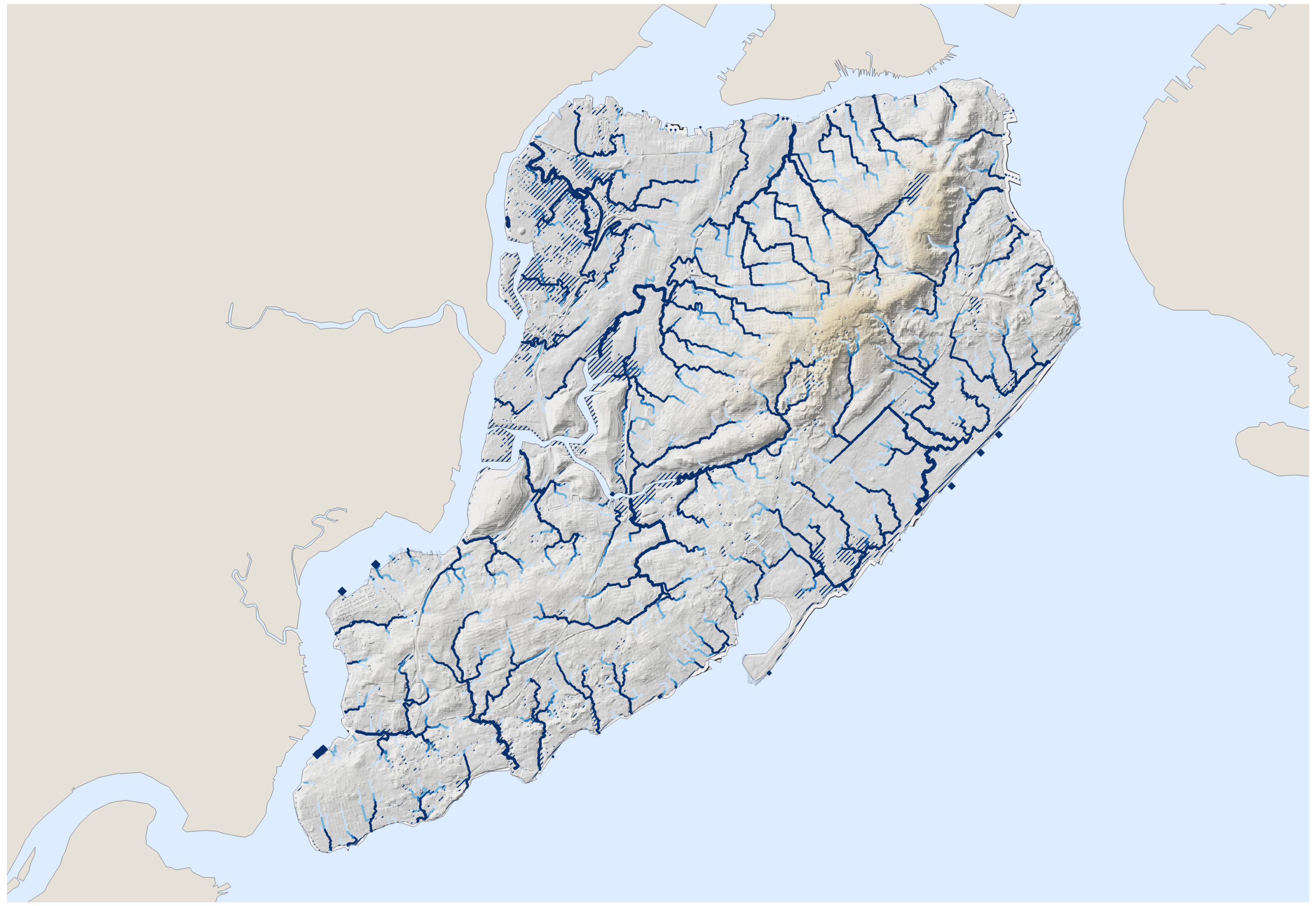
GOING GREEN BY THINKING BLUE:

A hydrological analysis of Staten Island and its implications for the Bluebelt pilot of sustainable drainage infrastructure



BACKGROUND

In natural ecological systems, water is recycled through a sophisticated system of reabsorption and collection. As rain meets land, the water is filtered by plants, reabsorbed by soil, and collected into rivulets and streams by the natural topography of the land. Together these systems prevent flooding and erosion.

In urban areas, man-made structures impede this process. As plants are replaced by concrete sidewalks and asphalt roads, water is unable to drain. This is caused by the *imperviousness* of these surfaces. While natural landcover such as root systems and loose soils let water seep through (ie. have low imperviousness), many built materials such as concrete, asphalt, and compacted soils do not (ie. have high impervi ousness).[1]

When a significant portion of a municipal neighborhood is covered by impervious surfaces, water has nowhere to go. It runs downhill across streets and sidewalks, pools in flat areas, and floods low-lying neighborhoods. As it flows, rainwater collects dangerous contaminants from cars and people.[2] Unmanaged stormwater runoff is a physical and health hazard to residents.

Cities have historically handled this issue with a web of artificial drainage infrastructure. Catch basins in the streets collect the polluted rainwater. Underground piping carries it to filtration plants. And a final set of conveyances discharge the filtered runoff to natural bodies of water or recycle it for urban use.[1]

This system has a number of limitations though. In many cities across the United States, including most of New York City, the piping that handles the stormwater runoff is the same piping that handles sewage. When there is a heavy rainfall, the filtration plants cannot keep up with the volume, and release valves in the piping dump excess sewage and stormwater to release pressure. These events, known as Combined Sewer Overflows (CSOs), typically empty sewage and contaminated stormwater into natural bodies of water, polluting these areas with dangerous and environmentally disruptive bacteria.[3]

Furthermore, even in areas with separate systems for sewage and stormwater runoff, drainage systems often have trouble keeping up with the major rainfall events. This leads to flooding. As climate change alters atmospheric and surface temperatures, these events, known as *cloudbursts*, are becoming more and more frequent in many cities. It is critical that cities explore other methods of efficient drainage.[1]

One possible alternative is the incorporation of natural drainage solutions into existing infrastructure, an approach that New York has begun to test. In this analysis, I focus on aspect of this Green Infrastructure program: the Bluebelt Initiative.

The program, currently piloted on Staten Island, "restores, preserves, and enhances natural drainage corridors through a series of structural controls such as constructed wetlands, sand filters, and detention basins." By connecting neighborhoods with natural drainage networks (ie. streams, lakes, and oceans), this program is able to leverage the natural filtering abilities of plants and relieve the burden put on catch basins and underground piping.[4]

For green infrastructure projects like the Bluebelt Initiative to effectively drain stormwater though, the wetlands and basins built to extend existing drainage corridors must be placed in areas that water naturally collects. In this project, I model where on Staten Island these areas are and examine whether the Bluebelt pilot sites are effectively placed. The results of this analysis are also used to highlight potential areas for program expansion.

The goals, methodology, and results of this study are discussed in the following sections.

ANALYSIS SCOPE

As discussed in the previous section, the efficacy of programs like the Bluebelt Initiative relies on building green infrastructure in areas that unabsorbed rainwater is already likely to flow.

There are two primary methods for assessing where these areas are[1]:

a) examining historic stream networks
b) modeling the flow of water implied by the topography of the land.

In this project, I employ the latter.

This modeling exercise, known as a *hydrological analysis*, is focused on two specific areas of inquiry:

1. Are the Staten Island pilot locations of the Bluebelt Initiative effectively positioned along areas that have a topographically high propensity to channel water?

2. According to the topography and imperviousness of the land, where on Staten Island might it make sense to expand this Bluebelt Initiative next?

In the next section, I describe how this analysis is conducted, and how its results can be mapped to help answer these important questions.

METHODOLOGY

ANALYSIS METHODOLOGY

A hydrological analysis uses the topography of the land to model where water would naturally be inclined to flow. For this hydrological analysis I used the GRASS toolbox in QGIS 3.10.14. It is important to note that there are other reputable toolboxes, such as SAGA, that could be used to execute this analysis. If similar parameters were used in another toolbox, it is expected that it would produce comparable results. In this section, I describe the step-by-step processed employed in SAGA[5]:

1. Loaded USGS ⅓ arc-second (ie. 10m) DEM raster tiles for Staten Island

2. Used raster merge tool to mosaicize the DEM raster tiles into one continuous tile covering Staten Island

3. Used warp tool to reproject DEM tile to EPSG:2263 (ie. from degrees to meters). The GRASS toolbox expects a projected CRS.

4. Used the r.fill.dir tool in the GRASS toolbox to create a sink-free DEM. A sink is an imperfection in the DEM that would incorrectly disrupt the modeled flow of water.[6]

5. Ran a channel analysis on the sink-free DEM using the r.watershed tool in the GRASS toolbox. For this step, I changed the following default parameters:

- Minimum size of exterior watershed basin: 27 (ie. the pixel size of the sink-free DEM)

- Enabled single flow direction (D8)

The r.watershed tool analyzes the elevation and slope of the terrain to determine the flow direction in each 10m raster cell. Using these flow directions, the algorithm is able to draw the expected drainage channels and estimate the volume of water that each cell of each channel is responsible for transporting. This volume is reported as count of cells (ex. A value of 100 in the outputted accumulation raster layer would mean that cell was responsible for draining water accumulated from 100 surrounding cells in the area).

6. Masked the accumulation raster layer using a vector layer of Staten Island. This excludes the noise in the GRASS algorithm caused by where the land meets the sea.

POSTPROCESSING

While the accumulation raster layer contains all the information necessary to visualize where water would naturally flow on Staten Island (ie. the drainage channels), the default formatting of the outputted layer entirely obscures this information.

To reveal the channel network, I used the following strategy:

1. *Changed the formatting of the accumulation raster layer to singleband pseudocolor with a white to blue color ramp:* This makes the cells that are responsible for little or no drainage fade to white (ie. the majority of cells), and allows the other cells that comprise the drainage channels to pop out from the neutral background. With this color ramp, the larger drainage channels (ie. channels that are responsible for draining more cells) are dark blue and the smaller channels are increasingly light shades of blue that eventually fade into the white.

2. *Changed the MIN-MAX value settings of the accumulation raster layer to 0-99.3%:* This controls the specificity of the channel network. The appropriate threshold is dependent on the DEM that's being analyzed, the color ramp used, and the level of detail that is desired. In this case I found that an upper bound value of 90% showed more detail than could be discerned at a pan-island zoom, but that a value of 99.3% delineated all major watersheds (ie. areas of drainage).

3. *Vectorized the accumulation raster layer:* This allowed me to increase the width of the channel networks proportional to the number of cells they are responsible for draining. Without this, the channels in the raster layer were too small to see at a pan-Staten Island zoom, even with a high contrast background-foreground color choice.

4. *Filtered out accumulation vector geometries (ie. cells) that were responsible for draining fewer than 1,000 10m cells:* This filters out the fanned beginnings of each channel which just add noise to the visualization at a pan-Staten Island zoom level. No meaningful information is lost when these are filtered out.

5. *Applied white to blue color ramp to the accumulation vector geometries:* This was binned to match the raster formatting used in step 2.

6. *Changed the formatting of the accumulation vector to a simple line fill and sized the waterways according to the number of cells they were responsible for draining using a .5 exponential scale in the stroke width assistant:* This made the channels responsible for the most drainage appear the most prominently on the map (ie. thick and dark blue). This formatting also makes it easy to intuit the flow direction of the water in the drainage channels: from light to dark and small to big.

7. *Used the difference geoprocessing vector tool to extract the waterways that fall outside of existing waterways:* This makes it easier to see where hypothetical channels meet existing waterways (ie. the goal of the Bluebelt program).

VISUALIZATION

The resultant channel networks were then visualized in the following two maps:

Figure 1: Drainage channels and topography of Staten Island

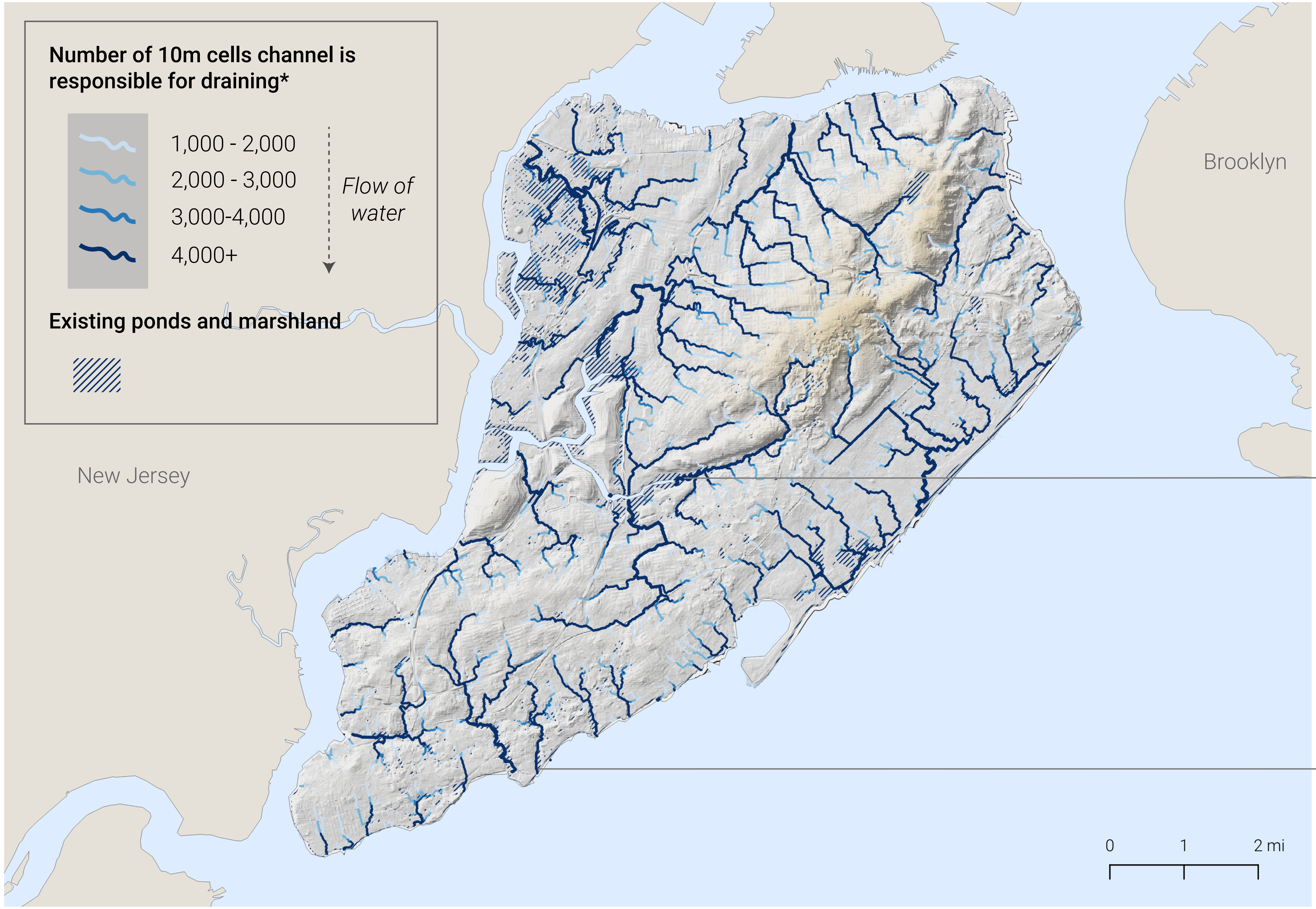
This map overlays the drainage channels (as calculated and formatted using the methodology described in the previous section) onto a hillshade basemap. This contextualizes the analysis results in the slope and elevation data that the algorithm used to derive the drainage results.

Figure 2: Drainage channels in relation to Bluebelt pilot areas and imperviousness of land

This map overlays the drainage channels as visualized in Figure 1 with imperviousness data and the location of the Bluebelt pilot sites. The information on this map is designed to help answer the proposed research questions (ie. assess the efficacy of the pilot placement and identify candidates for expansion of the Bluebelt program).

The content in these maps, as it relates to the analysis questions, is discussed in the Results section.

Figure 1: Drainage channels and topography of Staten Island



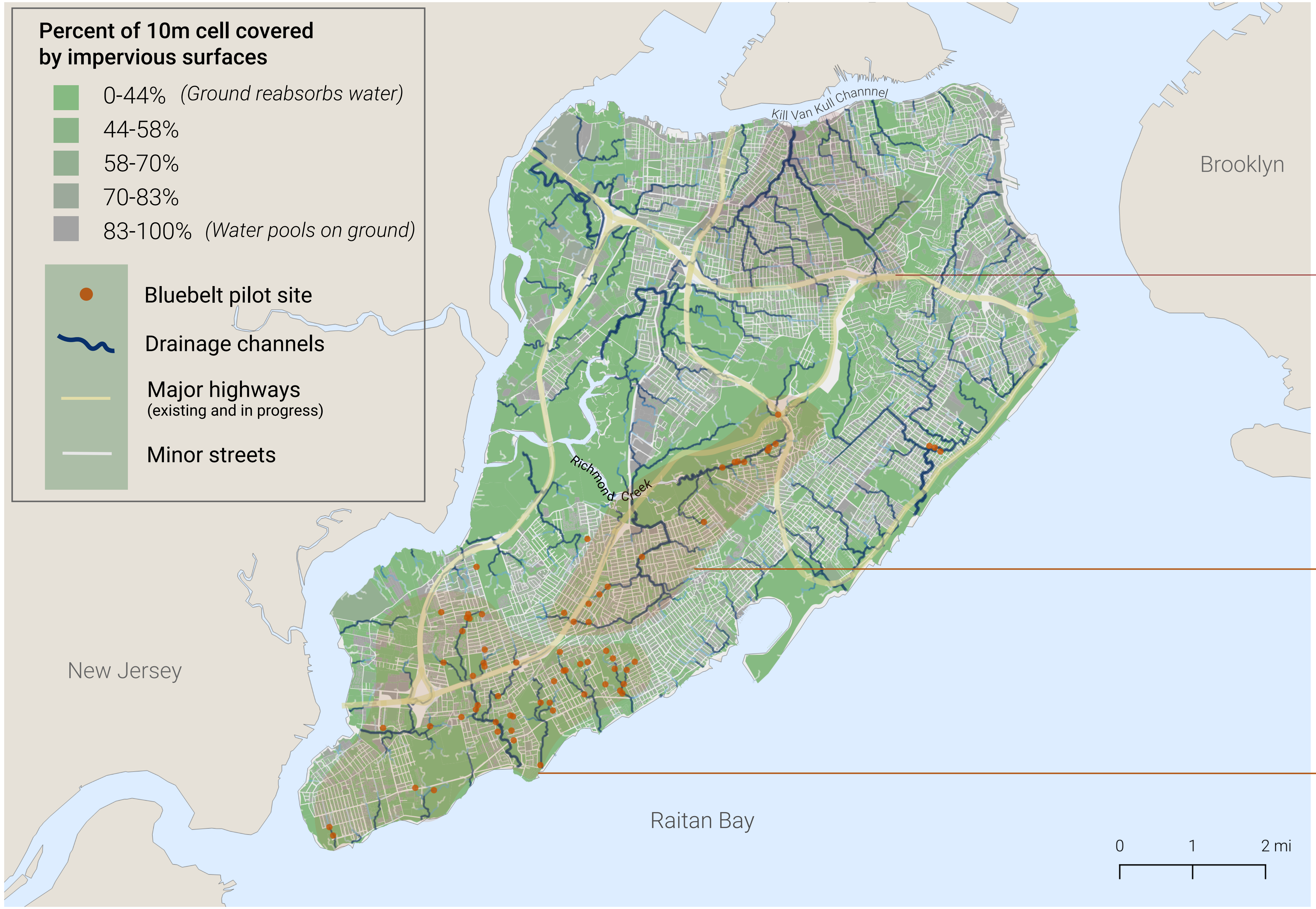
As expected, the hydrological analysis produces drainage channels that flow from areas of high to low elevation and follow the topography of the island. In this map, you can see the implied flow of the water in the progression of light to dark blue.

Example of channels that drain into existing waterway

Example of channels that drain into the sea

**The drainage channels are NOT true rivers, but hypothetical channels through which water is likely to drain. Existing waterways and marshlands are included on the map to demonstrate where hypothetical channels would drain into existing hydrology.*

Figure 2: Drainage channels in relation to Bluebelt pilot areas and imperviousness of land



Most Bluebelt pilot sites effectively fall along the drainage channels (ie. along where water will naturally pools). This increases the likelihood that the green infrastructure being built will succeed at transporting the water to natural drainage networks. These networks also succeed at draining some of the most impervious neighborhoods in the southwest of the island.

Area with potential for Bluebelt expansion draining into Kill Van Kull Channel

Bluebelt infrastructure draining into Richmond Creek

Bluebelt construction draining into Raitan Bay

RESULTS

As expected, the hydrological analysis generated from the DEM of Staten Island derived drainage channels that flow from high to low elevation and follow the countours of the land. In this section, I discuss the implications of these channels for the Bluebelt initiative. Drawing from the derived drainage channels, Bluebelt pilot sites, and imperviousness data visualized in Figure 2, I address each research question in turn.

1. Are the Staten Island pilot locations of the Bluebelt Initiative effectively positioned along areas that have a topographically high propensity to channel water?

As can be seen by the positioning of the orange dots in Figure 2, the majority of Bluebelt pilot sites are effectively positioned along the drainage channels. In other words, the Bluebelt pilot sites are located in areas where the water is most likely to naturally collect due to the slope and elevation of the land. Given that the Bluebelt green infrastructure is designed to expand natural drainage networks, it makes sense that the pilot placement site would leverage the ability of the land's topology to channel water. The current pilot placement site advantageously does this.

2. According to the topography and imperviousness of the land, where on Staten Island might it make sense to expand this Bluebelt Initiative next?

Most of the current Bluebelt pilot sites lie along drainage channels that have a few important characteristics in common:

- The drainage channel is part of a network with one major artery branching into many smaller channels. The major artery of the network flows directly into a natural water body (ie. stream or ocean) without joining another major artery or winding at length through the island. This structure is important for the Bluebelt program because it maximizes the return on the infrastructure investment by limiting the amount of construction necesssary to serve a large area. By building a small amount of green drainage infrastructure along the main artery, it becomes possible to provide natural drainage for all the neighborhoods on the smaller branches.

- The drainage channel network connects an impervious area to a natural drainage network (ie. a river or the sea). This characteristic is important because it prioritizes creating sustainable drainage infrastructure in the areas that are most likely to flood.

Based on these characteristics, the channel network in the central northern region of Staten Island is an excellent candidate for future Bluebelt expansion. Expanding the Bluebelt program to this area has the potential to naturally drain heavily impervious neighborhoods into the Kill Van Kull Channel with a relatively small amount of construction per square mile served.

CONCLUSIONS AND FUTURE WORK

This hydrological analysis verifies that the Bluebelt pilot sites in Staten Island are advantageously placed along the areas that have a naturally high propensity to collect water. Furthermore, the drainage channel network structure and imperviousness data suggest that there is great potential to expand this program to the northern part of the island.

This analysis does have limitations though that could be valuably addressed in future work. First and foremost, the algorithm that dervied the drainage channels currently only accounts for the elevation and slope of the land. While these are major factors that influence the flow of water, it would be interesting to account for the exsiting (non-sustainable) drainage infrastructure present on the island. Highly impervious areas that lack sufficient muncipal drainage infrastructure could be particularly good candidates for Bluebelt expansion. Secondly, it could be interesting to incorporate population density data into site selection to maximize the number of people served by each Bluebelt expansion.

Modeling such as this has the potential to improve the efficacy and feasibility of sustainable drainage solutions, development that is critical to avoid serious flooding and water pollution in the face of increasing rainfall.

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[6]“Preprocessing and catchment delineation,” SAGA GIS Tutorials. Accessed: Apr. 15, 2021. [Online]. Available: https://sagatutorials.wordpress.com/preprocessing-and-catchment-deliniation/.

DATA SOURCES

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2. NYC Borough Boundaries clipped at shoreline - https://www1.nyc.gov/site/planning/data-maps/open-data.page#district_political
3. NYC Digital City Map, Major Streets - https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-digital-city-map.page
4. Parcel-based imperviousness percentage - https://data.cityofnewyork.us/City-Government/DEP-s-Citywide-Parcel-Based-Impervious-Area-GIS-St/uex9-rfq8
5. MS4 Bluebelt locations - https://data.cityofnewyork.us/Environment/Municipal-Separate-Storm-Sewer-System-MS4-Data/j57c-rqtq
6. Hydrography - https://data.cityofnewyork.us/Environment/Hydrography/drh3-e2fd