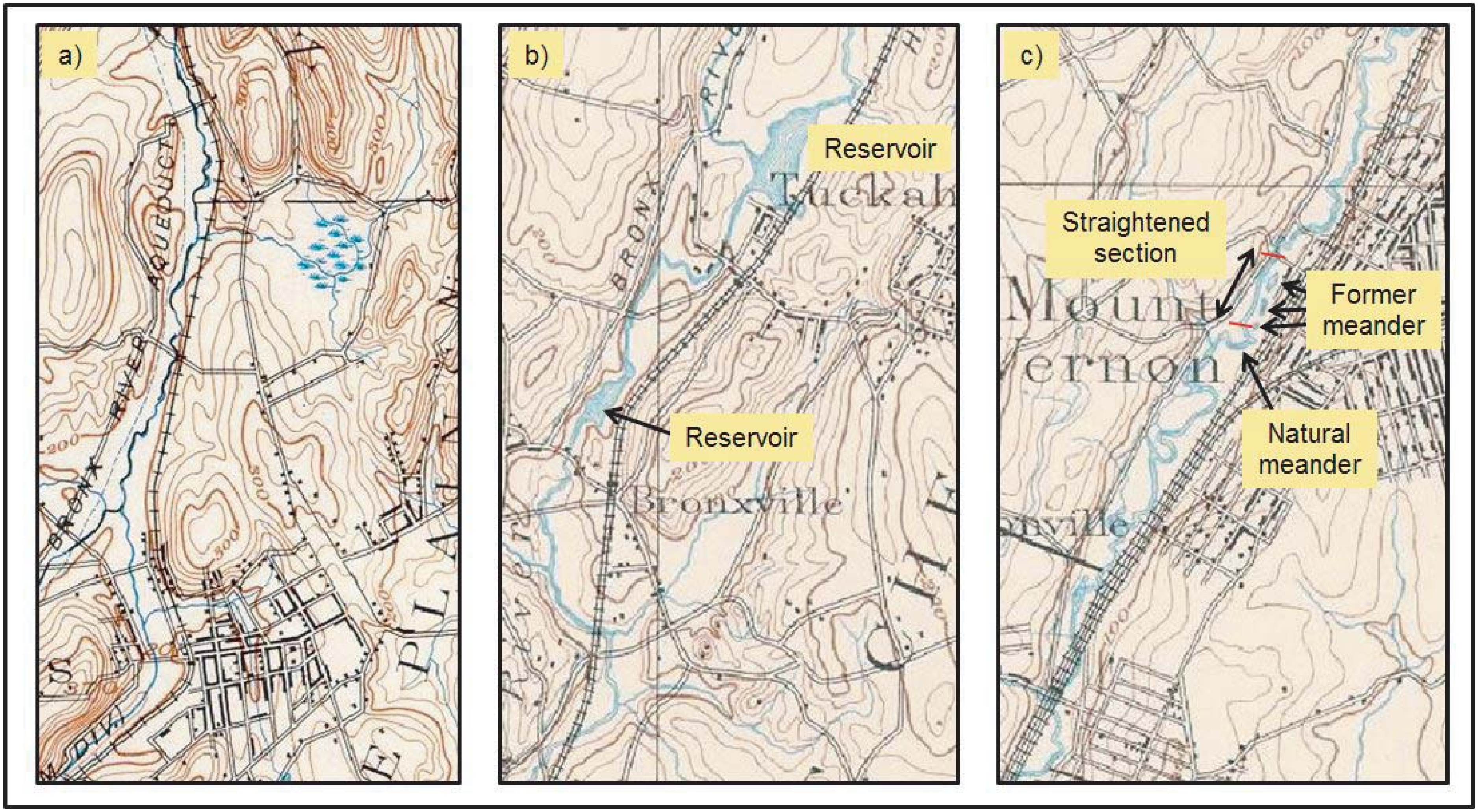


Figure 14. Portions of historic topographic maps surveyed between 1888 and 1890 showing a) a meandering planform despite introduction of the railroad, b) reservoirs upstream of dams, and c) evidence of artificial channel straightening.

Figure 15. Historic ground photograph showing buildings along the edge of a long straightened section of the Bronx River in 1913. From the Westchester County Archives.

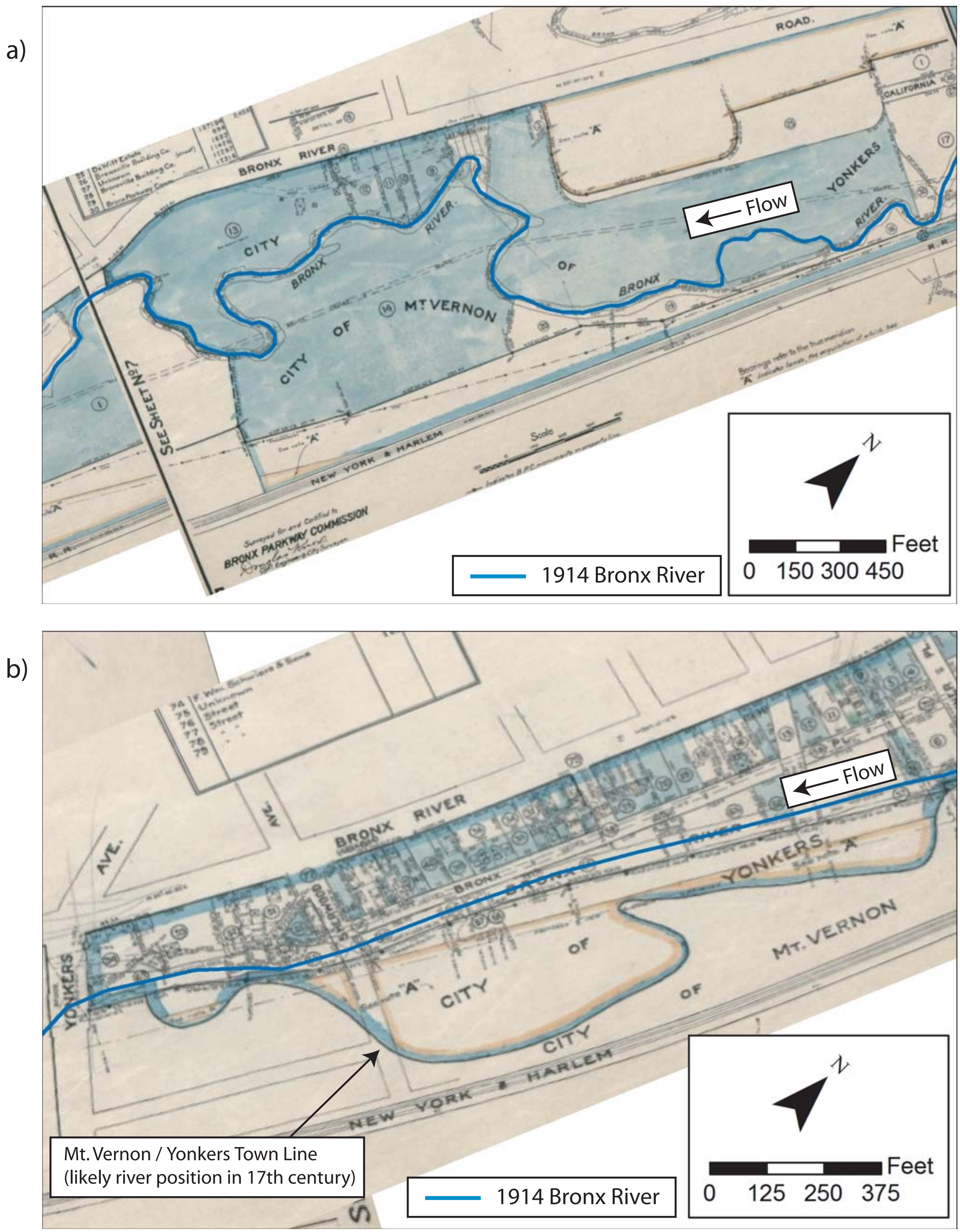


Figure 16. Survey maps of the Bronx River from 1914 show a) meandering portions and b) artificially straightened portions. From Westchester County Archives.

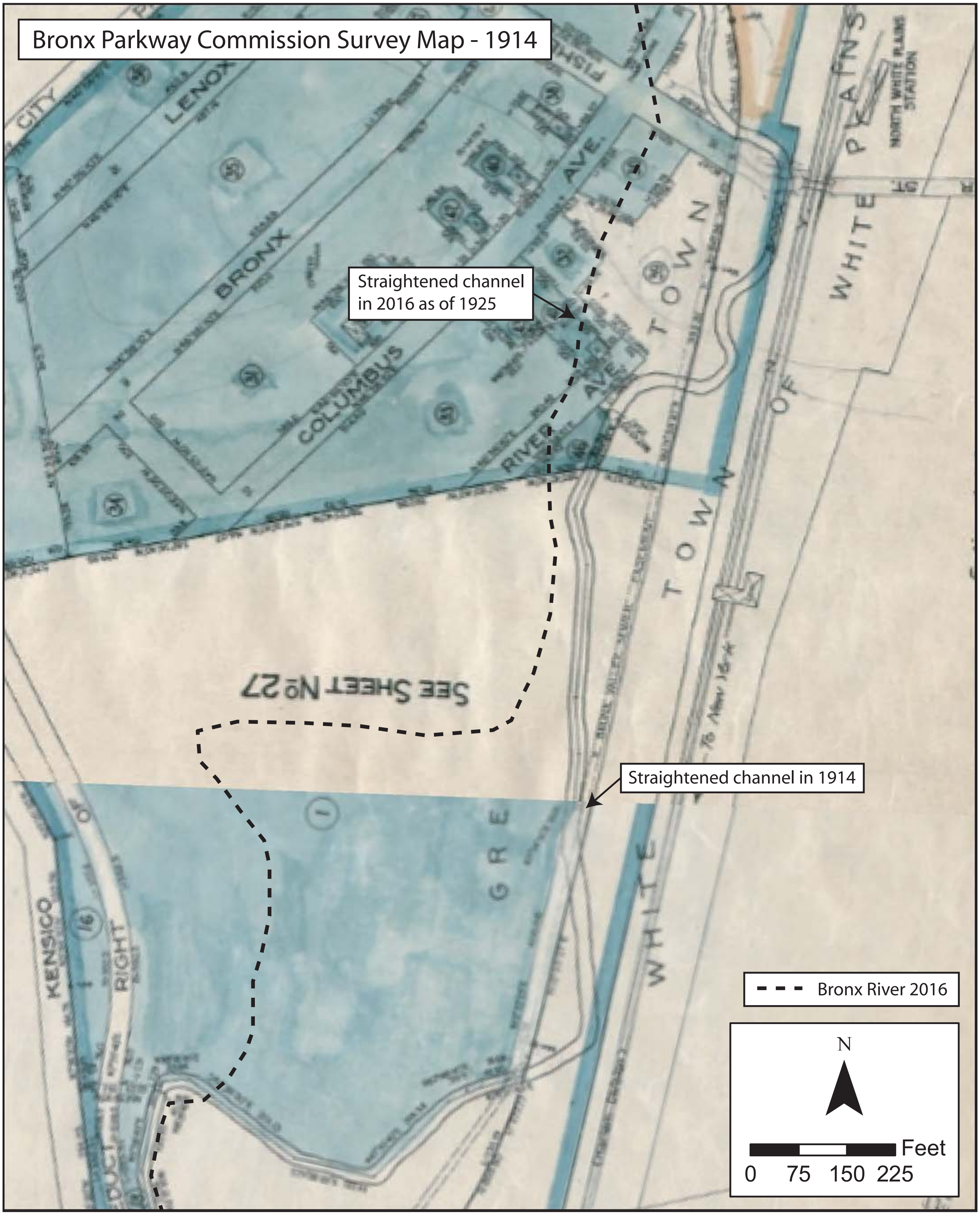


Figure 17. A straightened section of the river in 1914 was abandoned to form a new straightened section of the river during construction of the Bronx River Parkway.

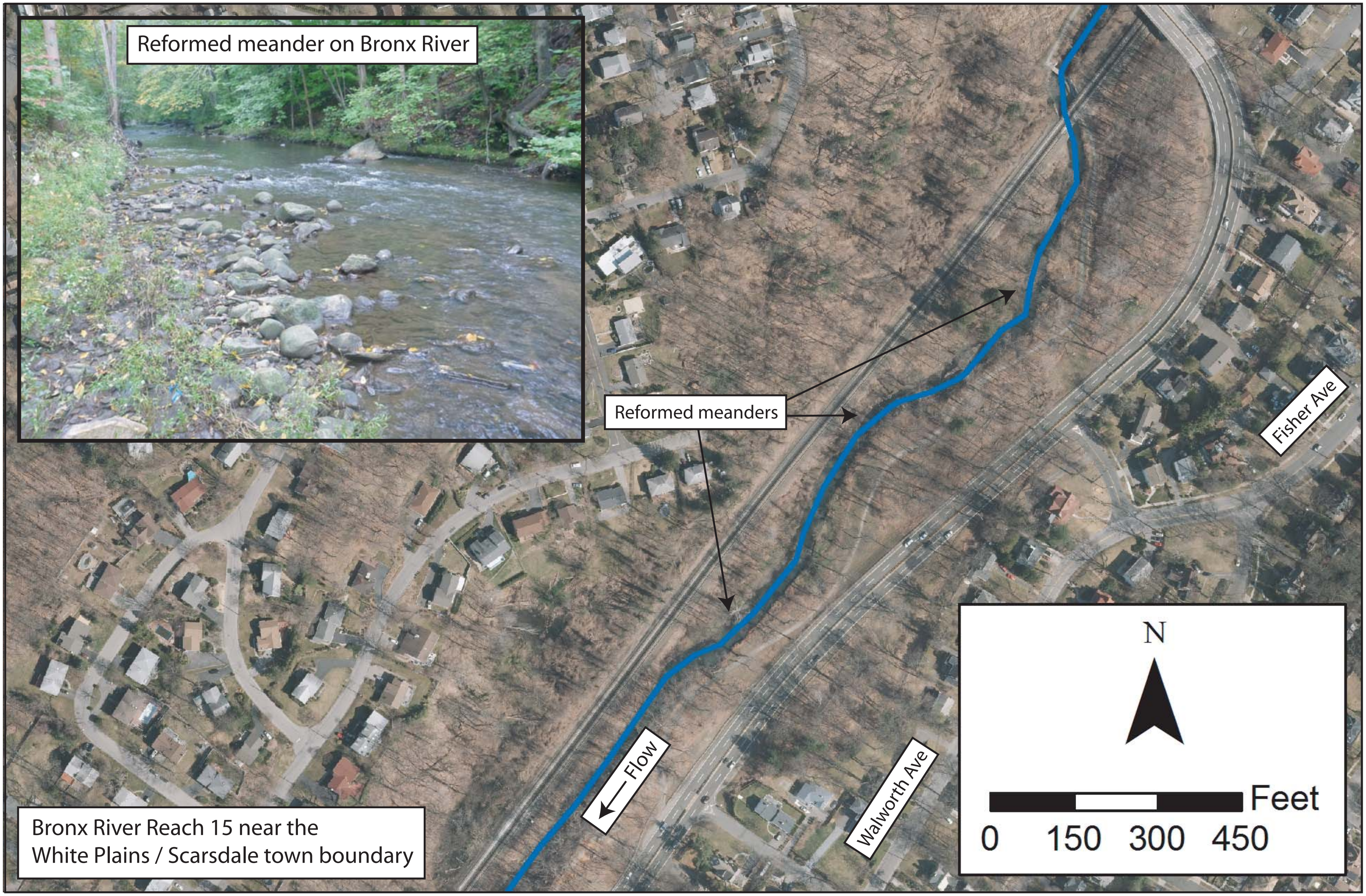


Figure 18. Naturally reformed meanders along an artificially straightened portion of the Bronx River.

a) b) c) d)

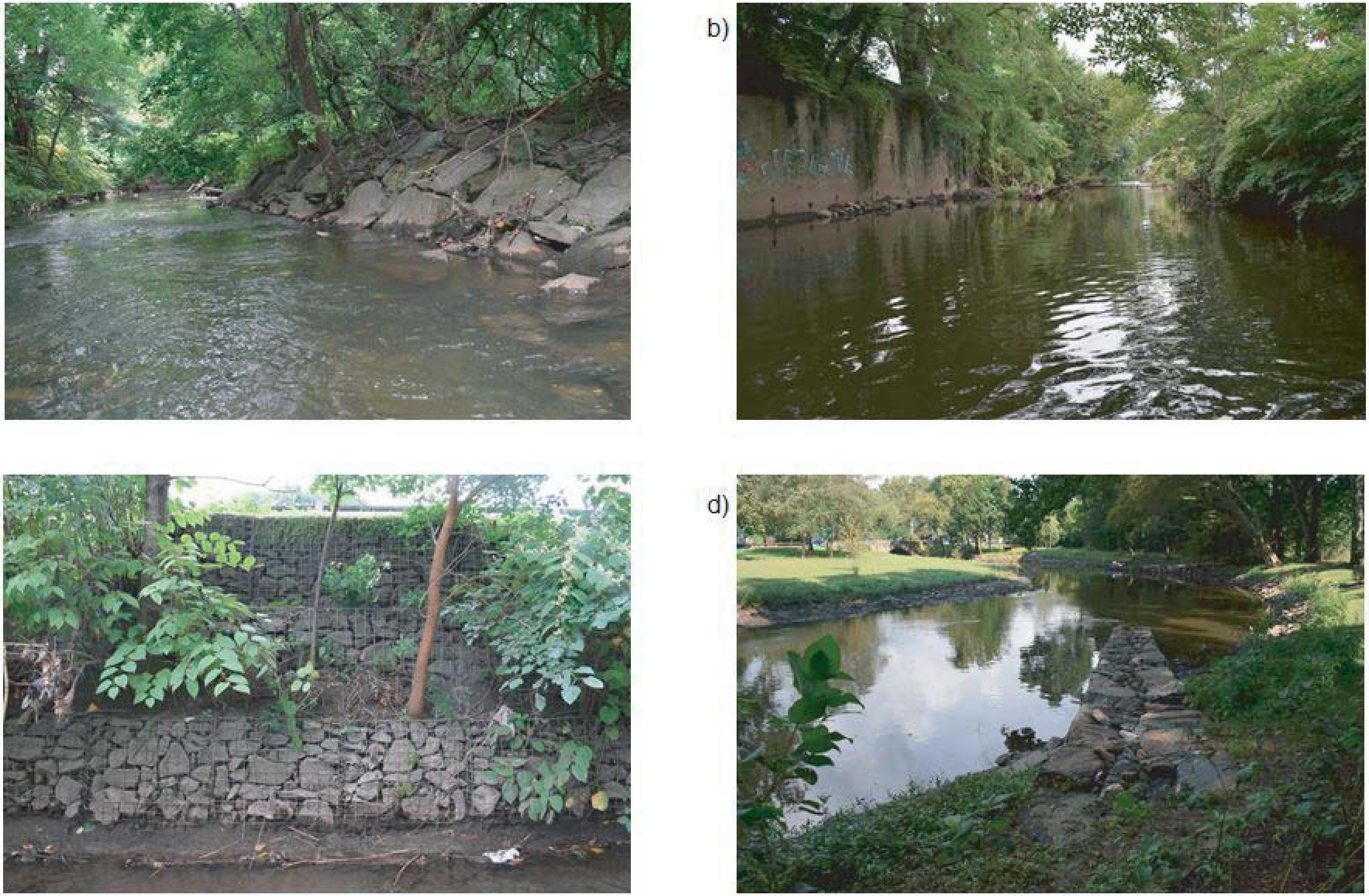


Figure 19. Armoring of the banks on the Bronx River has been done with a) large riprap stone, b) walls of concrete, c) gabion baskets, and d) boulder deflectors.

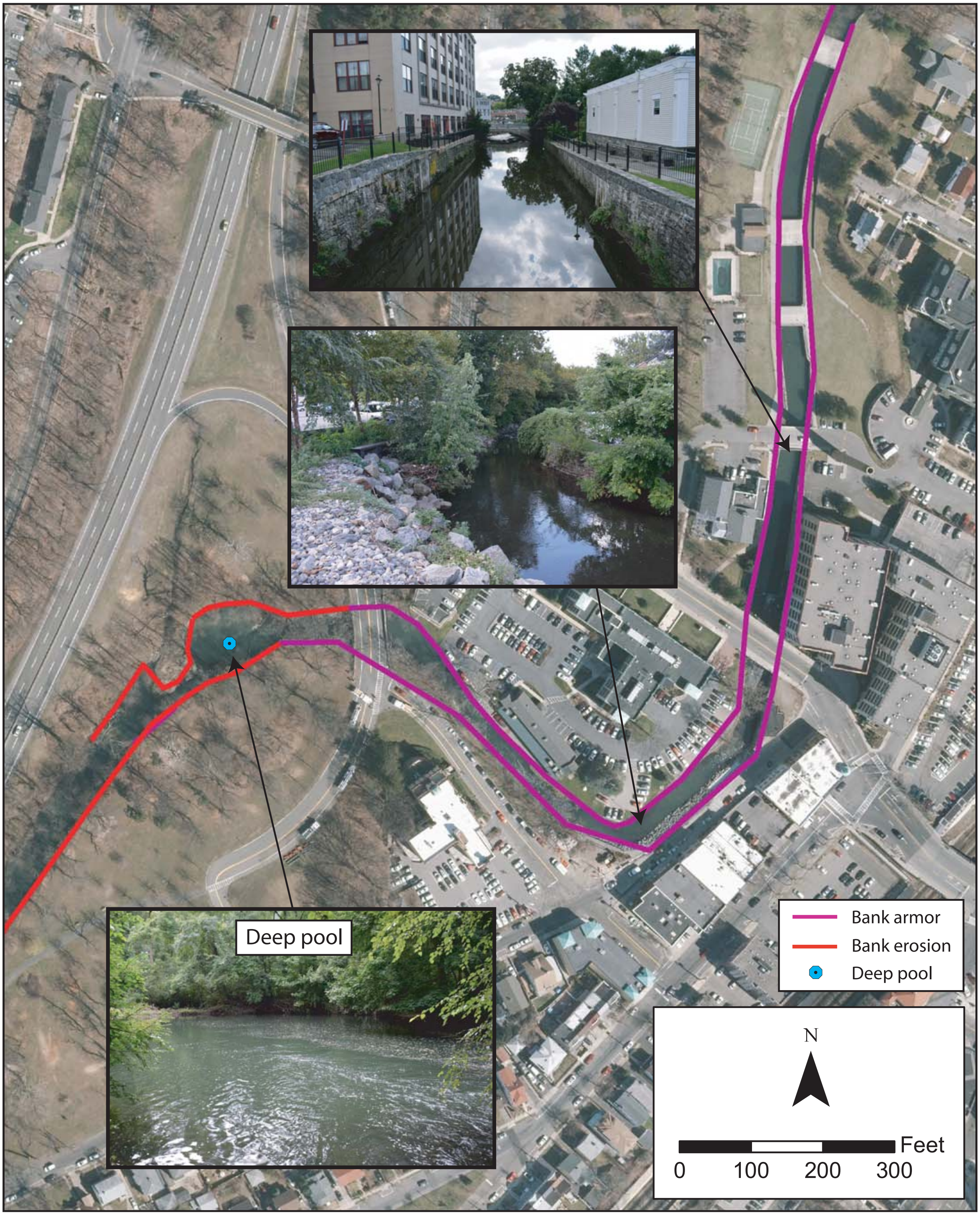


Figure 20. Armoring is found on both banks for a great distance through Tuckahoe and, as a result a large deep scour pool with unstable banks is located immediately downstream where the armoring ends.

Figure 21. Erosion attacking a bank where the armor has failed on the Bronx River.

a)

b)

Figure 22. a) Deposition upstream and b) bank armor downstream (to arrest previous erosion) of the check dam at Harney Road.

a)

b)

Figure 23. Channel adjustments around undersized stream crossings include a) deposition upstream and b) erosion downstream.

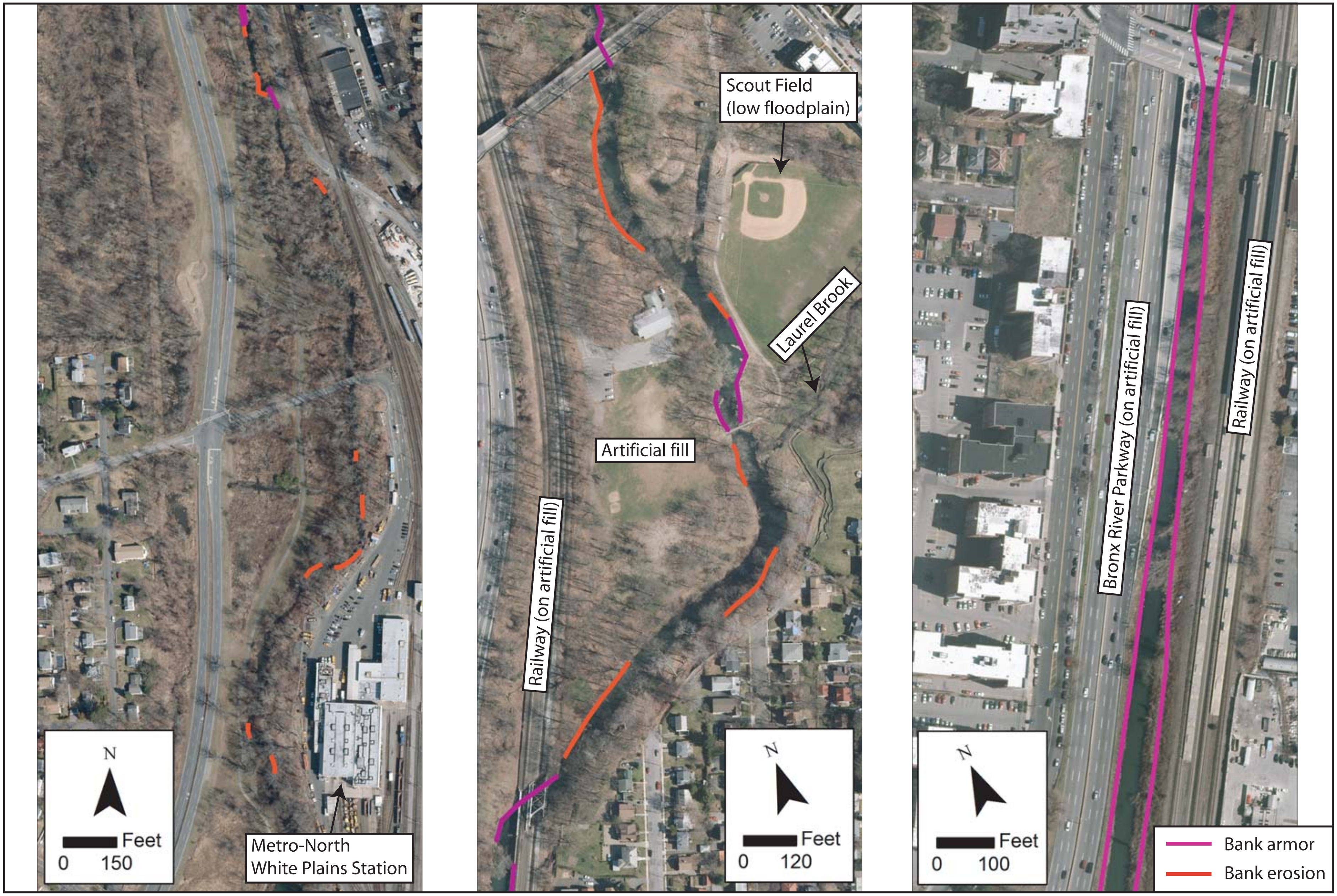


Figure 24. Artificial fill constraining channel can a) have limited impact, b) result in channel instability, and c) habitat degradation.

Figure 25. Long straightened sections of the Bronx River are often devoid of any depositional features.

Figure 26. Mature riparian trees along the Bronx River provide shading of and wood recruitment to the channel.

a)

b)

Figure 27. On Grassy Sprain Brook, a) armoring and straightening may be increasing sediment transport and bank instability downstream that led to b) construction of a bioengineering project at the confluence with the Bronx River.

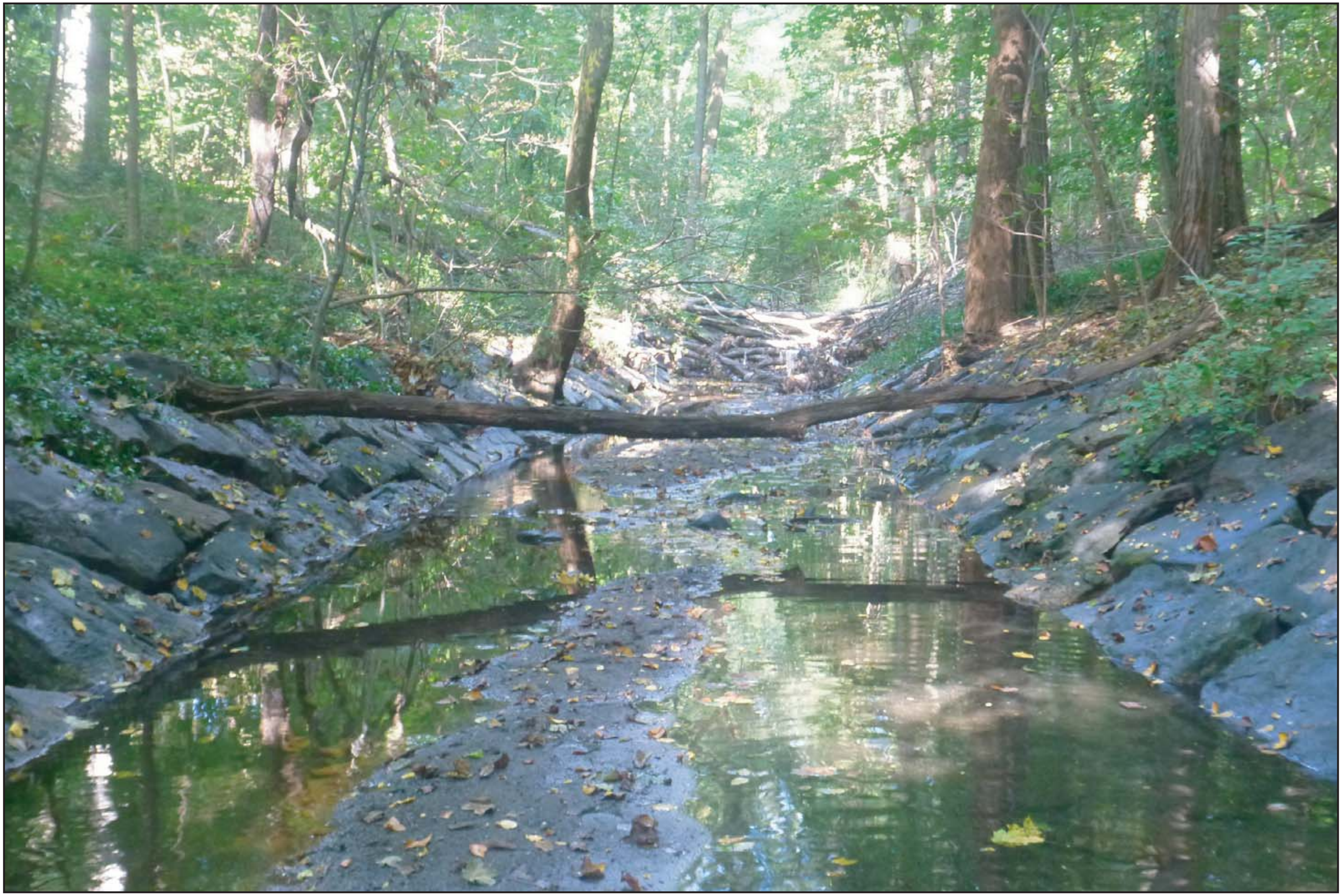


Figure 28. Laurel Brook is artificially straightened for much of its length and heavily armored.

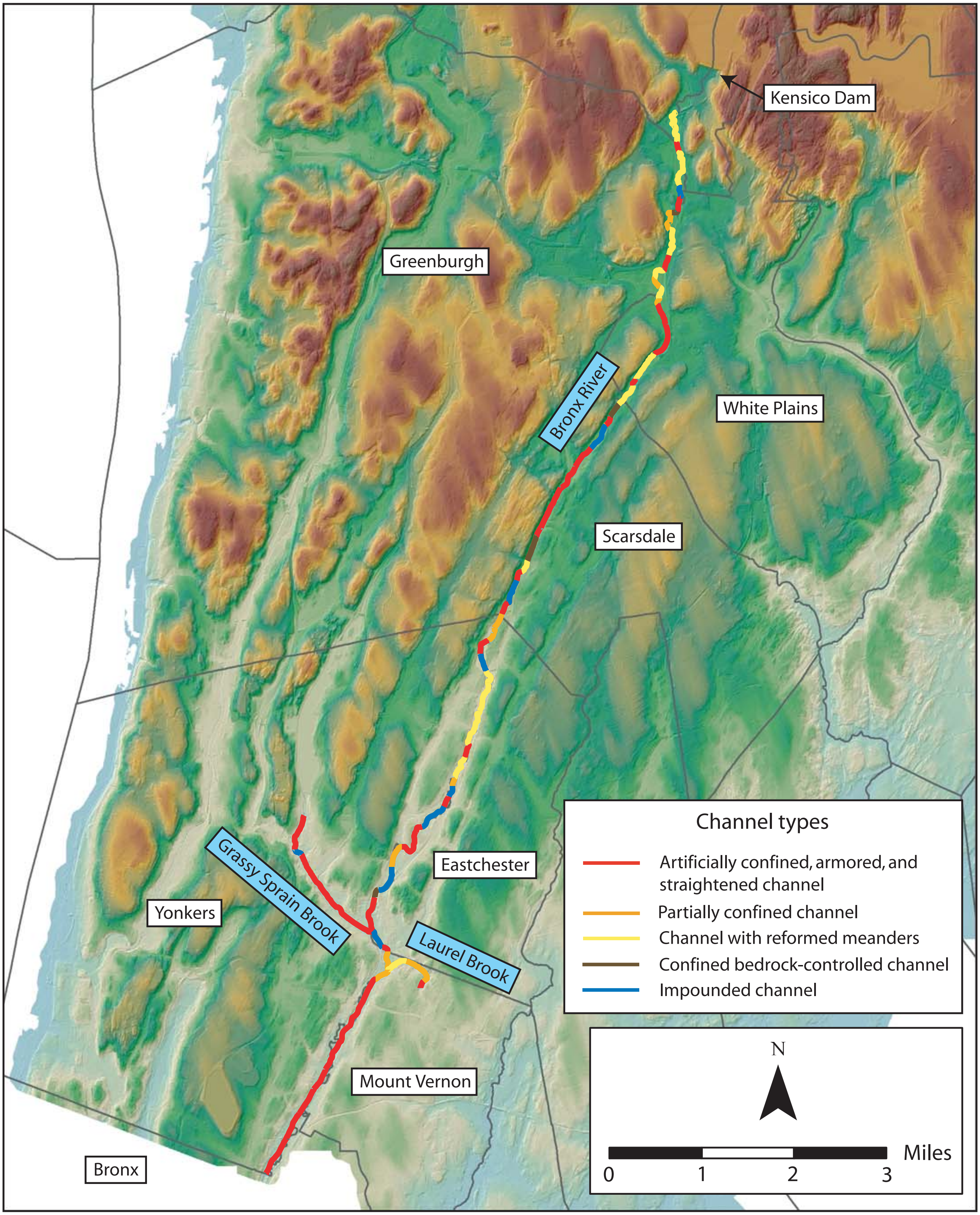


Figure 29. Map of channel types by segment.

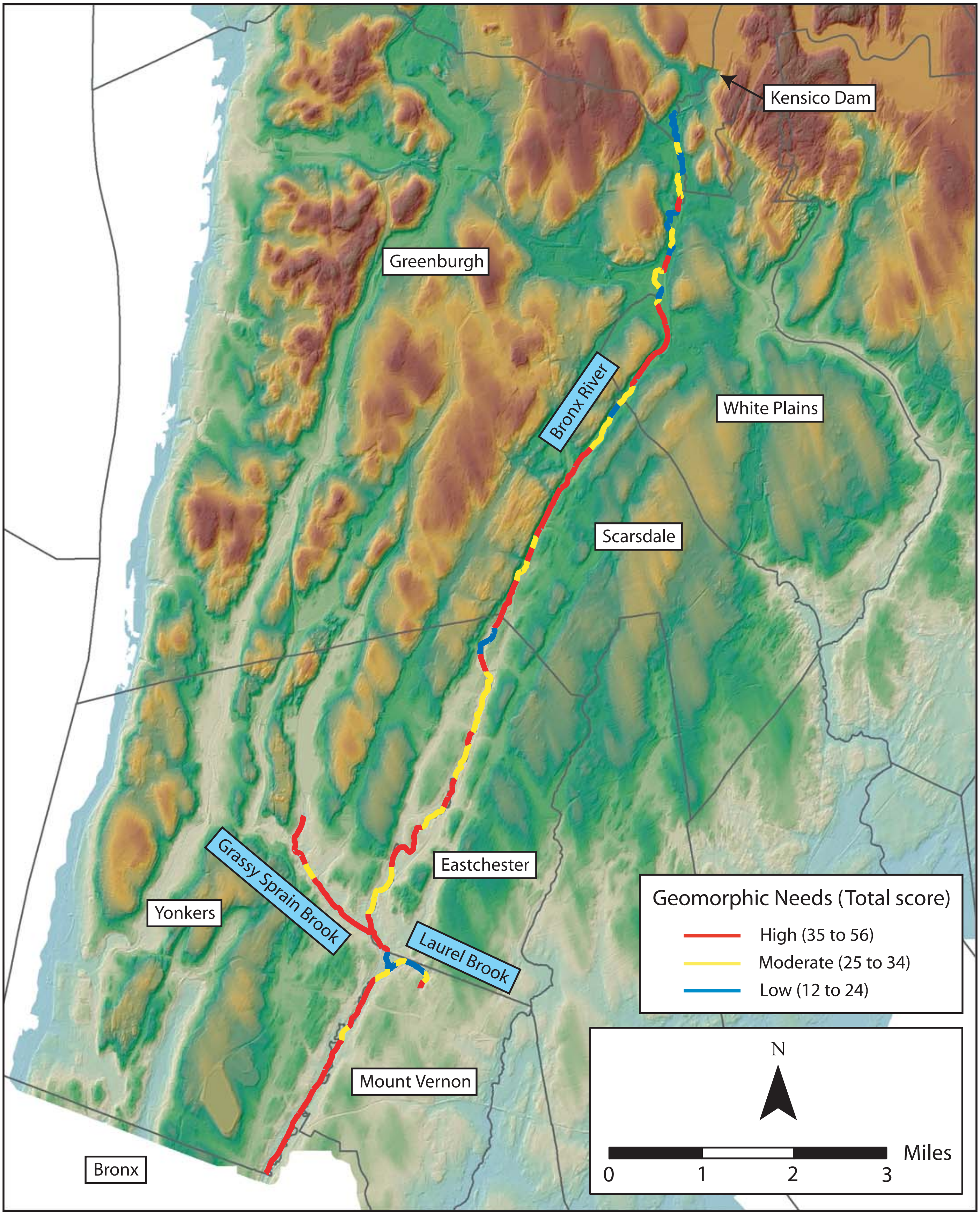


Figure 31. Map of geomorphic needs by segment.

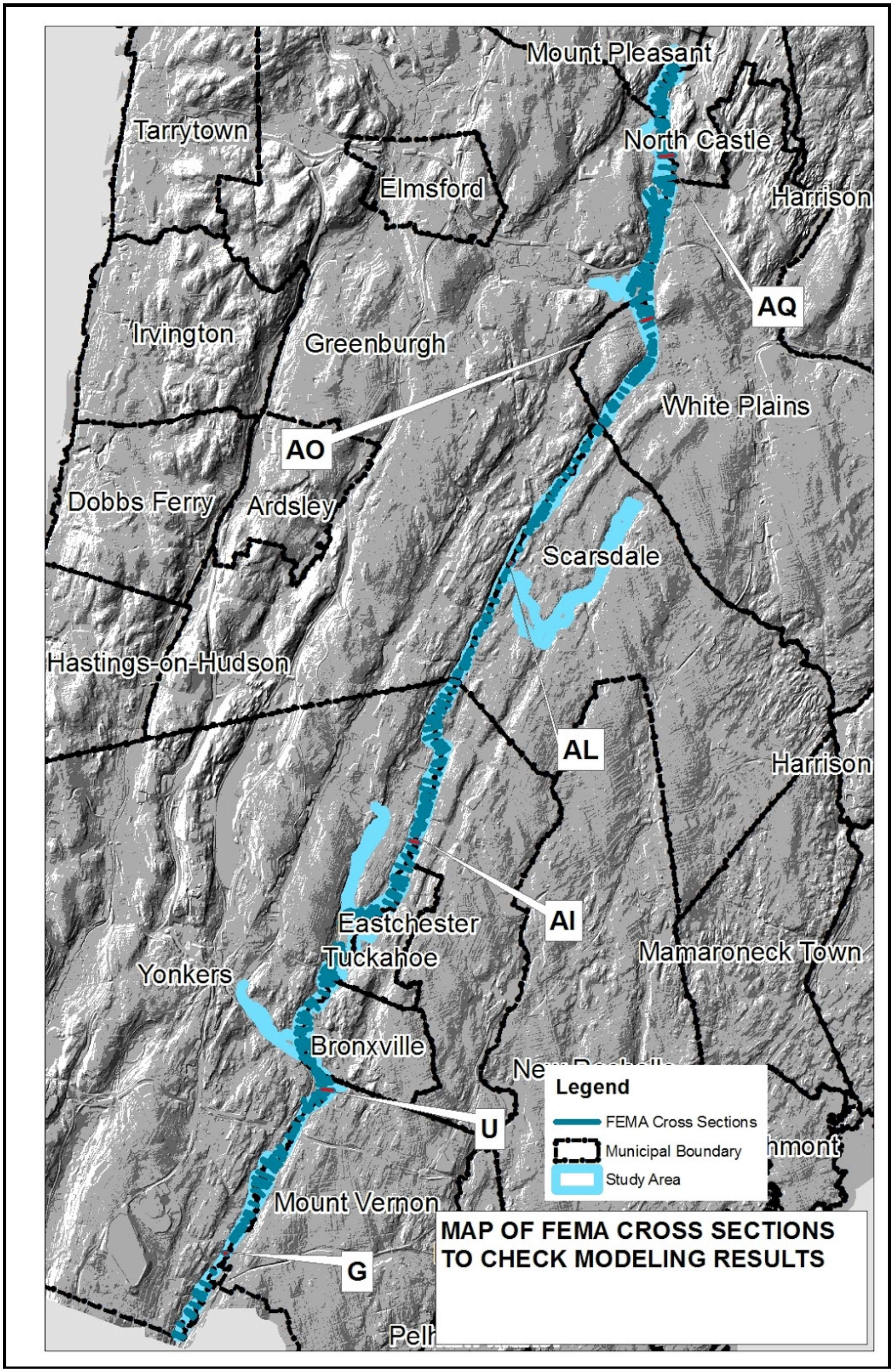


Figure 32. Location of comparative cross sections in FEMA Flood Insurance Study.

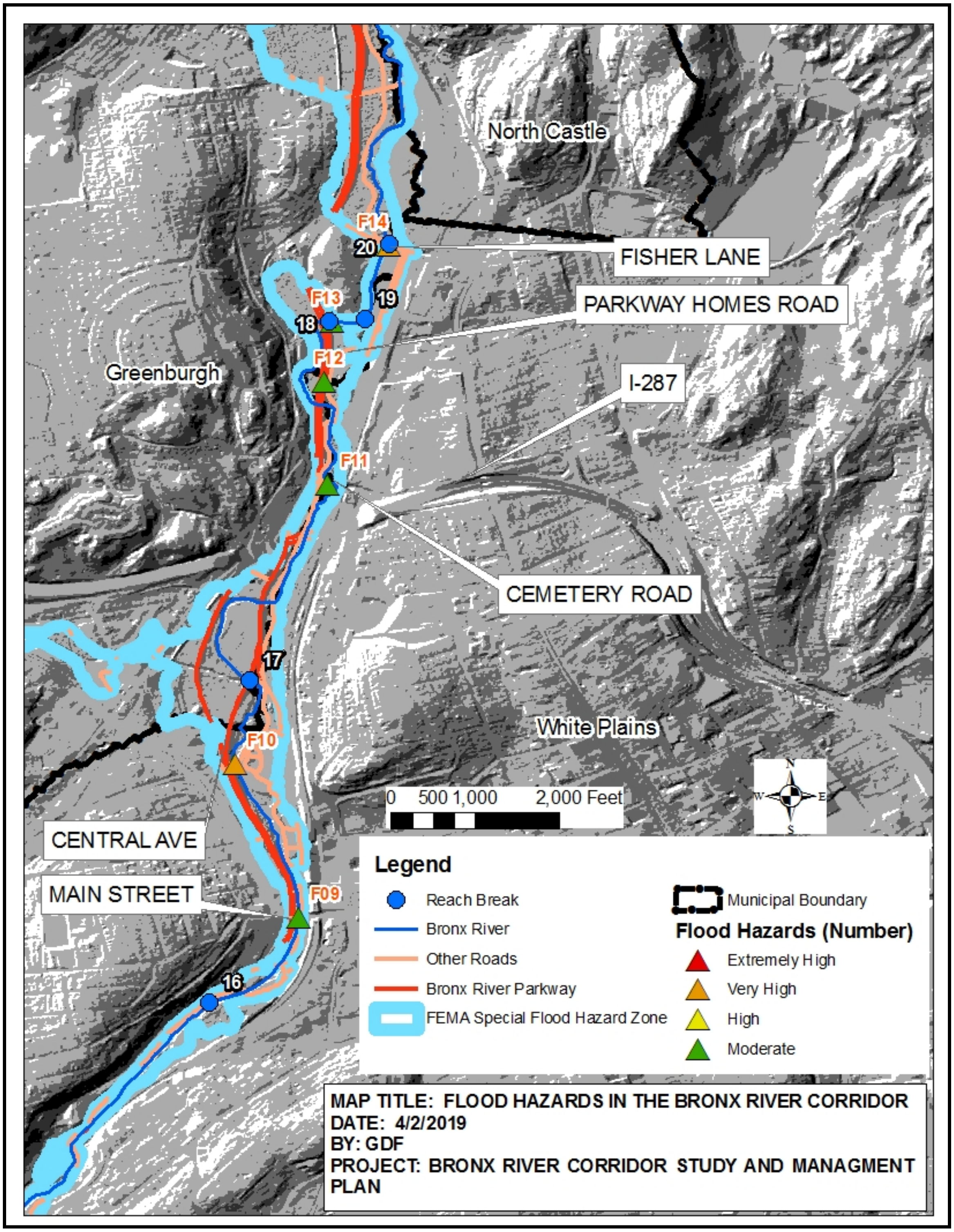


Figure 33. Map 1 of flood hazards in corridor (reach #16 to reach #20)

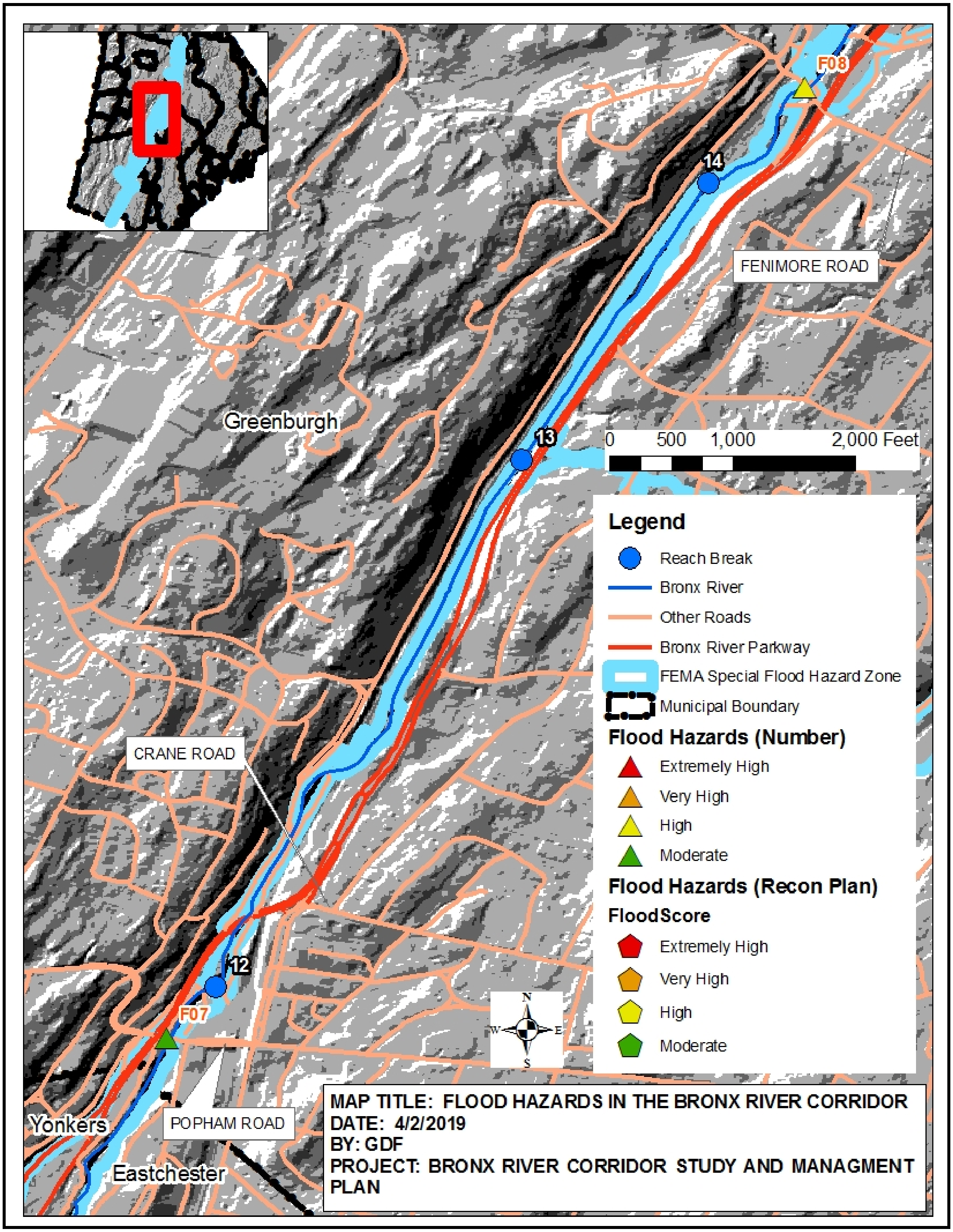


Figure 34. Map 2 of flood hazards in corridor (reach #12 to reach #14)

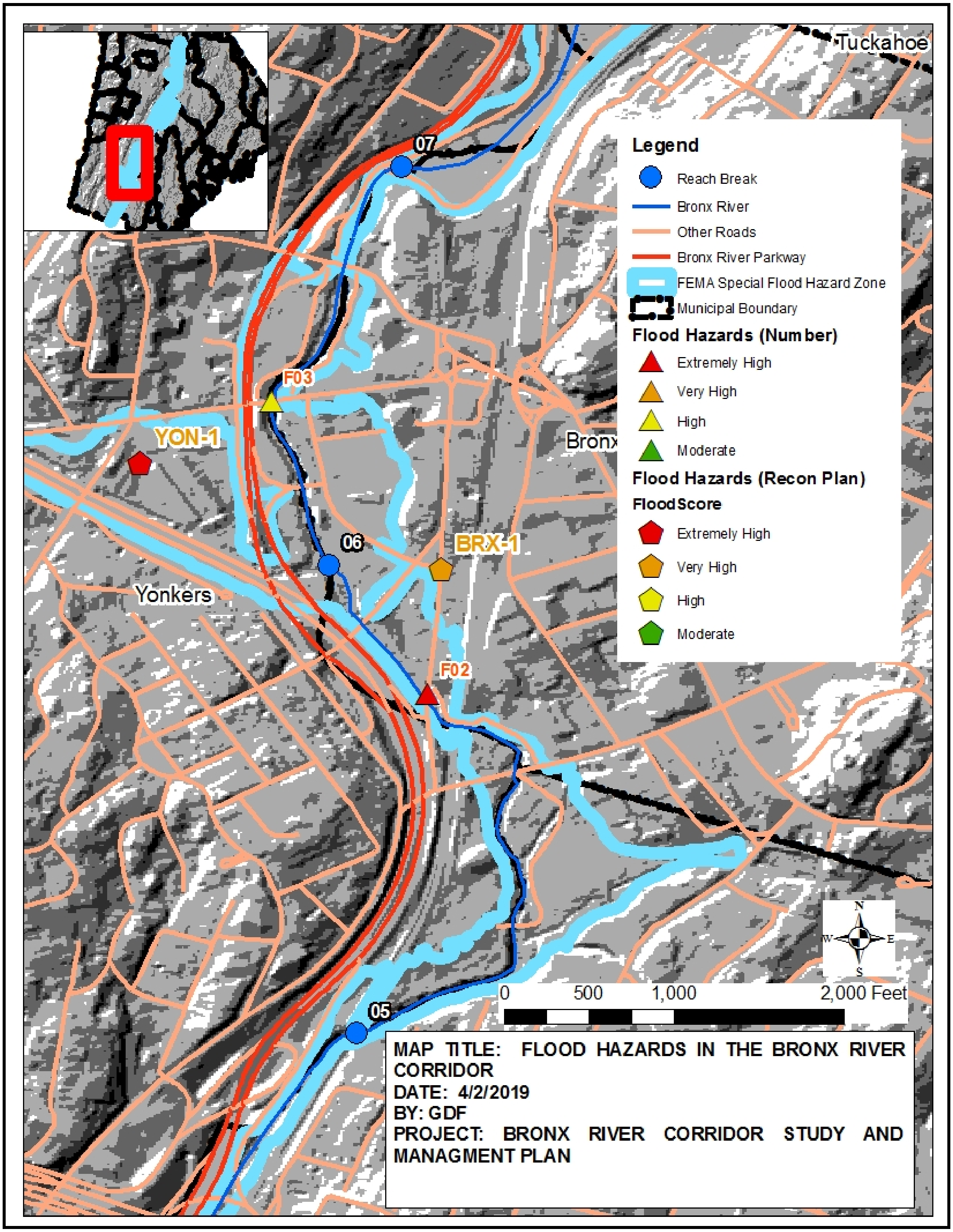


Figure 35. Map 3 of flood hazards in corridor (reach #05 to reach #09)

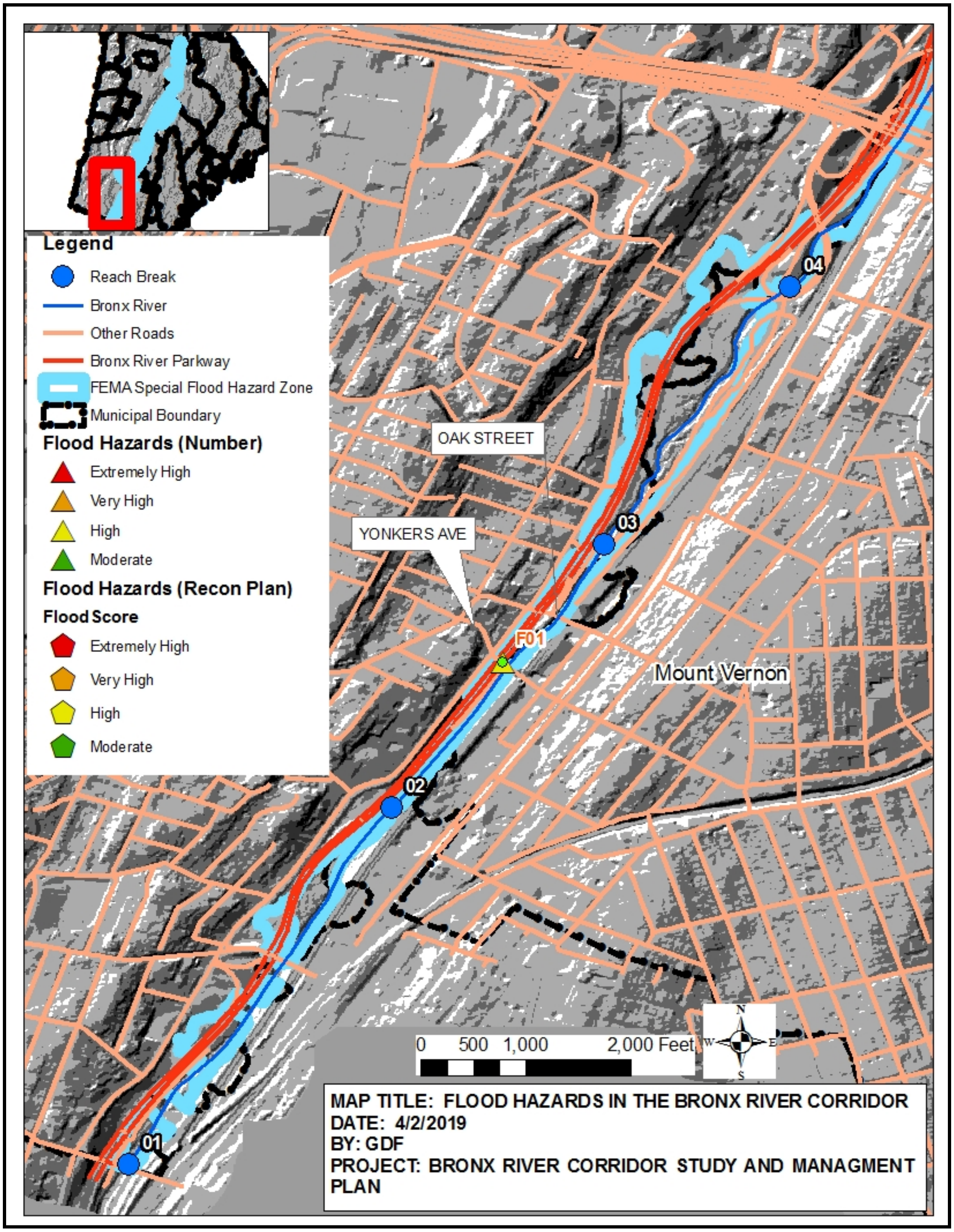


Figure 36. Map 4 of flood hazards in corridor (reach#01 to reach #04)

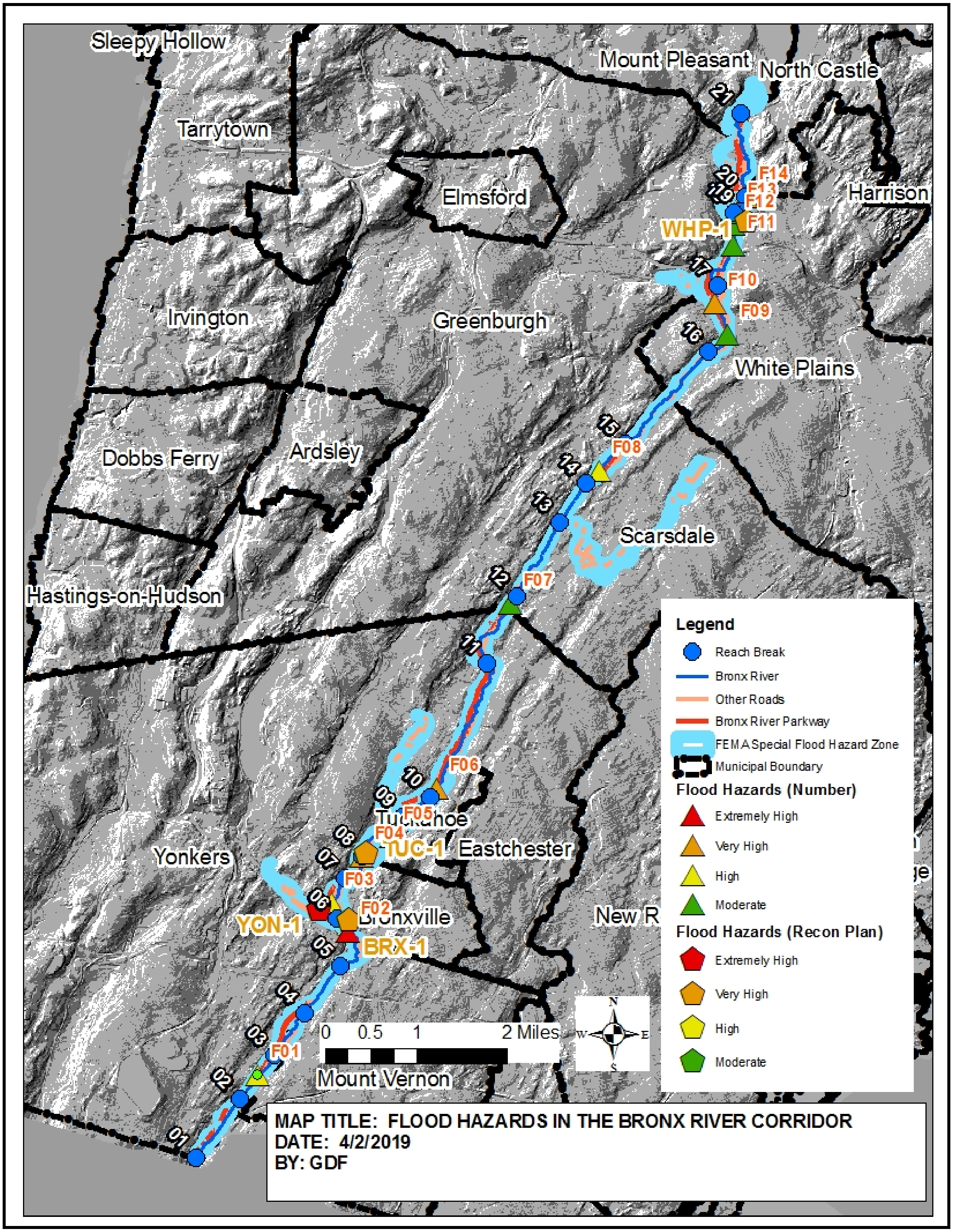


Figure 37. Flood Hazards in the Bronx River corridor.

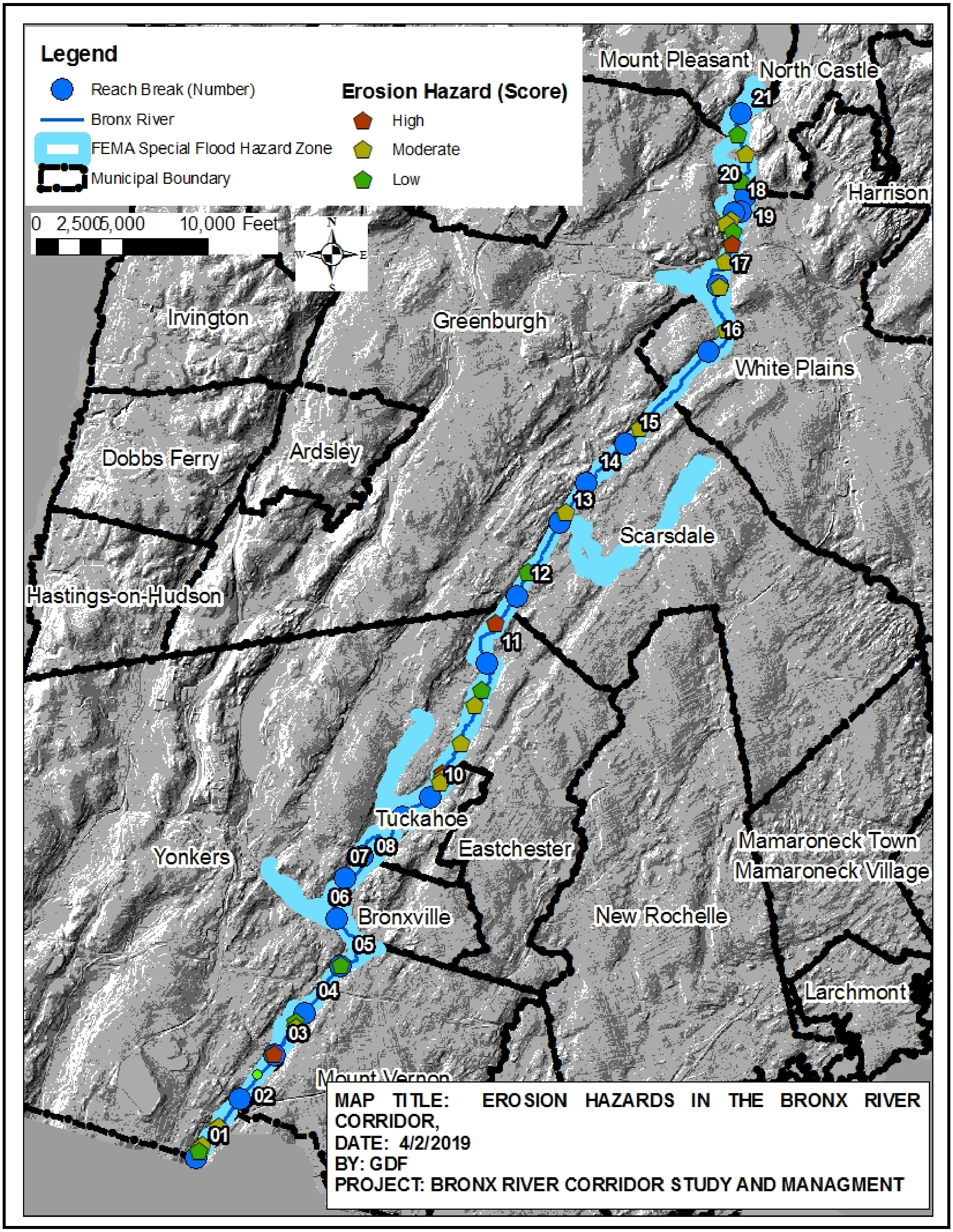


Figure 42. Location of erosion hazards.

TABLES

Stream	Reach	Reach length (ft)	Location of reach break Latitude	Longitude	Location Intersection / landmark	Reason for break†	Channel slope (%)	Channel sinuosity
Bronx River	US end	-	41.0666978358	-73.7735452152	S Kensico Ave; Pat Henry Field	US END	-	-
Bronx River	BR20	5,960	41.0535602150	-73.7726821638	Fisher Ln; Metro-North White Plains	AC	0.107	1.24
Bronx River	BR19	936	41.0511150394	-73.7734781600	Metro-North White Plains parking lot	VC, BR	0.072	1.01
Bronx River	BR18	343	41.0510361659	-73.7746421637	Bronx River Pkwy	VE, BR	0.708	1.01
Bronx River	BR17	5,596	41.0393289559	-73.7772273813	Bronx River Pkwy NB; County Center	T	0.105	1.26
Bronx River	BR16	4,495	41.0288549577	-73.7785250084	Bronx River Pkwy; 0.3 mi ds of Hamilton Ave	VC	0.029	1.10
Bronx River	BR15	6,733	41.0141307003	-73.7918094938	Brook Ln; County Tennis Club	D	0.250	1.04
Bronx River	BR14	2,989	41.0079248759	-73.7981414114	0.2 mi ds of Fenimore Rd; Metro-Hartsdale parking lot	VC, P	0.305	1.05
Bronx River	BR13	2,536	41.0017582902	-73.8023035622	Fox Meadow Rd and Kent Rd	T	0.157	1.00
Bronx River	BR12	4,824	40.9900107553	-73.8091322483	Depot Pl; Metro-Scarsdale	D, BR	0.264	1.03
Bronx River	BR11	4,664	40.9792596376	-73.8138589685	Harney Rd; Garth Woods	D, VC	0.461	1.06
Bronx River	BR10	8,796	40.9580630912	-73.8228337243	Thompson St; County Parks and Rec Dep	US	0.162	1.08
Bronx River	BR09	1,795	40.9549260036	-73.8273819621	Read Ave and Clare Terr; Parkway Oval Park	D, VC	0.068	1.06
Bronx River	BR08	3,776	40.9486441110	-73.8337279954	300 ft ds of Tuckahoe Rd; Bronxville Lake	US	0.286	1.08
Bronx River	BR07	1,729	40.9451027453	-73.8365399396	640 ft us of Pondfield Rd; Bronxville Lake	D, VC	0.056	1.03
Bronx River	BR06	2,576	40.9386536210	-73.8377158480	Sprain Brook Pkwy and Bronx River Pkwy	T	0.447	1.01
Bronx River	BR05	3,624	40.9310801873	-73.8372610035	W Devonia Ave and Packman Ave; Scout Field	AC, P	0.064	1.10
Bronx River	BR04	3,194	40.9236846318	-73.8428582492	Bronx River Pkwy Ramp	C, VE	0.170	1.00
Bronx River	BR03	2,903	40.9169462934	-73.8477266580	750 ft us of Oak St	VC, P	0.092	1.04
Bronx River	BR02	2,958	40.9100519088	-73.8532756966	Bronx River Rd and Raybrook Rd	VE	0.066	1.01
Bronx River	BR01	3,921	40.9007199828	-73.8601664744	Nereid Ave	DS END	0.101	1.01
Grassy Sprain Brook	US end	-	40.9568122181	-73.8517635201	Grassy Sprain Rd and Ruskin Pl	US END	-	-
Grassy Sprain Brook	GS05	1,737	40.9524777919	-73.8535745809	Grassy Sprain Pkwy at Tuckahoe Rd	AC	0.057	1.05
Grassy Sprain Brook	GS04	874	40.9507090063	-73.8523713910	Grassy Sprain Pkwy Off Ramp	D	0.076	1.25
Grassy Sprain Brook	GS03	1,968	40.9460936092	-73.8488475487	Grassy Sprain Pkwy at Birchbrook Rd	T, VE	0.455	1.00
Grassy Sprain Brook	GS02	2,209	40.9414140613	-73.8440424254	Palmer Rd and Millard Ave	VC, P	0.070	1.02
Grassy Sprain Brook	GS01	2,095	40.9385957628	-73.8376988325	Sprain Brook Pkwy and Bronx River Pkwy	CON	0.090	1.03
Laurel Brook	US end	-	40.9296291499	-73.8280441912	Rhynas Dr; Hunt Woods Park	US END	-	-
Laurel Brook	LAU03	1,104	40.9321313210	-73.8271937024	Oakledge Rd; Hunt Woods Park	VE	0.833	1.01
Laurel Brook	LAU02	1,228	40.9338350229	-73.8308607502	Gramatan Ave	C	0.803	1.02
Laurel Brook	LAU01	1,323	40.9325675687	-73.8346703346	Edgewood Ave; Scout Field	CON	0.434	1.07

†Reason for reach break: VC = valley confinement; VE = valley expansion; T = major tributary confluence; D = dam site; US = upstream end impoundment; G = channel gradient; AC = Artificial channel confinement; P = planform; C = culvert inlet; BR = Bedrock ledge grade control; US END = upstream access point; DS END = County line; CON = confluence with Bronx River

Table 3. Characteristics of the geomorphic reaches identified on the Bronx River and the two assessed tributaries.

Reach	Channel Length (ft) 1914	Channel Length (ft) 2016	Percent shortening	Sinuosity 1914	Sinuosity 2016
BR20	5,998	5,960	0.6%	1.25	1.24
BR19	1,184	936	20.9%	1.28	1.01
BR18	993	343	65.5%	1.26*	1.01
BR17	4,697	5,596	-19.1%	1.06	1.26
BR16	4,525	4,495	0.7%	1.10	1.10
BR15	7,090	6,733	5.0%	1.09	1.04
BR14	3,001	2,989	0.4%	1.05	1.05
BR13	2,532	2,536	-0.2%	1.00	1.00
BR12	4,788	4,824	-0.8%	1.02	1.03
BR11	5,009	4,664	6.9%	1.14	1.06
BR10	9,261	8,796	5.0%	1.13	1.08
BR09	2,022	1,795	11.2%	1.20	1.06
BR08	4,591	3,776	17.8%	1.31	1.08
BR07	2,041	1,729	15.3%	1.22	1.03
BR06	3,569	2,576	27.8%	1.40	1.01
BR05	3,879	3,624	6.6%	1.18	1.10
BR04	4,278	3,194	25.3%	1.34	1.00
BR03	4,590	2,903	36.8%	1.64	1.04
BR02	3,064	2,958	3.5%	1.04	1.01
BR01	6,004	3,921	34.7%	1.54	1.01
Total	83,116	74,348	10.5%	1.19	1.07

*After 1914 Bronx River shifted to a new valley position resulting in a significant reduction in channel length. Valley length was adjusted to account for this change and eliminate potential errors in sinuosity calculations.

Table 4. Historic channel change on Bronx River from 1914 to 2016.

	Bronx River		Assessed Tributaries			
			Grassy Sprain Brook		Laurel Brook	
Drainage area (mi^2)	51		8.0		0.7	
Channel length (ft)	74,346		8,883		3,655	
(miles)	14.1		1.7		0.7	
Reaches	20		5		3	
Segments	78		13		6	
Channel manipulation	Length (ft)	%	Length (ft)	%	Length (ft)	%
Artificially straightened	69,622	93.6	8,883	100.0	3,338	91.3
Impounded	12,343	16.6	350	3.9	0	0.0
No mature riparian buffer	33,480	22.5	12,717	71.6	0	0.0
Bank stability						
Erosion	25,363	17.1	3,057	17.2	1,617	22.1
Armoring	51,196	34.4	7,486	42.1	1,361	18.6
Depositional Features						
Left Bank	Length (ft)	%	Length (ft)	%	Length (ft)	%
Point bars	4,454	6.0	0	0.0	858	23.5
Side bars	2,422	3.3	0	0.0	43	1.2
Delta bars	399	0.5	0	0.0	0	0.0
Right Bank						
Point bars	3,579	4.8	400	4.5	370	10.1
Side bars	782	1.1	0	0.0	548	15.0
Delta bars	286	0.4	0	0.0	0	0.0
Combined Banks						
Point bars	8,033	5.4	400	2.3	1,228	16.8
Side bars	3,204	2.2	0	0.0	591	8.1
Delta bars	685	0.5	0	0.0	0	0.0
Mid-channel						
Mid-channel bars	2,655	3.6	162	1.8	980	26.8
Islands	1,529	2.1	0	0.0	274	7.5
Diagonal bars	81	0.1	0	0.0	0	0.0
Grade controls	Count	per mile	Count	per mile	Count	per mile
Dams*	8	0.6	0	0.0	0	0.0
Weirs / sewer lines	4	0.3	5	3.0	0	0.0
Bedrock ledge	5	0.4	0	0.0	0	0.0
Stream crossings						
Bridges**	62	4.4	6	3.6	1	1.4
Culverts	1	0.1	6	3.6	1	1.4
Other features						
Mass failures	1	0.1	0	0.0	0	0.0
Deep pool	283	20.1	19	11.3	8	11.6
Log jams	29	2.1	10	5.9	7	10.1
Large wood (pieces)	479	34.0	101	60.0	70	101.1

*Includes dam on side channel near County Tennis Club in Scarsdale

**Includes pedestrian bridges

Table 5. Summary statistics of channel features mapping

Channel Type	Bronx River		Grassy Sprain Brook		Laurel Brook	
	Segment length (ft)	Percentage of total length	Segment length (ft)	Percentage of total length	Segment length (ft)	Percentage of total length
Confined bedrock-controlled channels	3,233	4.3%	0	0.0%	0	0.0%
Partially confined channels	8,046	10.8%	0	0.0%	1,904	52.1%
Artificially confined, armored, and straightened channels	34,753	46.7%	8,361	94.1%	428	11.7%
Channels with reformed meanders	18,267	24.6%	0	0.0%	1,323	36.2%
Impounded channels	10,047	13.5%	522	5.9%	0	0.0%

Table 6. Channel types and their lengths.

Attribute Fields	Description Options
Point	Upstream, Downstream , Middle, On
Location	Left Bank, Right Bank, Across, In, Left Bed, Right Bed, on Center Bar
Height	In Feet
Length	In Feet
General Failure Mechanism	Hydraulic Erosion, Mass Failure, Surficial, Hydraulic/Mass, Hydraulic/Surficial, Mass/Surficial, Unknown
Specific Failure Mechanism	Fluvial Entrainment, Rotational Slip, Planar/Slab, Rills/Gullies, Shallow Sliding, Piping, Cantilever, Combination, Soil Fail, Dry Granular Flow, Wet Earth Flow, Other
Active	True, False, Unknown
Stratified	True, False
Bank Angle	Bank angle expressed in degrees
Bank Geology	Alluvial/Fluvial, Lacustrine Sediment, Glacial Till, Construction Fill, Solum(Top Soil), Other
Bank Material	Clay, Silt, Sand, Gravel, Cobbles, Bedrock, Till, Boulder, Silt/Clay, Sand/Silt/Clay, Sand/Silt, Sand/Gravel, Gravel/Cobbles, Cobbles/Boulders, Boulders/Bedrock
Vegetation	None, Roots, Grass/Sedge, Shrub, Tree, Roots/Woody, Shrub/Tree, Grass/Shrub, Grass/Tree, Deciduous, Coniferous, Non-Native, Invasive
Width of Wood Buffer	In Feet
Land Classification	Wetland, Forest, Agriculture, Parks/Recreation, Residential, Commercial, Transportation, Utility, Old Field
Undercut	True, False

Table 7. Eroding bank qualities and characteristics.

Table 8. Segment needs scores

Order	Stream	Length (ft)	Segment	Channel Type	FPACC	Meander	PartSeg	Flows	Pools	Wood	CAPADJ	Canopy	Eroding	Armor	GRAPRO	Rec	Total
1	Bronx River	2,294	BR_01A	Artificially confined, armored and straightened channel	3	4	3	4	5	4	3	2	2	2	0	4	36
2	Bronx River	1,626	BR_01B	Artificially confined, armored and straightened channel	5	4	5	5	5	5	3	3	2	2	0	5	44
3	Bronx River	1,638	BR_02A	Artificially confined, armored and straightened channel	5	5	5	5	3	5	5	4	0	5	0	5	47
4	Bronx River	1,320	BR_02B	Artificially confined, armored and straightened channel	5	5	5	4	4	3	5	3	0	5	0	4	43
5	Bronx River	1,974	BR_03A	Artificially confined, armored and straightened channel	2	3	3	4	4	4	3	2	3	4	0	3	35
6	Bronx River	929	BR_03B	Artificially confined, armored and straightened channel	3	3	4	3	2	0	3	1	2	4	0	3	28
7	Bronx River	663	BR_04A	Artificially confined, armored and straightened channel	4	3	4	4	5	2	5	1	1	5	0	5	39
8	Bronx River	860	BR_04B	Artificially confined, armored and straightened channel	4	4	4	4	3	2	5	1	1	5	0	5	38
9	Bronx River	1,671	BR_04C	Artificially confined, armored and straightened channel	5	5	4	4	3	1	5	3	2	5	0	5	42
10	Bronx River	997	BR_05A	Partially confined channel	2	3	3	4	2	2	1	2	3	1	0	5	28
11	Bronx River	1,064	BR_05B	Partially confined channel	1	2	2	1	0	3	1	0	3	3	0	2	18
12	Bronx River	456	BR_05C	Artificially confined, armored and straightened channel	4	4	4	4	2	4	5	2	0	5	3	5	42
13	Bronx River	1,107	BR_05D	Impounded channel	4	3	5	5	3	3	3	2	2	4	3	5	42
14	Bronx River	1,061	BR_06A	Artificially confined, armored and straightened channel	0	4	5	5	4	5	4	1	4	5	0	4	41
15	Bronx River	1,014	BR_06B	Artificially confined, armored and straightened channel	1	3	4	3	4	3	3	1	4	4	0	3	33
16	Bronx River	502	BR_06C	Confined bedrock-controlled channels	5	5	0	0	0	4	5	0	0	5	0	3	27
17	Bronx River	1,729	BR_07	Impounded channel	0	2	5	5	3	4	4	3	0	1	4	0	31
18	Bronx River	1,391	BR_08A	Partially confined channel	1	4	5	5	3	4	3	2	4	3	3	2	39
19	Bronx River	1,018	BR_08B	Artificially confined, armored and straightened channel	5	3	5	5	3	5	5	5	0	5	4	4	49
20	Bronx River	845	BR_08C	Artificially confined, armored and straightened channel	5	5	5	5	3	5	5	5	0	5	4	5	52
21	Bronx River	522	BR_08D	Artificially confined, armored and straightened channel	4	3	4	4	2	4	4	0	0	5	4	4	38
22	Bronx River	1,795	BR_09	Impounded channel	0	3	5	5	3	4	4	4	0	0	4	0	32
23	Bronx River	675	BR_10A	Artificially confined, armored and straightened channel	0	4	5	5	5	4	3	4	0	4	3	0	37
24	Bronx River	636	BR_10B	Impounded channel	1	5	5	4	3	5	2	3	5	1	3	3	40
25	Bronx River	497	BR_10C	Partially confined channel	4	5	5	5	3	5	3	2	5	0	0	3	40
26	Bronx River	1,042	BR_10D	Channel with reformed meanders	0	3	4	4	3	3	2	2	5	3	0	3	32
27	Bronx River	365	BR_10E	Channel with reformed meanders	0	1	5	5	3	5	0	3	2	0	0	3	27
28	Bronx River	769	BR_10F	Artificially confined, armored and straightened channel	0	5	3	3	2	2	1	3	5	3	0	3	30
29	Bronx River	842	BR_10G	Channel with reformed meanders	5	4	5	4	3	5	3	3	2	4	0	4	42
30	Bronx River	649	BR_10H	Channel with reformed meanders	0	4	4	4	4	5	2	3	5	1	0	2	34
31	Bronx River	726	BR_10I	Channel with reformed meanders	0	2	3	2	2	4	3	1	4	2	0	2	25
32	Bronx River	1,760	BR_10J	Channel with reformed meanders	1	4	5	4	3	5	3	1	4	0	0	2	32
33	Bronx River	835	BR_10K	Channel with reformed meanders	0	1	2	2	3	5	5	4	0	5	4	2	33
34	Bronx River	1,069	BR_11A	Impounded channel	3	5	5	5	4	5	4	4	1	0	4	0	40
35	Bronx River	1,044	BR_11B	Artificially confined, armored and straightened channel	3	4	0	0	1	3	3	2	1	4	0	2	23
36	Bronx River	519	BR_11C	Partially confined channel	3	3	0	0	0	1	3	1	2	4	0	2	19
37	Bronx River	346	BR_11D	Partially confined channel	4	1	0	0	0	2	3	1	1	2	0	2	16
38	Bronx River	897	BR_11E	Partially confined channel	2	5	3	3	4	5	1	2	4	1	3	2	35
39	Bronx River	788	BR_11F	Artificially confined, armored and straightened channel	3	5	4	3	4	5	4	3	1	4	5	2	43
40	Bronx River	1,388	BR_12A	Impounded channel	3	4	5	4	1	1	5	2	0	5	5	2	37
41	Bronx River	640	BR_12B	Artificially confined, armored and straightened channel	3	3	4	4	0	2	3	1	2	4	0	5	31
42	Bronx River	739	BR_12C	Channel with reformed meanders	4	3	2	2	3	4	3	1	2	4	0	5	33
43	Bronx River	809	BR_12D	Confined bedrock-controlled channel	5	5	2	2	1	4	5	1	0	5	0	5	35
44	Bronx River	720	BR_12E	Confined bedrock-controlled channel	5	5	2	2	2	1	4	2	0	5	0	5	33
45	Bronx River	529	BR_12F	Artificially confined, armored and straightened channel	5	5	3	3	0	5	5	2	0	5	0	5	38
46	Bronx River	1,424	BR_13A	Artificially confined, armored and straightened channel	5	5	4	4	3	5	4	3	3	5	0	5	46
47	Bronx River	1,112	BR_13B	Artificially confined, armored and straightened channel	5	5	4	4	3	3	2	3	5	1	0	5	40
48	Bronx River	851	BR_14A	Artificially confined, armored and straightened channel	5	4	3	3	1	2	4	2	2	5	0	5	36
49	Bronx River	742	BR_14B	Artificially confined, armored and straightened channel	4	4	3	3	2	5	5	3	0	5	0	5	39

*Highest need segments highlighted in grey

Order	Stream	Length (ft)	Segment		FPACC	Meander	PartSeg	Flows	Pools	Wood	CAPADJ	Canopy	Eroding	Armor	GRAPRO	Rec	Total
50	Bronx River	1,396	BR_14C	Artificially confined, armored and straightened channel	2	4	3	3	3	3	5	3	0	5	5	1	37
51	Bronx River	1,655	BR_15A	Impounded channel	1	3	5	5	1	2	3	4	1	1	5	3	34
52	Bronx River	569	BR_15B	Artificially confined, armored and straightened channel	5	3	2	2	1	1	3	2	2	4	3	3	31
53	Bronx River	859	BR_15C	Confined bedrock-controlled channel	5	3	2	1	1	2	2	2	0	0	0	3	21
54	Bronx River	1,414	BR_15D	Channel with reformed meanders	4	2	3	2	2	3	3	1	3	2	0	3	28
55	Bronx River	467	BR_15E	Artificially confined, armored and straightened channel	5	3	2	3	1	5	5	3	0	5	0	3	35
56	Bronx River	1,768	BR_15F	Channel with reformed meanders	4	4	4	4	4	4	3	3	5	0	0	3	38
57	Bronx River	809	BR_16A	Artificially confined, armored and straightened channel	4	3	4	5	3	4	2	2	3	2	0	3	35
58	Bronx River	629	BR_16B	Artificially confined, armored and straightened channel	4	5	5	4	3	4	4	3	1	5	0	3	41
59	Bronx River	647	BR_16C	Artificially confined, armored and straightened channel	2	5	4	4	1	5	4	3	1	5	0	3	37
60	Bronx River	1,264	BR_16D	Artificially confined, armored and straightened channel	0	5	5	5	5	4	5	4	0	5	0	3	41
61	Bronx River	357	BR_16E	Partially confined channel	1	2	3	3	2	5	2	3	2	2	0	3	28
62	Bronx River	788	BR_16F	Channel with reformed meanders	0	1	2	1	1	3	1	2	2	0	0	3	16
63	Bronx River	650	BR_17A	Partially confined channel	0	5	5	4	2	2	3	5	2	1	0	5	34
64	Bronx River	880	BR_17B	Channel with reformed meanders	0	3	4	4	3	1	1	2	2	2	0	5	27
65	Bronx River	927	BR_17C	Artificially confined, armored and straightened channel	0	5	4	4	4	4	3	3	3	3	0	3	36
66	Bronx River	618	BR_17D	Channel with reformed meanders	0	2	2	1	1	1	2	1	0	0	0	3	13
67	Bronx River	1,192	BR_17E	Channel with reformed meanders	0	3	2	3	1	4	3	1	3	3	0	3	26
68	Bronx River	512	BR_17F	Partially confined channel	3	3	1	2	1	0	2	2	3	1	0	5	23
69	Bronx River	816	BR_17G	Partially confined channel	1	2	2	1	0	0	2	3	3	3	0	5	22
70	Bronx River	343	BR_18	Confined bedrock-controlled channel	3	4	1	1	0	3	3	0	0	0	0	4	19
71	Bronx River	936	BR_19	Artificially confined, armored and straightened channel	3	5	4	5	5	3	4	3	0	4	3	5	44
72	Bronx River	668	BR_20A	Impounded channel	0	4	5	5	3	5	4	4	0	0	3	0	33
73	Bronx River	771	BR_20B	Channel with reformed meanders	0	2	4	4	3	3	2	3	1	0	2	3	27
74	Bronx River	696	BR_20C	Channel with reformed meanders	0	2	4	3	2	1	1	1	2	0	0	3	19
75	Bronx River	787	BR_20D	Channel with reformed meanders	0	0	4	3	1	0	1	2	1	0	0	3	15
76	Bronx River	644	BR_20E	Artificially confined, armored and straightened channel	0	3	5	5	3	1	3	3	2	4	0	3	32
77	Bronx River	1,106	BR_20F	Channel with reformed meanders	0	0	2	1	0	2	1	2	2	2	0	3	15
78	Bronx River	1,289	BR_20G	Channel with reformed meanders	0	0	2	1	0	0	1	2	2	2	0	3	13
79	Grassy Sprain Brook	528	GS_01A	Artificially confined, armored and straightened channel	3	5	5	5	5	5	5	4	0	5	3	5	50
80	Grassy Sprain Brook	1,145	GS_01B	Artificially confined, armored and straightened channel	5	5	5	5	5	5	5	5	2	5	4	5	56
81	Grassy Sprain Brook	422	GS_01C	Artificially confined, armored and straightened channel	4	5	5	4	2	5	5	4	0	5	4	5	48
82	Grassy Sprain Brook	761	GS_02A	Artificially confined, armored and straightened channel	2	2	3	4	3	4	3	3	5	2	0	5	36
83	Grassy Sprain Brook	626	GS_02B	Artificially confined, armored and straightened channel	4	5	4	4	4	4	5	4	4	2	0	5	45
84	Grassy Sprain Brook	822	GS_02C	Artificially confined, armored and straightened channel	5	5	4	4	4	2	4	4	4	4	3	5	48
85	Grassy Sprain Brook	448	GS_03A	Artificially confined, armored and straightened channel	4	4	3	4	2	4	4	3	0	5	3	5	41
86	Grassy Sprain Brook	937	GS_03B	Artificially confined, armored and straightened channel	3	4	3	3	2	0	3	1	3	3	3	5	33
87	Grassy Sprain Brook	583	GS_03C	Artificially confined, armored and straightened channel	4	5	5	5	4	3	5	5	0	5	4	5	50
88	Grassy Sprain Brook	522	GS_04A	Impounded channel	4	3	3	4	2	0	4	4	2	4	4	5	39
89	Grassy Sprain Brook	352	GS_04B	Artificially confined, armored and straightened channel	4	4	4	3	0	2	3	1	2	4	4	5	36
90	Grassy Sprain Brook	574	GS_05A	Artificially confined, armored and straightened channel	5	5	3	3	2	0	3	1	1	3	4	5	35
91	Grassy Sprain Brook	1,163	GS_05B	Artificially confined, armored and straightened channel	5	5	5	5	3	3	4	5	0	3	3	5	46
92	Laurel Brook	689	LAU_01A	Channel with reformed meanders	2	0	1	1	1	1	2	2	4	1	0	3	18
93	Laurel Brook	634	LAU_01B	Channel with reformed meanders	2	3	2	3	4	3	3	0	2	2	0	3	27
94	Laurel Brook	687	LAU_02A	Partially confined channel	0	1	1	1	4	0	1	0	5	1	0	3	17
95	Laurel Brook	541	LAU_02B	Partially confined channel	2	2	1	1	2	1	0	0	0	0	0	3	12
96	Laurel Brook	676	LAU_03A	Partially confined channel	3	3	3	3	4	3	1	0	2	2	0	3	27
97	Laurel Brook	428	LAU_03B	Artificially confined, armored and straightened channel	5	5	5	5	5	0	5	0	0	5	0	3	38

*Highest need segments highlighted in grey

	Number of segments	Total geomorphic needs High (35 - 56)	Moderate (25 - 34)	Low (12 - 24)	Percentage High
Confined bedrock-controlled channels	5	1	2	2	20%
Partially confined channels	14	3	4	7	21%
Artificially confined, armored, and straightened channels	48	40	7	1	83%
Channels with reformed meanders	21	2	12	7	10%
Impounded channels	9	5	4	0	56%
Total study area	97	51	29	17	53%

Table 9. Summary of needs scores by channel type.

Flood Hazard Identification	Latitude	Longitude	Municipality	Nearest Road	Flooding Description
F05	40.951766	-73.829214	Yonkers/ Tuckahoe	Scarsdale Road	Two buildings in flood prone area, 10-year flood
F02	40.936576	-73.836122	Bronxville	Parkway Road	Buildings in flood prone area, 10-year flood. Bronx River Parkway inundated at 10-year flood, >4' water depth

Table 12. "Extremely high" priority flood hazards.

Flood Hazard Identification	Latitude	Longitude	Municipality	Nearest Road	Flooding Description
F14	41.053518	-73.772717	Greenburgh	Fisher Lane	Buildings in flood prone area, Bronx River Parkway inundated at 10-year flood, >2' water depth
F10	41.036645	-73.777729	White Plains	Central Ave	Buildings in flood prone area, Bronx River Parkway inundated at 10-year flood, >1' water depth
F06	40.959518	-73.821934	Yonkers	Thompson Street	Buildings in flood prone area, Bronx River Parkway inundated at 10-year flood, >1' water depth
F04	40.948593	-73.833956	Yonkers	Tuckahoe Road	Buildings in flood prone area, Bronx River Parkway inundated at 10-year flood, >0.5' water depth

Table 13. "Very high" priority flood hazards.

Flood Hazard Identification	Latitude	Longitude	Municipality	Nearest Road	Flooding Description
F01	40.913869	-73.850374	Mt. Vernon/ Yonkers	Mt. Vernon Ave/BRP	Bronx River Parkway inundated at 10-year flood, >4’ water depth
F03	40.941294	-73.838659	Yonkers/ Bronxville	Palmer Road	Bronx River Parkway inundated at 10-year flood, >4’ water depth
F08	41.01006	-73.796009	Greenburgh/ Scarsdale	Fisher Street	Bronx River Parkway inundated at 10-year flood, >2’ water depth

Table 14. “High” priority Flood hazards.

Flood Hazard Identification	Latitude	Longitude	Municipality	Nearest Road	Nearest Road
F13	41.051027	-73.774543	Greenburgh	Bronx River Parkway	Bronx River Parkway inundated at 10-year flood, >1'' water depth
F12	41.04906	-73.774831	White Plains	Old Kensico Road	Bronx River Parkway inundated at 10-year flood, >1' water depth
F11	41.045727	-73.774723	Greenburgh	Cemetery Road	Bronx River Parkway inundated at 10-year flood, >1' water depth
F09	41.031646	-73.775663	White Plains	Main Street	Bronx River Parkway inundated at 10-year flood, >1' water depth
F07	40.988878	-73.810241	Greenburgh	Ardsley Road	Bronx River Parkway inundated at 10-year flood, >0.5' water depth

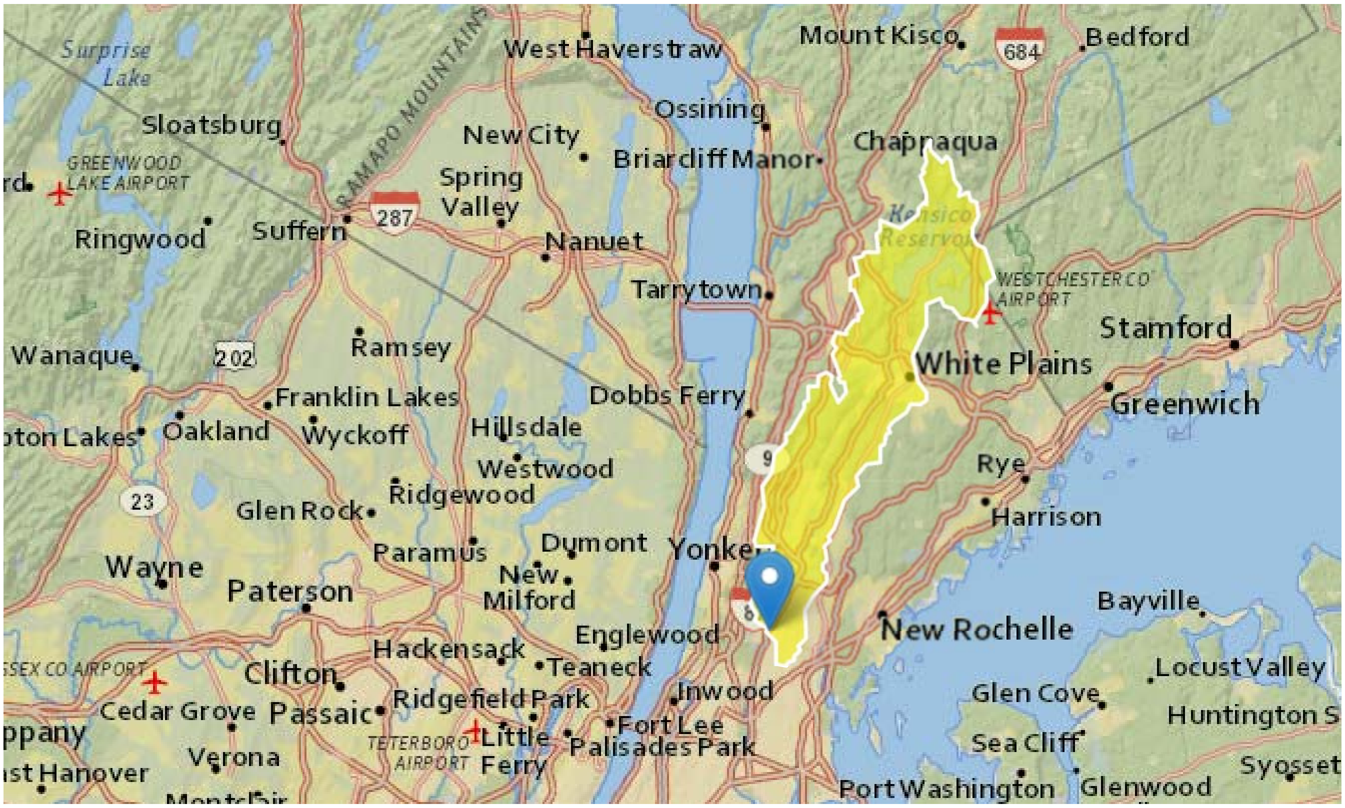
Table 15. "Moderate" priority flood hazards.

APPENDICES

APPENDIX 1
(Stream Stats report)

StreamStats Report

Region ID: NY
Workspace ID: NY20190214191347921000
Clicked Point (Latitude, Longitude): 40.90072, -73.86014
Time: 2019-02-14 14:14:02 -0500



Basin Characteristics

Parameter Code	Parameter Description	Value	Unit
DRNAREA	Area that drains to a point on a stream	51	square miles
LAGFACTOR	Lag Factor as defined in SIR 2006-5112	1.39	dimensionless
STORAGE	Percentage of area of storage (lakes ponds reservoirs wetlands)	8.09	percent
MAR	Mean annual runoff for the period of record in inches	22.5	inches

Parameter Code	Parameter Description	Value	Unit
BSLOPCM	Mean basin slope determined by summing lengths of all contours in basin mulitplying by contour interval and dividing product by drainage area	481	feet per mi
CENTROIDX	Basin centroid horizontal (x) location in state plane coordinates	601341.1	feet
CENTROIDY	Basin centroid vertical (y) location in state plane units	4542194	feet
CONTOUR	Total length of all elevation contours in drainage area in miles	245.37	miles
CSL1085LO	10-85 slope of lower half of main channel in feet per mile.	11.2	feet per mi
CSL1085UP	10-85 slope of upper half of main channel in feet per mile.	20.7	feet per mi
CSL10_85	Change in elevation divided by length between points 10 and 85 percent of distance along main channel to basin divide - main channel method not known	17.1	feet per mi
EL1200	Percentage of basin at or above 1200 ft elevation	0	percent
FOREST	Percentage of area covered by forest	34.6	percent
JULAVPRE	Mean July Precipitation	4.3	inches
JUNAVPRE	Mean June Precipitation	4.04	inches
JUNMAXTMP	Maximum June Temperature, in degrees F	79.2	degrees F
LC11DEV	Percentage of developed (urban) land from NLCD 2011 classes 21-24	72.5	percent
LC11IMP	Average percentage of impervious area determined from NLCD 2011 impervious dataset	24.8	percent
LENGTH	Length along the main channel from the measuring location extended to the basin divide	22.6	miles
MAYAVPRE	Mean May Precipitation	4.66	inches
MXSNO	50th percentile of seasonal maximum snow depth from Northeast Regional Climate Center atlas by Cember and Wilks, 1993	8.84	inches
OUTLETX	Basin outlet horizontal (x) location in state plane coordinates	596005	feet

Parameter Code	Parameter Description	Value	Unit
OUTLETY	Basin outlet vertical (y) location in state plane coordinates	4528365	feet
PRECIP	Mean Annual Precipitation	45.3	inches
PRJUNAUG00	Basin average mean precip for June to August from PRISM 1971-2000	12.6	inches
SLOPERATIO	Ratio of main channel slope to basin slope as defined in SIR 2006-5112	0.0356	dimensionless
SSURGOA	Percentage of area of Hydrologic Soil Type A from SSURGO	0.26	percent
SSURGOB	Percentage of area of Hydrologic Soil Type B from SSURGO	35.2	percent

Bankfull Statistics Parameters [Bankfull Region 3 SIR2009 5144]

Parameter Code	Parameter Name	Value	Units	Min Limit	Max Limit
DRNAREA	Drainage Area	51	square miles	0.42	329

Bankfull Statistics Flow Report [Bankfull Region 3 SIR2009 5144]

PIl: Prediction Interval-Lower, Plu: Prediction Interval-Upper, SEp: Standard Error of Prediction, SE: Standard Error (other -- see report)

Statistic	Value	Unit	PIl	Plu
Bankfull Area	288	ft^2	117	704
Bankfull Depth	3.79	ft	1.62	8.89
Bankfull Streamflow	1210	ft^3/s	252	5810
Bankfull Width	75.7	ft	31.8	180

Bankfull Statistics Citations

Mulvihill, C.I., Baldigo, B.P., Miller, S.J. , and DeKoskie, Douglas,2009, Bankfull Discharge and Channel Characteristics of Streams in New York State: U.S. Geological Survey Scientific Investigations Report 2009-5144, 51 p. (http://pubs.usgs.gov/sir/2009/5144/)

Peak-Flow Statistics Parameters [2006 Full Region 2]

Parameter Code	Parameter Name	Value	Units	Min Limit	Max Limit
DRNAREA	Drainage Area	51	square miles	1.93	996
LAGFACTOR	Lag Factor	1.39	dimensionless	0.014	6.997
STORAGE	Percent Storage	8.09	percent	0	11.88
MAR	Mean Annual Runoff in inches	22.5	inches	16.03	33.95

Peak-Flow Statistics Flow Report [2006 Full Region 2]

PIl: Prediction Interval-Lower, PIu: Prediction Interval-Upper, SEp: Standard Error of Prediction, SE: Standard Error (other -- see report)

Statistic	Value	Unit	SE	SEp	Equiv. Yrs.
1.25 Year Peak Flood	561	ft^3/s	25.5	25.5	4.8
1.5 Year Peak Flood	674	ft^3/s	25.6	25.6	4.3
2 Year Peak Flood	837	ft^3/s	25.8	25.8	4.4
5 Year Peak Flood	1330	ft^3/s	27	27	7.3
10 Year Peak Flood	1750	ft^3/s	28.2	28.2	10.1
25 Year Peak Flood	2380	ft^3/s	29.9	29.9	13.6
50 Year Peak Flood	2920	ft^3/s	31.5	31.5	15.8
100 Year Peak Flood	3530	ft^3/s	33.3	33.3	17.6
200 Year Peak Flood	4240	ft^3/s	35.3	35.3	18.9
500 Year Peak Flood	5320	ft^3/s	38.4	38.4	20.1

Peak-Flow Statistics Citations

Lumia, Richard, Freehafer, D.A., and Smith, M.J.,2006, Magnitude and Frequency of Floods in New York: U.S. Geological Survey Scientific Investigations Report 2006–5112, 152 p. (http://pubs.usgs.gov/sir/2006/5112/)

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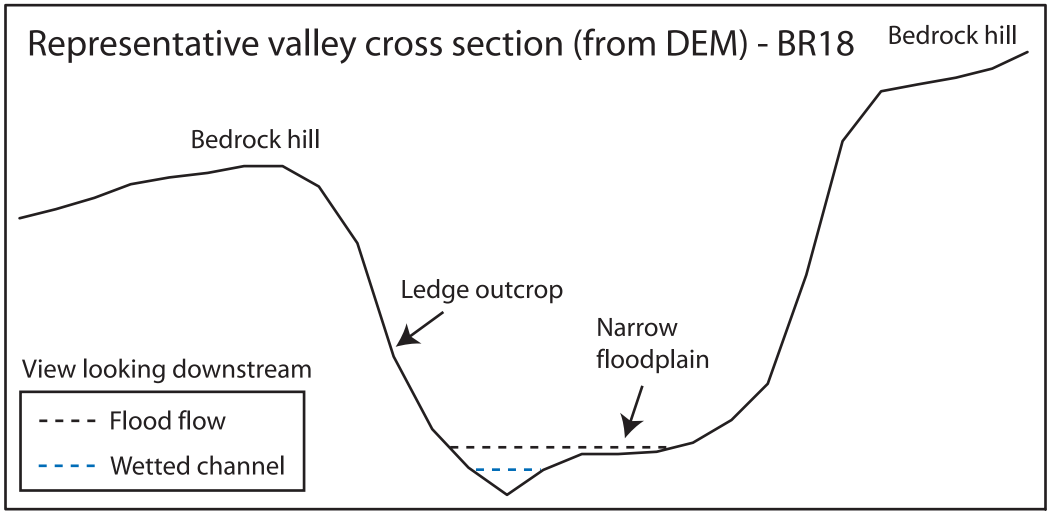
Application Version: 4.3.0

APPENDIX 2

(see attached digital GIS files)

APPENDIX 3
(Channel types)

Confined bedrock-controlled channels



Physical characteristics

- Channels confined on both banks where bedrock outcrops on one or both banks and in the channel bed
- Significant channel adjustments are unlikely
- Little to no floodplain access

Steep bedrock ledge outcrop along the left bank (BR12D)

Bedrock gorge downstream of Bronxville Lake (BR06C)

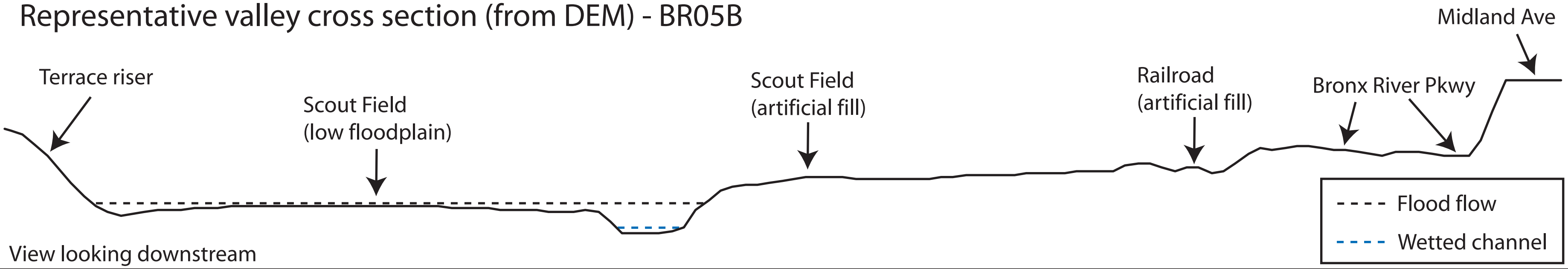
Appendix X. Bronx River - Channel types: Confined bedrock-controlled channels.

Partially confined channels

Physical characteristics

- Channels confined on one bank by natural landforms or artificial fill with floodplain access on the other bank
- Infrastructure encroachments and artificial fill can increase flood hazards within the stream segment and in adjacent segments

Representative valley cross section (from DEM) - BR05B

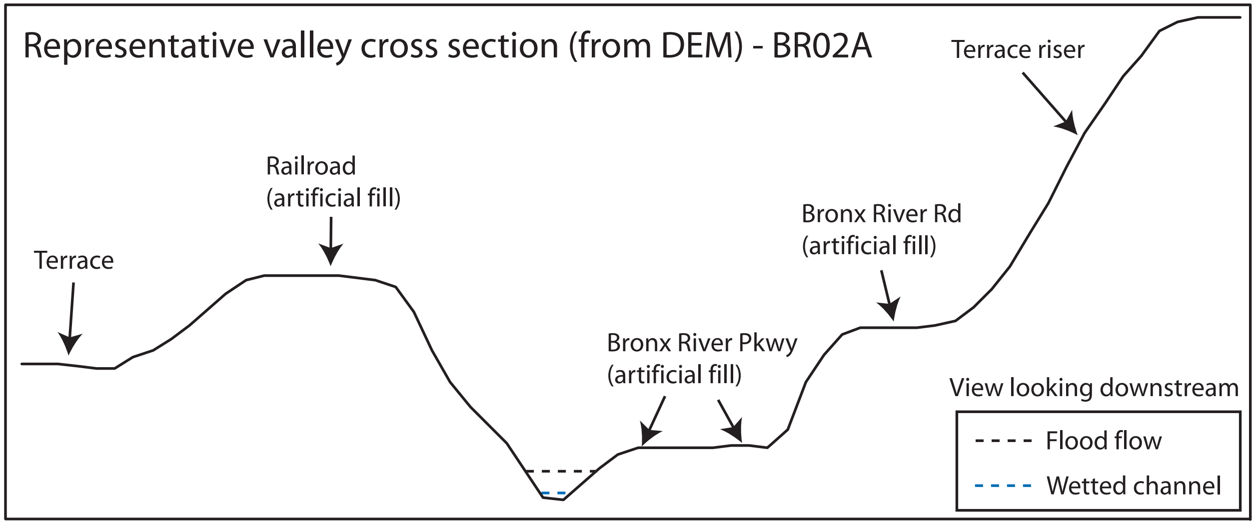


Low floodplain on left bank inundated by recent high water (BR05B)

Channel confined by artificial fill along right bank (BR05B)

Appendix X. Bronx River - Channel types: Partially confined channels.

Artificially confined, armored and straightened channels



Physical characteristics

- Confined by artificial constraints
- Banks armored along significant lengths
- Remain in straightened condition
- Little to no floodplain access

Railroad tracks built upon fill confine the Bronx River along its left bank (BR01B)

The concrete retaining wall of the Bronx River Pkwy along the right bank (BR02B)

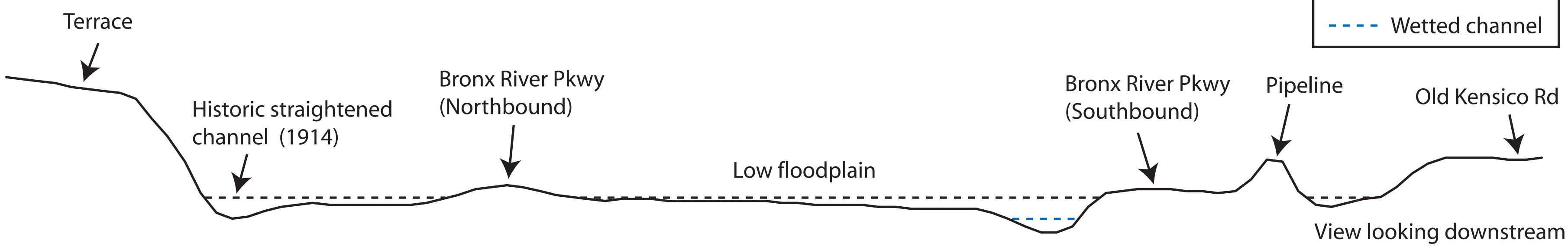
Appendix X. Bronx River - Channel types: Artificially confined, armored and straightened channels.

Channel with reformed meanders

Physical characteristics

- Previously straightened channels where meanders are in the process of reforming or have completely reformed
- Bank erosion often associated with bar deposition as channel sinuosity increases

Representative valley cross section (from DEM) - BR17B




Bank erosion along a forested meander bend (BR10J)


Failed bank armor has been outflanked along the remeandering channel (BR10I)

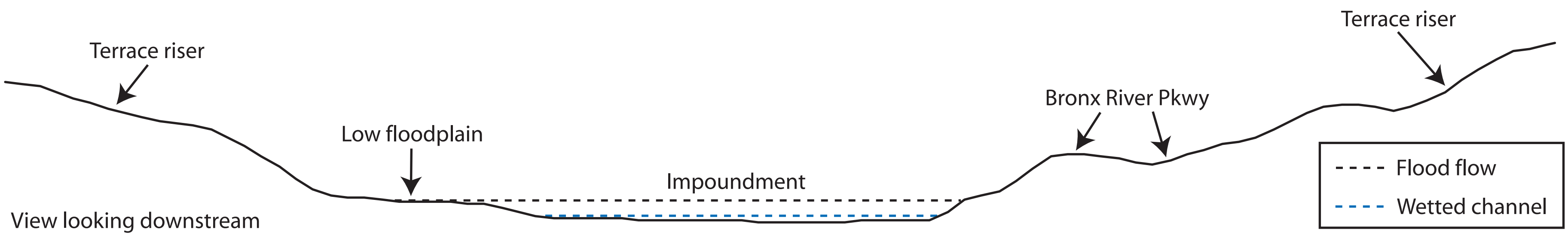
Appendix X. Bronx River - Channel types: Channel with reformed meanders.

Impounded channels

Physical characteristics

- Ponded area upstream of dam or weir where low flow velocities cause significant fine sediment deposition
- Low flow velocities and water depths lead to low habitat complexity

Representative valley cross section (from DEM) - BR07



Bronx River impounded to form Crestwood Lake (BR09)

Wide low floodplain along the left bank provides recreational opportunities (BR07)

Appendix X. Bronx River - Channel types: Impounded channels.