High-Speed GIS-Based Simulation of Storm Surge–Induced Flooding Accounting for Sea Level Rise

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Abstract: A storm surge–induced flood simulation methodology, called the GIS-based subdivision-redistribution (GISSR) methodology, is proposed for coastal urban environments. The methodology combines GIS with Manning's equation to calculate the volume of water flowing into the geographical area under consideration and then redistributes it appropriately over that area. It uses as input the time histories of the storm surge height and of tides along the coastline. It is capable of incorporating a variety of protective measures along the coastline, such as seawalls. For flood simulations in the future, it is straightforward to account for a prescribed value of sea level rise. The GISSR methodology is extremely efficient, from a computational point of view, compared to existing flood simulation tools, such as GeoClaw or ADCIRC, which take several orders of magnitude more computing time because of the underlying complexity of their physical models. The methodology is found to be highly accurate by comparing its results to the actual extent of flooding observed during Hurricane Sandy in New York City (NYC). Several examples demonstrating its capabilities are provided involving different protective measures in NYC's Lower Manhattan. The GISSR methodology is ideal for determining the optimal protective strategy for a coastal city because of its high computational efficiency since optimization requires a very large number of flood simulations. **DOI: 10.1061/(ASCE)NH.1527-6996.0000465.** *© 2021 American Society of Civil Engineers.*

Introduction

In 2012, Hurricane Sandy caused significant damage to the northeastern coastline of the US. Protective and adaptation strategies along the coastline are necessary now more than ever because of the additional risk caused by climate change–induced sea level rise (SLR). A large number of potential protective and adaptation measures are currently available, such as barrier island preservation, beach restorations and breakwaters, living shorelines, shoreline stabilization, artificial islands and reefs, artificial sand dunes, deployable flood walls, permanent seawalls and levees, storm surge barriers, individual structure retrofit/sealing/protection, raising of the infrastructure, land use and zoning laws, and strategic retreat.

An important part of the process to evaluate the relative efficiency of a specific protective or adaptation measure (or of a specific group of measures) to protect infrastructure and the associated community is the simulation of a storm-induced flood over a geographical area of interest. Such a simulation involves the calculation of the height of water at every point within this geographical area as a function of time. It should be noted that these simulations can become complex when a storm surge + tide overflows or damages any of the protective/adaptation measures. The ultimate objective is to determine the optimal protective/adaptation strategy given a prescribed budget.

Because the optimization procedure requires a very large number of flood simulations, it is critically important that these simulations be highly efficient from a computational point of view. Most currently available flood simulation tools [e.g., GeoClaw (Berger et al. 2011), an advanced three-dimensional circulation model (ADCIRC)] are computationally inefficient for such an optimization procedure. This is not a criticism of these tools; they were developed for different purposes and are based on solving numerically shallow water equations, which require major computational effort. The current work aims at resolving this issue using a geographical information systems (GIS) based methodology that is extremely efficient computationally (but less accurate than the other mentioned tools). It should be noted that the time history of the total water level height (storm surge + tides) along a coastline is required for the proposed methodology.

Nobre et al. (2011) proposed a GIS-based flood simulation methodology called Height Above the Nearest Drainage (HAND). This methodology compares the height of the land of adjacent cells to simulate the movement of a flood. However, it does not work for storm-induced flood events because it does not account for flood simulation on coastlines. The methodology is also not able to account for protective measures, such as seawalls. The Hazus package developed by the Department of Homeland Security, Federal Emergency Management Agency (2018) includes a Flood Information Tool as an extension of GIS. However, it does not account for any protective measures, either.

The proposed high-speed flood simulation methodology is GIS based and works in two stages. First, it calculates the total volume of floodwater over the geographical area under consideration, and then it distributes it appropriately over that area. The time evolution of the storm surge height and of the tides along the coastline is the necessary input. The output includes the time history of the flood height at every location within the geographical area of interest (some locations could remain dry of course). Various protective measures can be considered, and the computational cost is minimal.

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The methodology's high computational efficiency renders it an ideal tool to be used as part of a general procedure to determine the optimal protective/adaptation strategy for a specific coastal area facing the combined hazards of storms and SLR (Miura et al. 2021). The optimal strategy for a given budget is the strategy that produces the maximum reduction in storm-induced losses over a prescribed period of time (e.g., 20, 50, and 80 years) compared to the scenario of *doing nothing*, accounting, of course, for the actual cost of the protective/adaptation strategy. The optimal strategy is determined via optimization involving a large number of iterations.

To verify and validate the proposed flood simulation methodology, its results are compared to the actual available flood data in New York City (NYC) from Hurricane Sandy in 2012. After that, the methodology is used to evaluate the performance of the Big U project (Rebuild By Design 2015), one of the potential protective measures suggested for NYC against future coastal storms and SLR.

Methodology

The proposed methodology combines GIS with Manning's equation and the principle of mass conservation to conduct the simulation of a storm surge–induced flood event with high computational efficiency (i.e., low resources). It uses topographical features of the geographical area under consideration such as elevation, slope, and surface roughness, as well as the time histories of the storm surge height evolution with the astronomical tide estimation and SLR along coastlines [e.g., storm surge estimation methodology (Lopeman et al. 2015)]. The use of Manning's equation has the advantage of being able to account for various protective measures and to be used in various types of topographies, including wetlands and floodplains. A number of simplifying assumptions are made. First, the geographical area under consideration is partitioned into a number of subareas called divisions. As will be shown later, the partitioning is done in such a way that every division possesses a coastline segment. Each division is then idealized as a channel bringing floodwater into the division's area via its coastline segment that is impacted by the storm surge and tide. After calculating all the water volumes entering each division, these flood volumes are appropriately redistributed among the various divisions accounting for mass conservation (since water can, of course, cross the imaginary boundaries between divisions). The process of the flood simulation methodology is implemented on GIS and Python platforms and is schematically depicted in Fig. 1.

Topography

The proposed methodology requires topographical features (e.g., ground elevation, slope, surface roughness) of the area under consideration and the time histories of the storm surge and tide heights along the coastline. Detailed ground elevation information is needed at every point of a dense grid within the area considered. The area has to face the coastline partially or fully to calculate coastal flooding.

Coastline Division into Segments and Area Partitioning into Corresponding Divisions

Storm surge and tide waters flood the geographical area under consideration via the coastline. The floodwater volume is proportional to the length of the coastline exposed to the storm surge and tide (among other parameters). To avoid overestimating the floodwater volume entering the area through narrow piers and spikes along the coastline, the exact outline of the coastline is first smoothed out (buffered). For example, buffering 30 m inward is sufficient to exclude all the narrow piers in Lower Manhattan (below 34th Street), as shown in Fig. 2. Once the coastline is smoothed out, it is divided into several segments of approximately equal length. Each coastal segment is assigned ground elevation heights along its length, corresponding to the elevation of the street nearest to the coastline. Then, the geographical area behind the coastline is partitioned into several divisions (each division corresponding to a coastline segment). The coastline segmentation and the corresponding partitioning of the area into divisions are arbitrarily done so that: (1) the volume of floodwater entering a specific division via its coastline segment can be distributed with reasonable accuracy inside the division (following the principle of mass conservation); and (2) the slope S and surface roughness (Manning's roughness coefficient n) values within one division are approximately constant. As an example, Fig. 2 depicts 18 coastline segments and corresponding divisions in Lower Manhattan below 34th Street. In this case, the coastline segmentation and the corresponding partitioning of the area into divisions are done considering the ground elevation and slope. The coastline segmentation is done approximately every kilometer along its length. For the partitioning of the area into divisions, the relatively high-elevation ridge running north to south in the middle of Lower Manhattan is selected to separate west-facing from east-facing divisions because water cannot cross this north-south ridge. For example, in Fig. 2, water cannot be exchanged between Divisions 8 and 12. In general, it is advisable to use natural

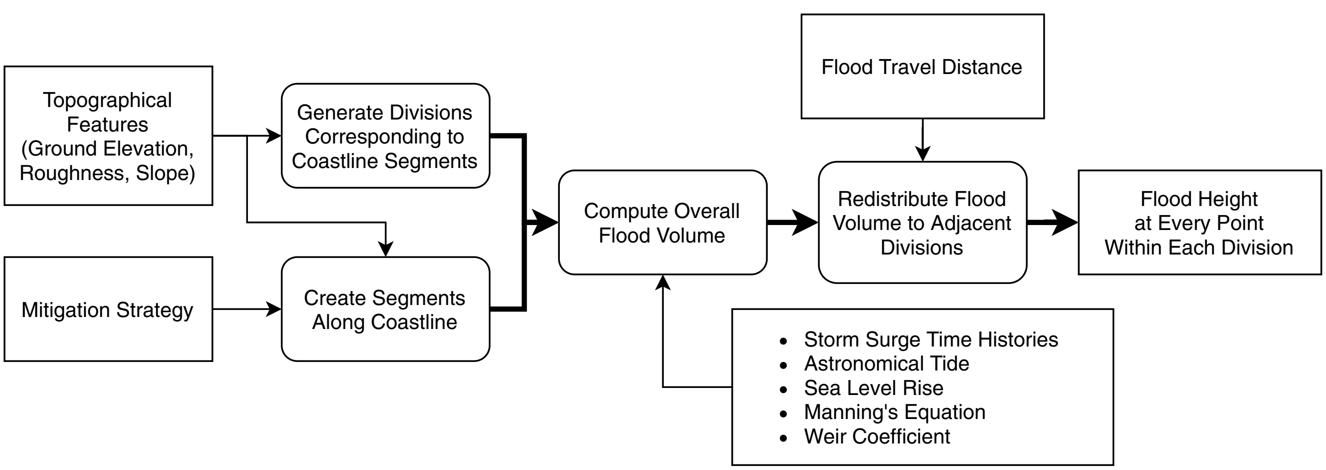

Fig. 1. Flood simulation schematic diagram; rectangles: inputs, rounded rectangles: processes.

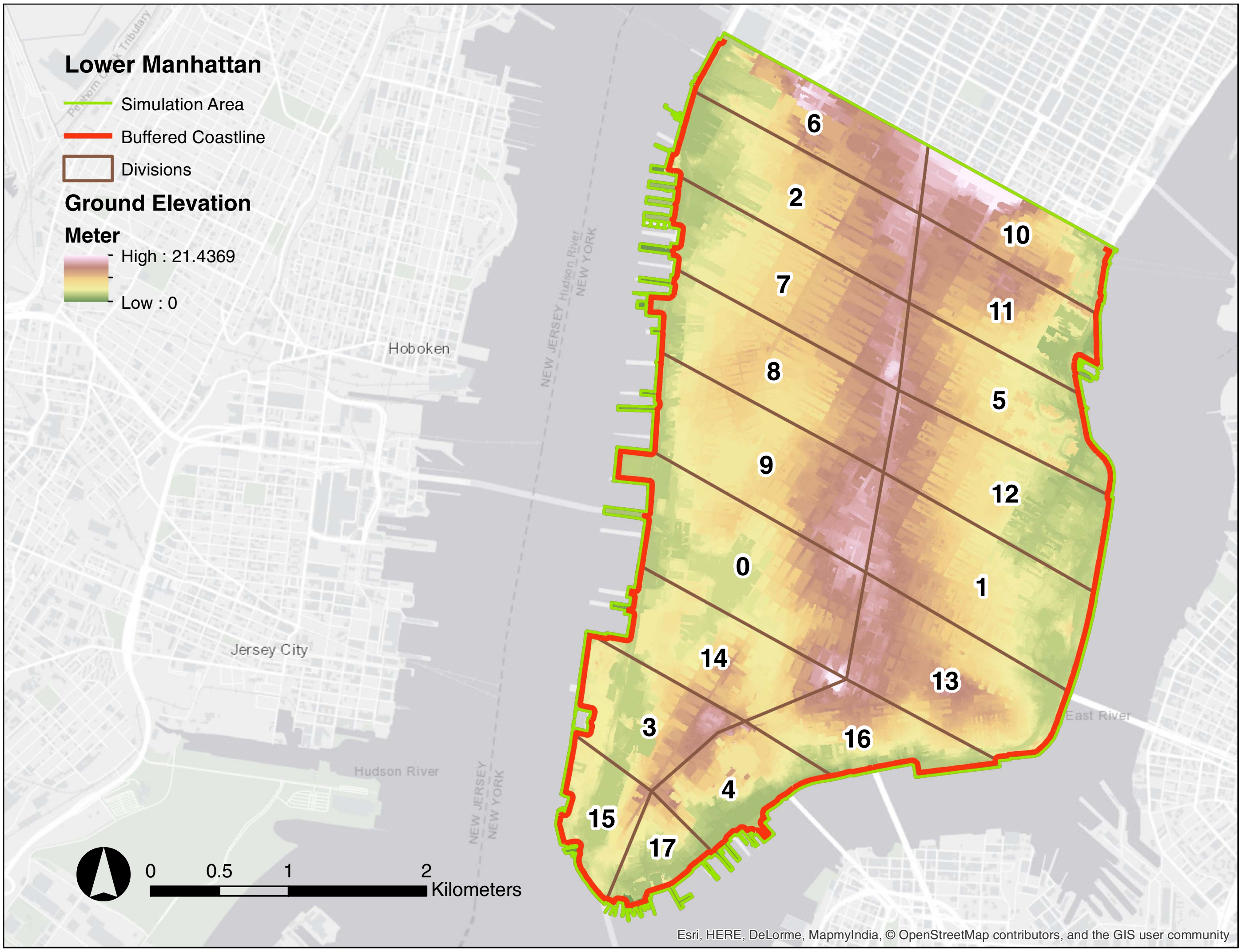

Fig. 2. Lower Manhattan (below 34th Street) with its coastline divided into segments and area behind coastline partitioned into corresponding divisions. The brown line is the original exact outline of the area including all piers. The bold line shows the coastline buffered 30 m inward to avoid overcalculation of floodwater volume. The coastline segmentation and the corresponding partitioning of the area into divisions is done considering the ground elevation and slope. Division numbering is arbitrary. (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

ridges that are high enough as boundaries among divisions. However, water can certainly travel among adjacent divisions along the coastline (e.g., among Divisions 7, 8, and 9 in Fig. 2). This process will be discussed subsequently in detail. The elevation data in Fig. 2 are from the 1-ft digital elevation model (DEM) provided by the Department of Environmental Protection & the Department of Information Technology and Telecommunications (2018). Other criteria used for this partitioning of the area into divisions include Public Use Microdata Areas (PUMAs) (United States Census Bureau 2010) and zip code partitions.

Protective Measures

Any protective measures that can be modeled as a series of line segments (e.g., artificial sand dunes, deployable flood walls, permanent seawalls and levees, storm surge barriers) can be easily accounted for in the proposed methodology by providing the corresponding information (e.g., height, length, location). For example, to account for the presence of a seawall, its elevation, location, and length information along the coastline segment should be used to update the coastline ground elevation height (above the height of the nearest street). It is possible to have multiple or combinations of protective measures in a target area simultaneously.

Flood Simulation

The simulation of a storm-induced flood over a geographical area of interest involves the calculation of the height of water at every point within this area as a function of time. Referring to Fig. 2, this means at every point within the 18 divisions depicted on the map (some high-elevation points can, of course, remain dry). The proposed flood simulation methodology is highly efficient computationally, compared to other simulation tools that are based on the solution of the shallow water equations (e.g., GeoClaw, ADCIRC), while maintaining reasonable accuracy. To perform the simulation, it is necessary to know the time histories of the storm surge and tide heights (as well as any SLR) along the coastline (i.e., bold line in Fig. 2).

The floodwater volume in each division in Fig. 2 is calculated by considering each coastline segment and corresponding division behind it as a channel with water flowing in from the coastline with velocity obtained from Manning's equation. The simulation uses the principle of mass conservation. It is assumed that the calculated floodwater volume for a specific division is distributed evenly over the area of the division, accounting for the DEM of the division. Once floodwater volumes are calculated for all divisions, they are redistributed among adjacent divisions as water can flow through the imaginary boundaries between divisions (i.e., floodwater can be transferred/exchanged between neighboring divisions). This is discussed subsequently in detail. The final outcome is the determination of the inundation area and the time history of the floodwater height at every point within the inundation area.

Calculation of Floodwater Volume Entering a Division

To calculate the volume of water entering a division, its coastline segment is divided into a number of subsegments of approximately equal length and its area is partitioned into corresponding subdivisions. This is depicted schematically in Fig. 3, where the coastline of Division 12 is divided into eight subsegments, each approximately 100 m long (the coastline length of Division 12 is approximately 800 m). This is done to account for different coastline elevations along the length of the division's coastline. The assumption is that within each subsegment, the coastline elevation is approximately constant. Fig. 3 shows also the corresponding eight subdivisions within Division 12. Consequently, referring to Fig. 3, Division 12 is modeled as a set of eight open channels through which floodwater enters the division.

Consider now division j being partitioned into N_j subsegments/subdivisions. The velocity of the water flow v_i entering subdivision i is computed by Manning's equation as

$$v_i(t) = \frac{1}{n_i} R_i^{\frac{2}{3}}(t) S_i^{\frac{1}{2}}, \quad i = 1, 2, \ldots, N_j \tag{1}$$

where n_i, $R_i(t)$, and S_i are Manning's roughness coefficient, the hydraulic radius, and the average slope of subsegment/subdivision i, respectively. Manning's roughness coefficient and the average slope are constant in time, but the hydraulic radius is a function of time as the storm surge + tide height evolves in time (the hydraulic radius is defined as the ratio of the cross-sectional area of the flow over the wetted perimeter of the channel). The parameter S_i is the average slope of subdivision i and can be estimated using DEM data. The parameter n_i is the average Manning's

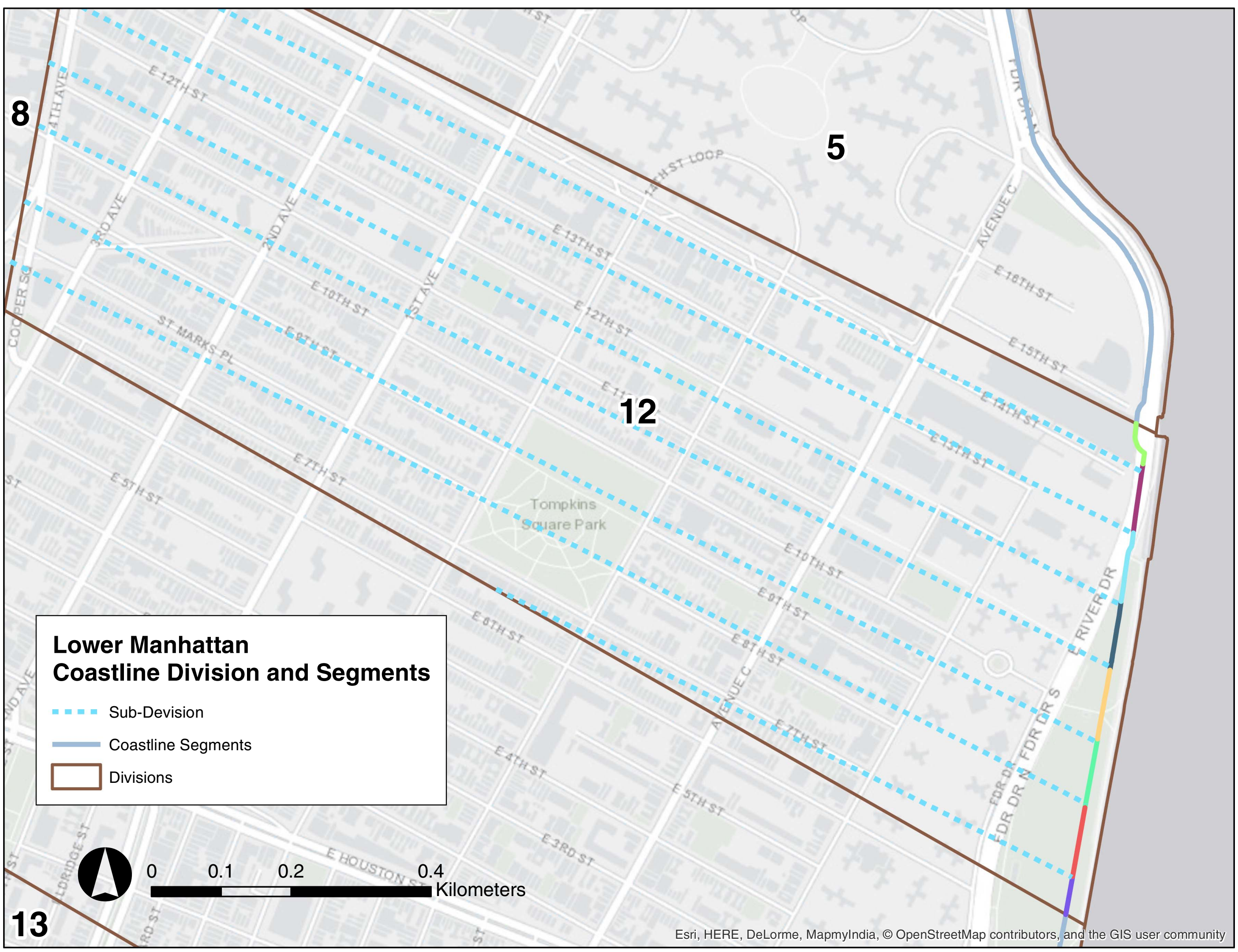

Fig. 3. Coastline subsegments and corresponding subdivisions within Division 12. (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

Table 1. Values for roughness coefficient $\mathcal{N}$ for individual structures/entities

Structure/entity	Roughness coefficient $\mathcal{N}$
Building	0.4
Forest	0.15
Shrub	0.1
River	0.05
Road	0.016
Crop/grass	0.035
No data	0.03

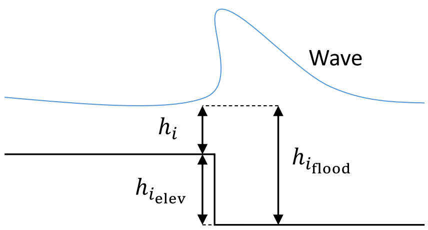

Fig. 4. Definitions and relationship between $h_i(t)$, $h_{i\text{flood}}(t)$, and $h_{i\text{elev}}$.

roughness coefficient over subdivision i and can be estimated using the following formula:

$$n_i = \sum_k \mathcal{N}_k P_k \tag{2}$$

where $\mathcal{N}_k$ = roughness coefficient of an individual type of structure/entity; and P_k = percentage of subdivision area occupied by this type of structure/entity. According to an experiment conducted by Syme (2008), the roughness coefficient $\mathcal{N}$ for an individual building is 0.4 in urban areas. Values for $\mathcal{N}$ for other individual structures/entities are provided in Table 1 (Dorn et al. 2014). Additional values can be found in Arcement and Schneider (1989).

As division j is partitioned into N_j subsegments/subdivisions, the total volumetric flow rate $V_j(t)$ entering the entire division at time instant t is calculated as

$$V_j(t) = \sum_{i=1}^{N_j} v_i(t) l_i h_i(t) \tag{3}$$

where l_i = length of coastal subsegment i; and $h_i(t)$ = land-side water height at coastal subsegment i, defined as difference between storm surge + tide height $h_{i\text{flood}}(t)$ (obtained from storm surge and tide data) and the critical elevation of the coastline $h_{i\text{elev}}$ (see Fig. 4 for definitions and relationships between these three quantities). It should be pointed out that the value of $h_{i\text{elev}}$ can be different for different subdivisions within a division. However, within every subdivision, the value of $h_{i\text{elev}}$ is assumed to be constant.

A storm surge + tide overtopping a protective measure along the coastline such as a seawall can be modeled as a rectangular weir in an open-channel flow. In such a case, the velocity of the flow overtopping the seawall, $v_{i,\text{wall}}(t)$, can be computed by multiplying the weir coefficient $C_{wr}(t)$ by the flow velocity $v_i(t)$ obtained from Eq. (1) (Chow 1959). It should be noted that the weir coefficient is used here without any consideration of viscous effects. In the case of other types of protective measures, such as artificial dunes, viscous effects might have to be considered in Eq. (5) (Swamee 1988). Here, $h_{i\text{elev}}$ will be the total height of the ground elevation plus the wall height

$$v_{i,\text{wall}}(t) = C_{wr}(t) v_i(t) \tag{4}$$

where

$$C_{wr}(t) = 0.611 + \frac{0.075 h_i(t)}{h_{i\text{elev}}} \tag{5}$$

and

$$V_{j,\text{wall}}(t) = \sum_{i=1}^{N_j} v_{i,\text{wall}}(t) l_i h_i(t) \tag{6}$$

Finally, to compute the overall (total) volume of water V_j entering division j over the entire duration of a storm event, the volumetric flow rates $V_j(t)$ and $V_{j,\text{wall}}(t)$ must be numerically integrated over the entire duration of the storm as follows:

$$V_j = \int_{t_i}^{t_f} (V_j(t) \quad \text{or} \quad V_{j,\text{wall}}(t)) dt \tag{7}$$

where t_i and t_f denote the times where the storm starts and ends, respectively.

Flood Height within a Division

Once the total volume of water V_j flooding division j during a storm event is calculated using Eq. (7), V_j has to be distributed evenly over the area of the division to determine which part of the division will be flooded and at what depth. This can be accomplished indirectly using standard tools available in GIS software packages, such as the Surface Volume tool in ArcGIS (ESRI 2020), that can calculate the area and volume of a triangulated irregular network (terrain dataset surface) above or below a given reference plane. In our case, this is going to be the volume of water between the plane surface of the floodwaters and the actual surface of the division under consideration (i.e., the DEM of the part of the city corresponding to the division). ArcGIS's Surface Volume tool uses as input the height of floodwaters and provides as output the volume of floodwater within a division. Consequently, the tool can be used repeatedly to establish a *flood height estimation curve* for a specific division. The procedure is very simple: the tool is used with a number of different floodwater heights to calculate corresponding flood volumes within a division. A typical example is shown in Fig. 5, where each blue dot represents a pair of flood height → flood volume for Division 12 in Fig. 2. The data points are then fitted with the following square root function:

$$h_j = \alpha \sqrt{V_j} + \beta V_j \tag{8}$$

where h_j is the estimated flood height of division j corresponding to flood volume V_j. The h_j value is defined with respect to the reference point of the mean sea level (MSL). The coefficients α and β are different for each division.

Such flood height estimation curves are established for every division in the general area under consideration. Then the flood height h_j at each division is easily estimated using as input the corresponding flood volume V_j calculated using Eq. (7). It should be noted that water height values determined from flood height estimation curves can become larger than the maximum storm surge + tide height. In general, the estimated flood height values h_j will be different for different divisions.

Floodwater Transfer/Exchange among Divisions

The boundaries between adjacent divisions are imaginary/artificial, and water can flow freely through them. Considering also that the estimated flood height values h_j can be different for different divisions, water *will* flow through division boundaries until equilibrium is reached. This transfer/exchange of floodwater among adjacent divisions is accomplished in an approximate way described in what follows.

The basic assumption made is that floodwater can travel only a limited distance d_{travel} from a division. This distance is computed as

$$d_{\text{travel}} = \bar{v}(t_f - t_p) \tag{9}$$

where $\bar{v}$ is the average flood velocity in a division from the time of the peak surge t_p to the final time of the storm event t_f (Lopeman et al. 2015). The assumption here is that floodwater enters and mostly accumulates within a division until time t_p, at which time it starts flowing in meaningful quantities to adjacent divisions. Once the value of d_{travel} is established, it is straightforward to determine the number of adjacent divisions of a given division where floodwaters will be potentially transferred/exchanged. The water transfer/exchange process is depicted schematically in Fig. 6 for

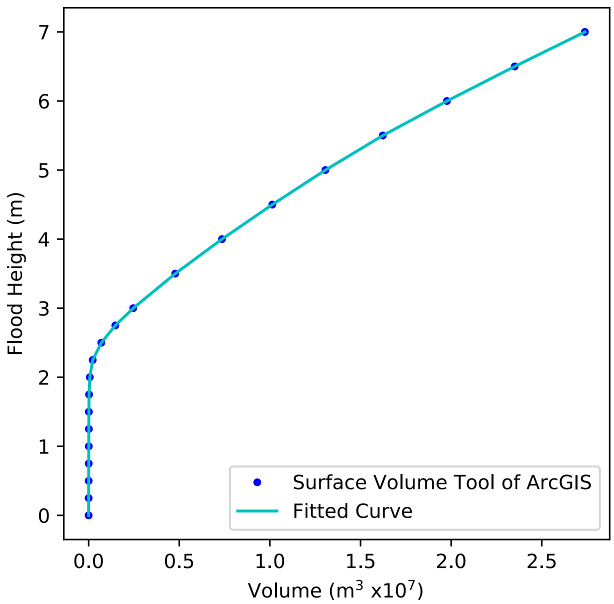

Fig. 5. Flood height estimation curve for Division 12 in Fig. 2. The data points computed by ArcGIS's Surface Volume tool are fitted with the square root function in Eq. (8).

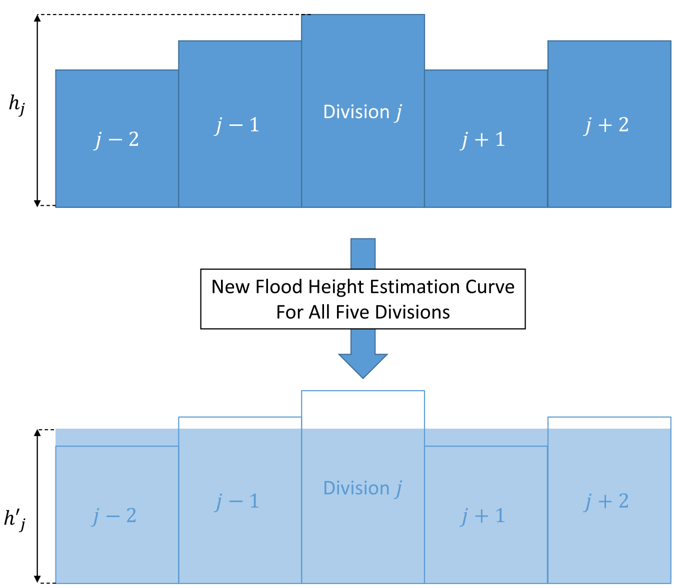

Fig. 6. Schematic of floodwater transfer/exchange among adjacent divisions for the case of two divisions on each side of a given division j. The new flood height estimation curve used is established for all five divisions considered as a single division in the figure. The total water volume in the divisions remains the same, satisfying the conservation of mass.

Table 2. New York City sea level rise projections (2000–2004 period is considered the sea level baseline)

Middle range	Low estimate	Middle estimate	High estimate
Baseline (2000–2004) [m (in.)]	10th percentile [m (in.)]	25th–75th percentile [m (in.)]	90th percentile [m (in.)]
2050s	0.203 (8)	0.279–0.533 (11–21)	0.762 (30)
2080s	0.330 (13)	0.457–0.991 (18–39)	1.473 (58)
2100	0.381 (15)	0.559–1.270 (22–50)	1.905 (75)

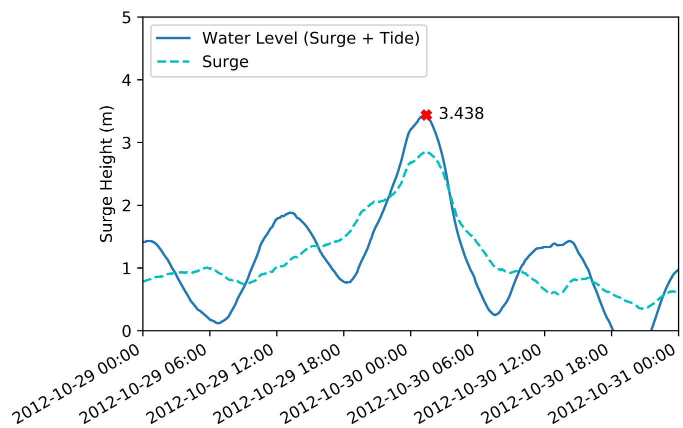

Fig. 7. Time history of total water level (storm surge + tide) observed at Battery in Manhattan (Station 8518750) during Hurricane Sandy. The number of data points is 480. (Data from National Oceanic and Atmospheric Administration 2012.)

Table 3. Average slope S_j for division j

Division j	S_j (m/m)
0	0.008445
1	0.009623
2	0.008757
3	0.010451
4	0.012746
5	0.012303
6	0.012070
7	0.008773
8	0.009391
9	0.008577
10	0.013596
11	0.010829
12	0.009188
13	0.010442
14	0.011111
15	0.009290
16	0.012446
17	0.009591

Table 4. Average roughness coefficient n_j for division j

Division j	n_j
0	0.1748
1	0.1160
2	0.1675
3	0.1358
4	0.1325
5	0.1210
6	0.1495
7	0.1876
8	0.1791
9	0.1629
10	0.1880
11	0.1665
12	0.1375
13	0.1008
14	0.1700
15	0.0967
16	0.0938
17	0.1423

the special case of two divisions left and right from each side of division j. First, a new flood height estimation curve is established for all five divisions (i.e., $j-2$, $j-1$, j, $j+1$, and $j+2$), and these are treated as a single division. Then the corresponding floodwater volumes of these five divisions [calculated using Eq. (7)] are added up

$$V_{\text{total}} = V_{(j-2)} + V_{(j-1)} + V_j + V_{(j+1)} + V_{(j+2)} \tag{10}$$

Eventually, the resulting value of V_{total} is used with the new flood height estimation curve for all five divisions to determine the single common flood height h'_j, as depicted in Fig. 6. It should be noted that the total water volume in the divisions under consideration remains the same, satisfying the conservation of mass.

To avoid unreasonable transfers/exchanges of floodwater among adjacent divisions, the newly established flood height h'_j is assigned only to division j. The process is repeated for each division in the geographical region under consideration. Referring to Fig. 2, Divisions 6 and 10 will only have water transfers/exchanges with divisions on only one side. It should be pointed out that the newly

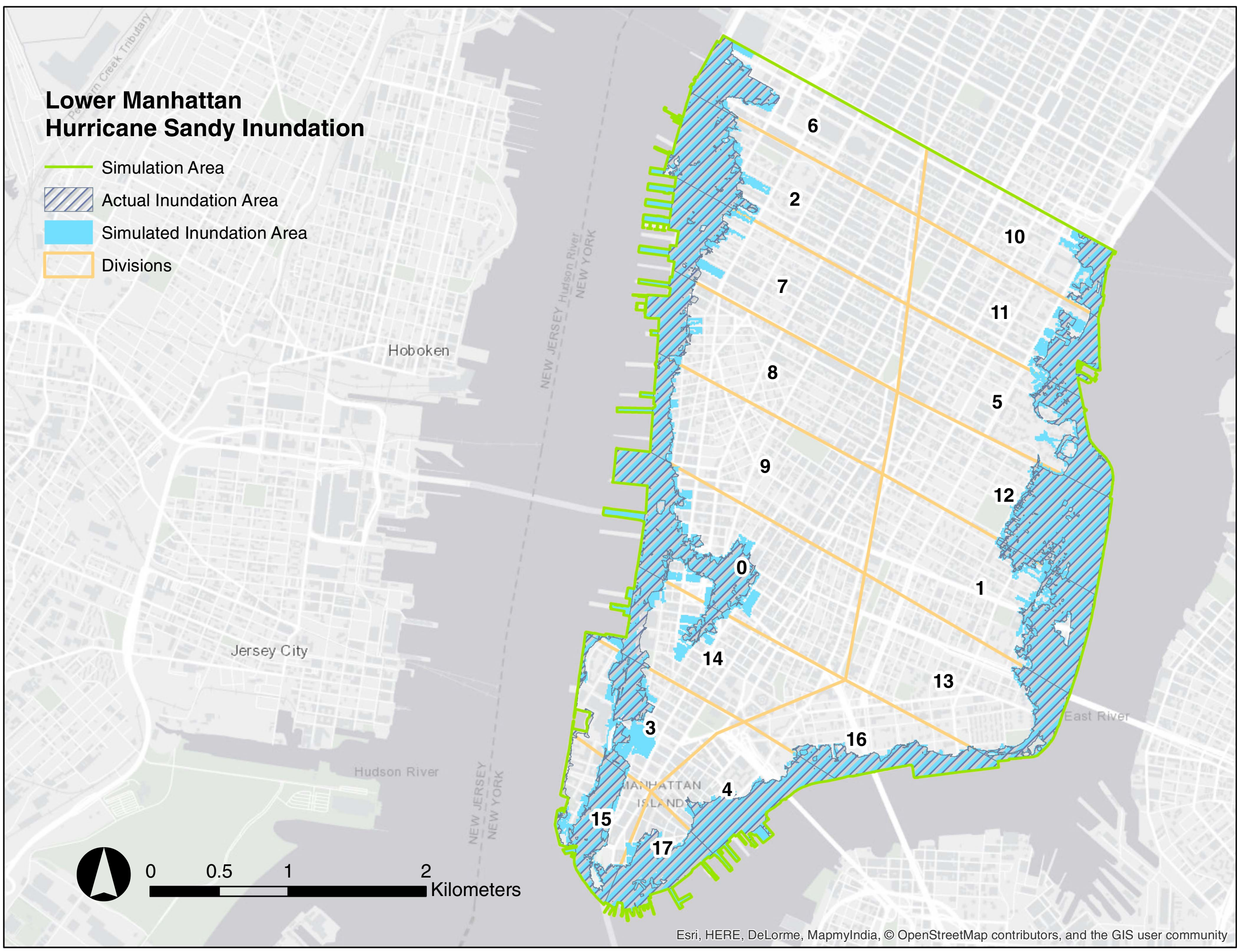

Fig. 8. Actual flooded area during 2012 Hurricane Sandy versus corresponding results obtained using proposed GISSR methodology. (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

Table 5. Comparison of actual inundated areas A_j and simulated inundated areas $A_{\mathrm{sim}j}$ of each division for Hurricane Sandy

Division j	A_j (km^2)	$A_{\mathrm{sim}j}$ (km^2)	Difference (%)
0	0.385	0.494	22.1
1	0.291	0.355	17.8
2	0.285	0.323	11.7
3	0.142	0.223	36.1
4	0.247	0.275	10.4
5	0.169	0.211	19.6
6	0.160	0.178	10.3
7	0.192	0.251	23.3
8	0.133	0.147	9.1
9	0.097	0.118	17.6
10	0.082	0.116	29.6
11	0.142	0.188	24.7
12	0.423	0.458	7.6
13	0.133	0.150	11.0
14	0.124	0.177	30.1
15	0.202	0.233	13.3
16	0.211	0.223	5.3
17	0.209	0.239	12.5
Total	3.630	4.359	16.7

estimated water height values h_j' cannot be at levels larger than the maximum storm surge + tide height. If the process depicted in Fig. 6 yields a value for h_j' that brings it above the maximum storm surge + tide height, then h_j' must be reduced to a value that brings it to the same level as the maximum storm surge + tide height.

Flood Simulations in Lower Manhattan, New York City

The capabilities of the proposed high-speed flood simulation methodology are demonstrated using Lower Manhattan in NYC as the target area. This is an area that was massively flooded during Hurricane Sandy in 2012. Flood simulations are provided without any SLR (current conditions), as well as with SLR anticipated in 2050 and 2100. The Lower Manhattan area studied is examined without any protective measures (current conditions), as well as with a number of different seawall alternatives having different heights and different lengths along the coastline. One of the suggested projects to protect Lower Manhattan from future storms and SLR is the so-called Big U project (Rebuild By Design 2015).

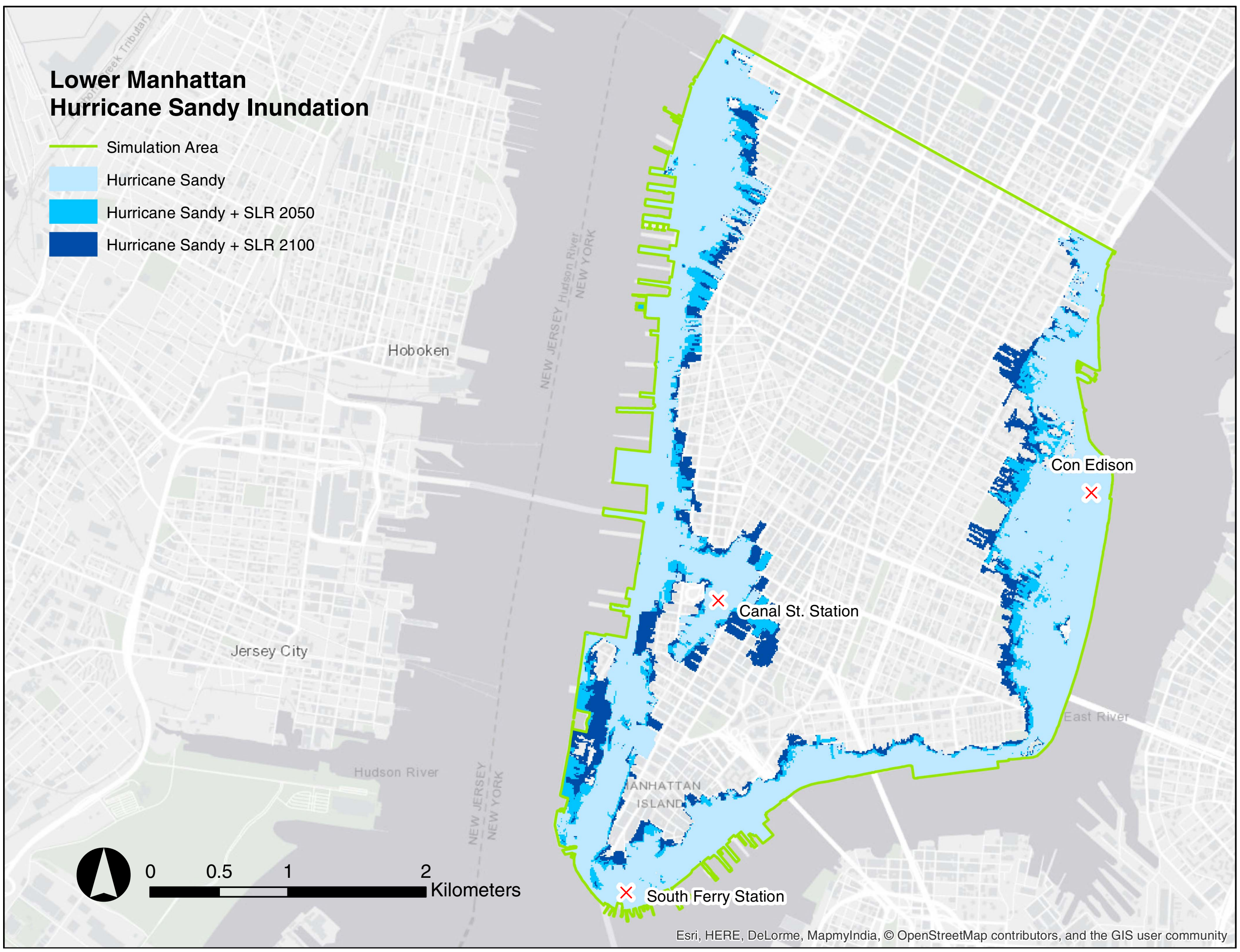

Fig. 9. Results for extent of flooding obtained using proposed GISSR methodology for following three scenarios: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. No protective measures are considered in these simulations. (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

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The Big U is essentially a seawall along parts of the coastline of Lower Manhattan. Consequently, two of the seawall alternatives considered here involve segments of the Big U project. Another seawall alternative involves a seawall along the entire length of the coastline of the Lower Manhattan area examined. To estimate the accuracy of the proposed methodology, the first flooding scenario examined is a simulation of Hurricane Sandy (simulation performed without any protective measures or SLR). The results of this simulation are then compared with the actual inundation data of Hurricane Sandy provided by the Department of Small Business Services (2018).

Future Anticipated Sea Level Rise and Storm Surge + Tide Height Time History during Storm in New York City

Projections of SLR at the Battery in NYC are provided by Horton et al. (2015) and Gornitz et al. (2019) in Table 2. These SLR projections are estimated with the 2000–2004 period as the reference baseline. The mean values of the middle estimates (50th percentile) from Table 2 are used in this study.

The time history of the storm surge + tide height (the combination of storm surge and astronomical tide) during a storm event is necessary to calculate the velocity of the water flow v_i entering a subdivision i according to Eq. (1) (the evolution of the water height is needed to calculate the hydraulic radius). The time history of the storm surge starts with an ascending part. It then reaches the maximum storm surge height (peak surge height) and is eventually followed by a descending part. The storm surge + tide values include the astronomical tide so that the storm surge may be increased when the tide is high and reduced when the tide is low. The actual time history observed during Hurricane Sandy at the Battery in Manhattan, NYC is shown in Fig. 7 (National Oceanic and Atmospheric Administration 2012), and these water height levels (storm surge + tide) are used in this study for every point along the coastline depicted by a bold line in Fig. 2. When an actual water height time history is not available, the exponential forms of the storm surge model suggested by Lopeman et al. (2015) can be used, along with an appropriately selected tidal height time history.

Average Roughness Coefficient and Slope for Division/Subdivision

To complete the calculation of the velocity of the water flow v_i entering a subdivision i according to Eq. (1), it is necessary to determine the values for the average roughness coefficient n_i and the average slope S_i. The slope values are assumed to be the same for all subdivisions within one division for simplicity (although this

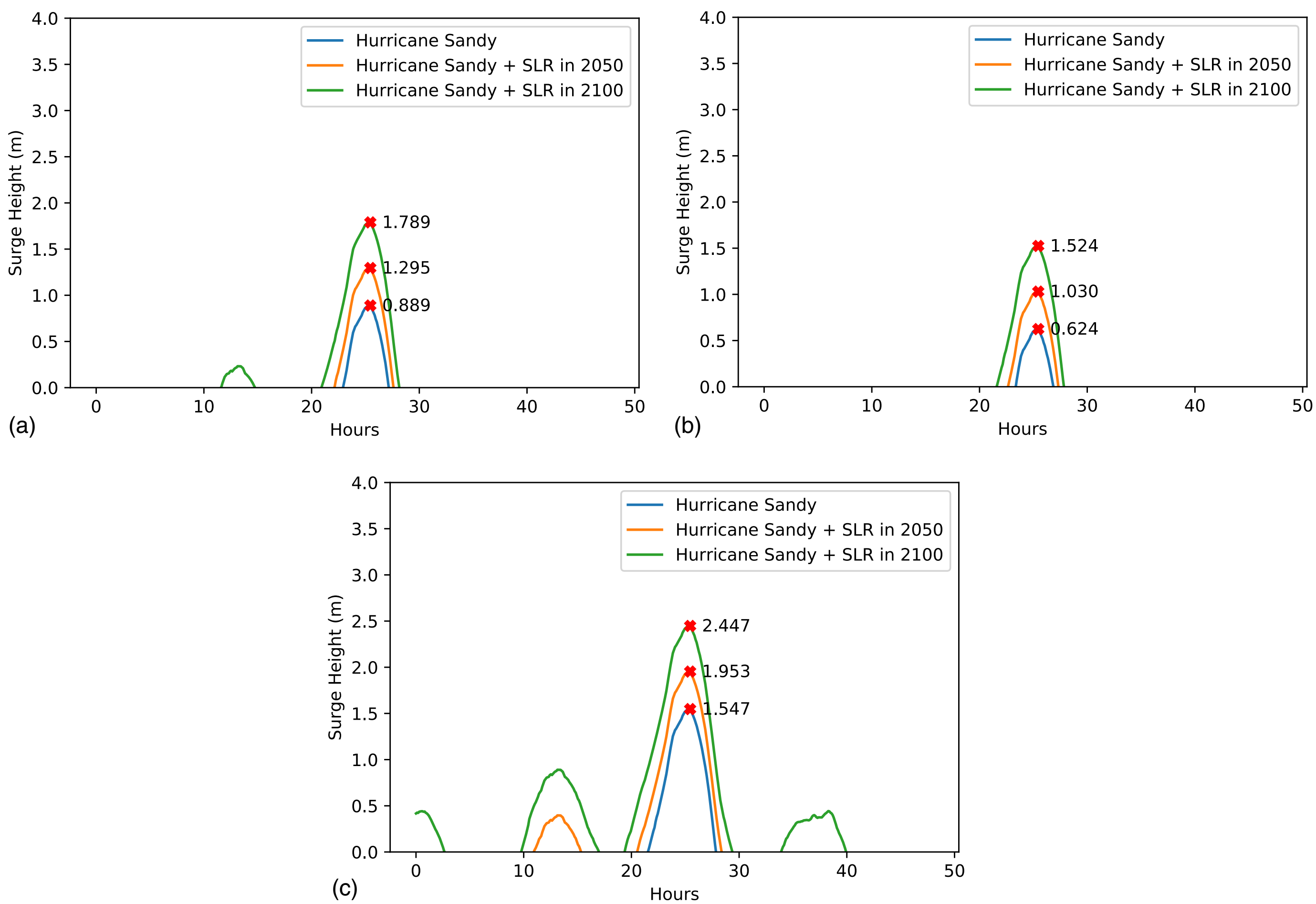

Fig. 10. Time histories of floodwater height at following locations: (a) South Ferry subway station entrance (latitude: 40.7013, longitude: −74.0135); (b) Canal Street subway station entrance on Seventh Avenue (40.7208, −74.0054); and (c) Con Edison Power Plant at East 14th Street (40.727835, −73.973181). At each location, three scenarios are considered: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. No protective measures are considered in these simulations: (a) South Ferry subway station; (b) Canal Street subway station; and (c) Con Edison Plant at 14th St.

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assumption is not necessary). Their corresponding values are determined via the GIS model using the DEM for Lower Manhattan and are displayed in Table 3.

The same assumption made for the slope is used for the roughness coefficient: its values are assumed to be the same for all subdivisions within one division (although, again, this is not necessary, especially when different subdivisions have sharply different topographical characteristics). The total area of a specific division is divided into a portion having buildings ($\mathcal{N} = 0.4$), a portion featuring roads ($\mathcal{N} = 0.016$), and a portion with no data ($\mathcal{N} = 0.03$) (Table 1). Each of these three portions is then assigned its percentage P_k of the total area of the division [Eq. (2)]. Using Eq. (2), the average roughness of the entire division is calculated and assigned to each of the subdivisions. The resulting average roughness coefficients are depicted in Table 4. All necessary information is now available to perform a number of flood simulation scenarios using the proposed methodology.

Flood Simulation Scenarios without Any Protective Measures

As mentioned earlier, the first flooding scenario examined is a simulation of Hurricane Sandy (simulation performed without any protective measures or SLR). The results of this simulation are then compared with the actual inundation data of Hurricane Sandy that have been recorded and are publicly available by the Department of Small Business Services (2018). This exercise is done to assess the accuracy of the proposed methodology by comparing its results to those of an actual event whose flooded area is known. The actual time history observed during Hurricane Sandy (Fig. 7) is used as input for this flooding scenario at every point along the coastline (bold line in Fig. 2).

The results of the proposed methodology are compared to the flooded area of Hurricane Sandy in Fig. 8 and Table 5. Fig. 8 indicates that the proposed methodology captures the actual inundated area with reasonably high accuracy. The match is not perfect, but the few areas overpredicted by the proposed methodology are all areas with very shallow inundations (the water depth can be found by subtracting the ground elevation from the total flood height). Consequently, overpredicting those few areas will have a negligible effect on loss estimation studies. Table 5 shows the actual and simulated inundated areas with the corresponding percentage difference. As the total area's difference of 16.7% implies, the simulation's accuracy is high, considering that the flood depth is very shallow in the overpredicted areas.

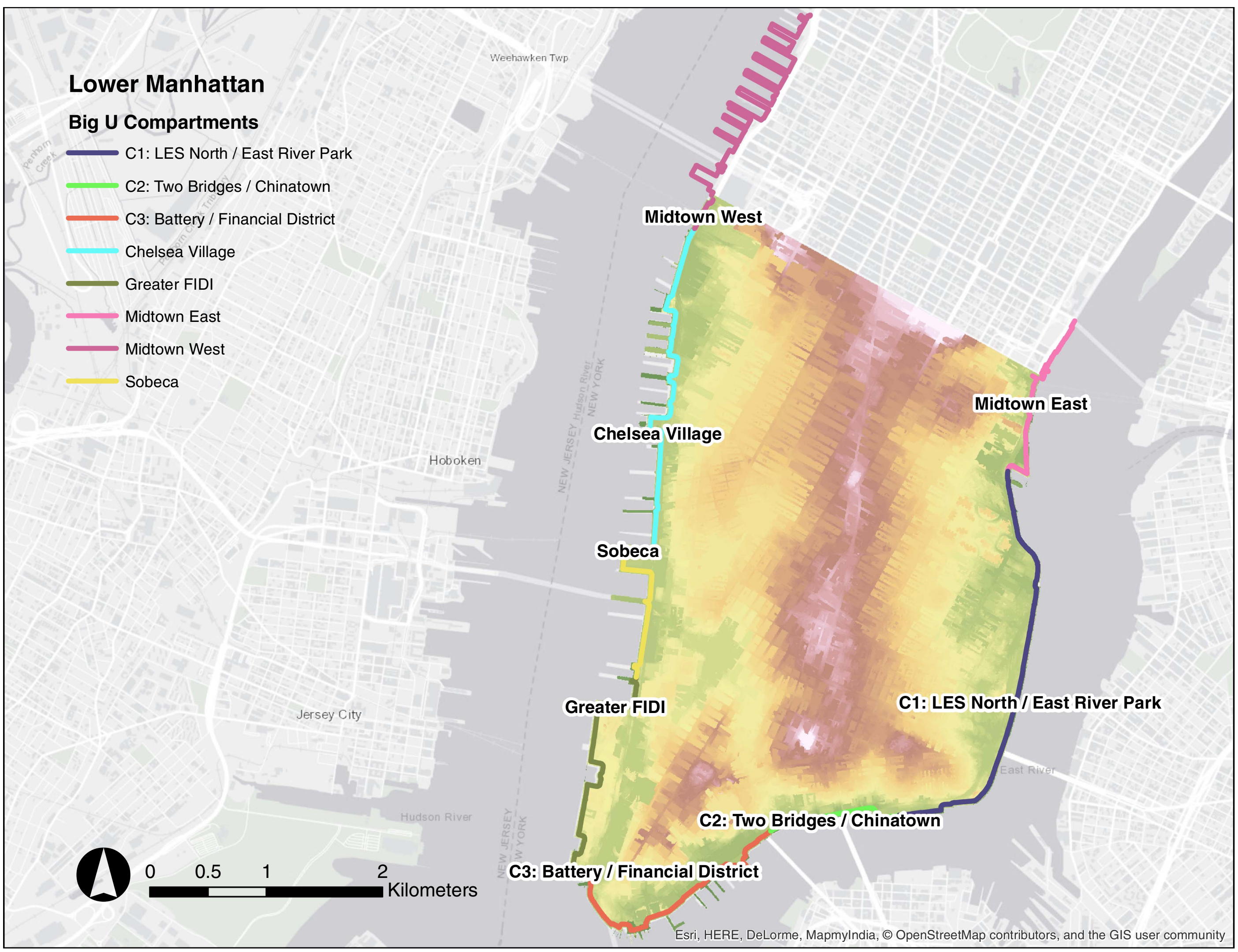

Fig. 11. Different segments/compartments of Big U project in Lower Manhattan. Compartments C1–C3 are given highest priority for construction. (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

What is critically important here is the computational efficiency of this flooding simulation. It only takes 0.01 s for a single storm event in this target area on an Intel Xeon X5650 CPU at 2.67 GHz (single processor) with 48 GB RAM. Two more flooding scenarios are considered without accounting for any protective measures in this area: Hurricane Sandy + middle SLR estimate in 2050s (0.4 m according to Table 2) and Hurricane Sandy + middle SLR estimate in 2100 (0.9 m according to Table 2). The corresponding results are displayed in Fig. 9, where it can be observed that as sea level continues to rise, the inundated area expands. It should be pointed out that the GISSR methodology not only is capable of estimating the extent of the inundated area during an event as shown in Fig. 9, but it can also compute the time history of the flood height at any point within this inundated area. This capability is demonstrated in Fig. 10, where the evolution of the floodwater height is provided at three locations in Lower Manhattan: South Ferry subway station entrance (latitude: 40.7013, longitude: −74.0135), Canal Street subway station entrance on Seventh Avenue (40.7208, −74.0054), and Con Edison Power Plant at East 14th Street (40.727835, −73.973181).

Flood Simulation Scenarios with Protective Measures

The three flooding scenarios (Hurricane Sandy, Hurricane Sandy + middle SLR estimate in the 2050s, and Hurricane Sandy + middle SLR estimate in 2100) used to determine the results shown in Fig. 9 will now be used in conjunction with a number of different seawall alternatives having different heights and different lengths along the coastline. This is done to assess the relative effectiveness of different protective measures in reducing the extent of flooding depicted in Fig. 9 (Fig. 9 assumes no protective measures present).

It is challenging to model flood behavior in an urbanized area with coastal protective measures such as seawalls, especially when the flood height exceeds the protective wall. In such cases, floodwater will flow into the city by overtopping the wall (albeit at a slower velocity compared to the case of no seawall present). The proposed methodology is capable of simulating flooding in such cases by modeling the wall as a weir [Eqs. (4) and (5)], and essentially without any increase in the computational cost. If the seawall is built only over limited segments of the coastline, water may come into the city in between wall segments or cascade around the horizontal edge of the wall.

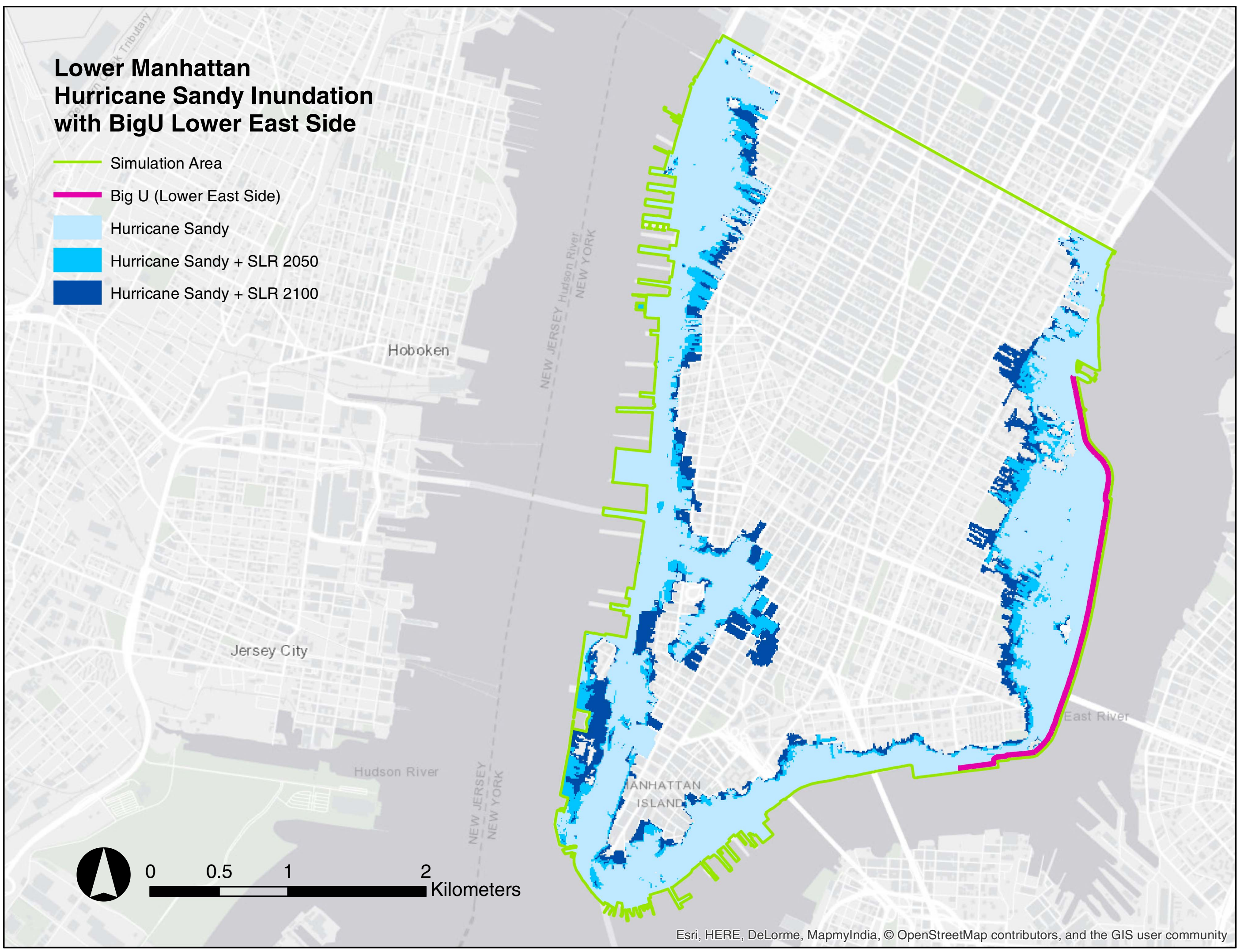

Fig. 12. Results for extent of flooding obtained using proposed GISSR methodology for following three scenarios: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. The following protective measure is considered: seawall of height 4.57 m (15 ft) along length of Compartment C1 (bold line on map). (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

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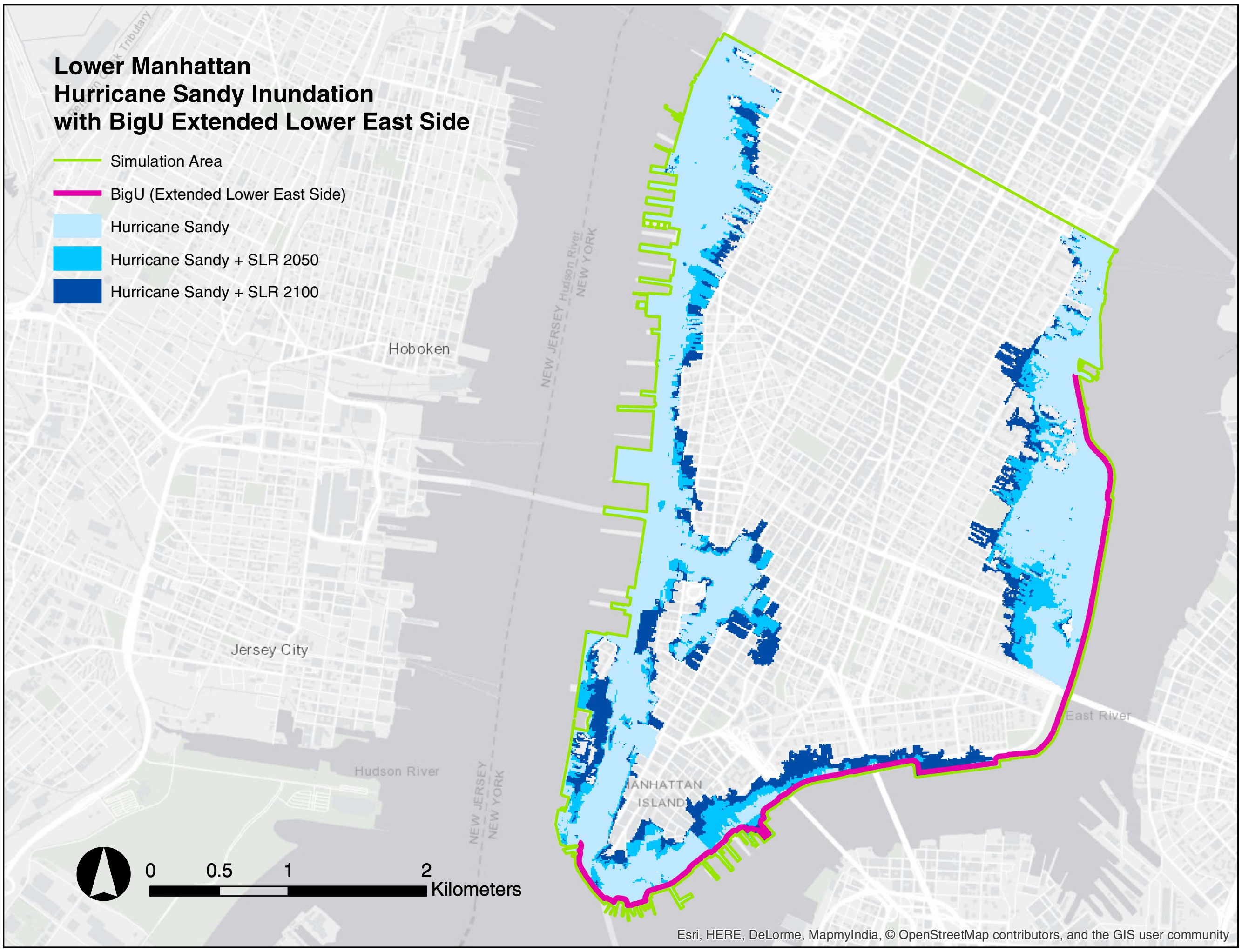

Fig. 13. Results for extent of flooding obtained using proposed flood simulation methodology for following three scenarios: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. The following protective measure is considered: seawall of height 4.57 m (15 ft) along length of Compartments C1–C3 (bold line on map). (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

Table 6. Comparison of inundated areas (in square kilometers) from Hurricane Sandy with different types of seawalls

Division j	No protection	C1	C1–C3	Entire coastline (1 m)	Entire coastline (2 m)
0	0.494	0.494	0.494	0.021	0.010
1	0.355	0.355	0.279	0.086	0
2	0.323	0.323	0.323	0.175	0
3	0.223	0.223	0.223	0.060	0
4	0.275	0.275	0.069	0.228	0
5	0.211	0.211	0.211	0.078	0
6	0.178	0.178	0.178	0.096	0
7	0.251	0.251	0.251	0.111	0
8	0.147	0.147	0.147	0.055	0
9	0.118	0.118	0.118	0.014	0
10	0.116	0.116	0.116	0.052	0
11	0.188	0.188	0.188	0.014	0
12	0.458	0.458	0.458	0.204	0
13	0.150	0.150	0.003	0.062	0
14	0.177	0.177	0.177	0.031	0
15	0.233	0.233	0.232	0.113	0
16	0.211	0.211	0.026	0.136	0
17	0.239	0.239	0.216	0.194	0.007
Total	4.359	4.359	3.708	1.836	0.017

Table 7. Comparison of inundated areas (in square kilometers) from Hurricane Sandy and sea level rise in 2100 with different types of seawalls

Division j	No protection	C1	C1–C3	Entire coastline (1 m)	Entire coastline (2 m)
0	0.671	0.671	0.671	0.671	0.014
1	0.496	0.496	0.496	0.496	0.085
2	0.398	0.398	0.398	0.398	0.156
3	0.377	0.377	0.377	0.377	0.059
4	0.315	0.315	0.292	0.315	0.231
5	0.326	0.326	0.326	0.326	0.097
6	0.210	0.210	0.210	0.210	0.090
7	0.313	0.313	0.313	0.313	0.119
8	0.214	0.214	0.214	0.214	0.013
9	0.163	0.163	0.163	0.163	0
10	0.129	0.129	0.129	0.129	0.056
11	0.234	0.234	0.234	0.234	0.126
12	0.540	0.540	0.540	0.540	0.221
13	0.206	0.206	0.003	0.206	0.062
14	0.328	0.328	0.328	0.328	0.026
15	0.368	0.368	0.368	0.368	0.110
16	0.273	0.273	0.175	0.273	0.138
17	0.274	0.274	0.274	0.274	0.001
Total	5.834	5.834	5.510	5.834	1.603

Flood Simulations Involving Parts of Big U Project [Compartment C1 of Lower East Side Segment and Entire Lower East Side Segment (Compartments C1–C3)]

Since experiencing the massive damage from Hurricane Sandy in 2012, NYC has been working on rebuilding along the lines of the concept of a so-called resilient city. A part of this effort involved a competition called Rebuild By Design, where the Big U project was one of the winners for Manhattan (Rebuild By Design 2015). The Big U project is essentially a seawall along the coastline of southern Manhattan. Specifically, it extends from West 57th Street down to the Battery and then up to East 42nd Street (Fig. 11).

Fig. 11 indicates that the Big U project is broken down into different segments/compartments that can be completed independently of each other. Compartments C1–C3 have been studied the most because they have been given the highest priority for construction. The design team has been working with the surrounding community and stakeholders to finalize their design. The target height of the C1–C3 compartments is 4.57 m (15 ft), as described in Rebuild By Design (2015). Two cases based on these three compartments will be examined now: (1) Compartment C1 (bold line in Fig. 12); and (2) Compartments C1–C3 (bold line in Fig. 13). In both of these cases, the height of the seawall is set equal to 4.57 m (15 ft).

Fig. 12 shows the extent of flooding when Compartment C1 (bold line in Fig. 12) is treated as the protective measure. Three flooding scenarios are examined: Hurricane Sandy, Hurricane Sandy + middle SLR estimate in 2050s, and Hurricane Sandy + middle SLR estimate in 2100. For all three flooding scenarios, the corresponding inundated areas are identical to those without any protective measure (Fig. 9). Although floodwater did not overtop the 4.57-m (15-ft) seawall, it did cascade around the edges of the seawall and flooded the area behind it. Consequently, building only Compartment C1 does not reduce the extent of flooding at all, as indicated in Tables 6 and 7.

Fig. 13 shows the extent of flooding when Compartments C1–C3 (bold line in Fig. 13) are treated as the protective measure. The same three flooding scenarios are examined. In contrast to the seawall case depicted in Fig. 12, the building of Compartments C1–C3 provides some level of protection in the middle of the

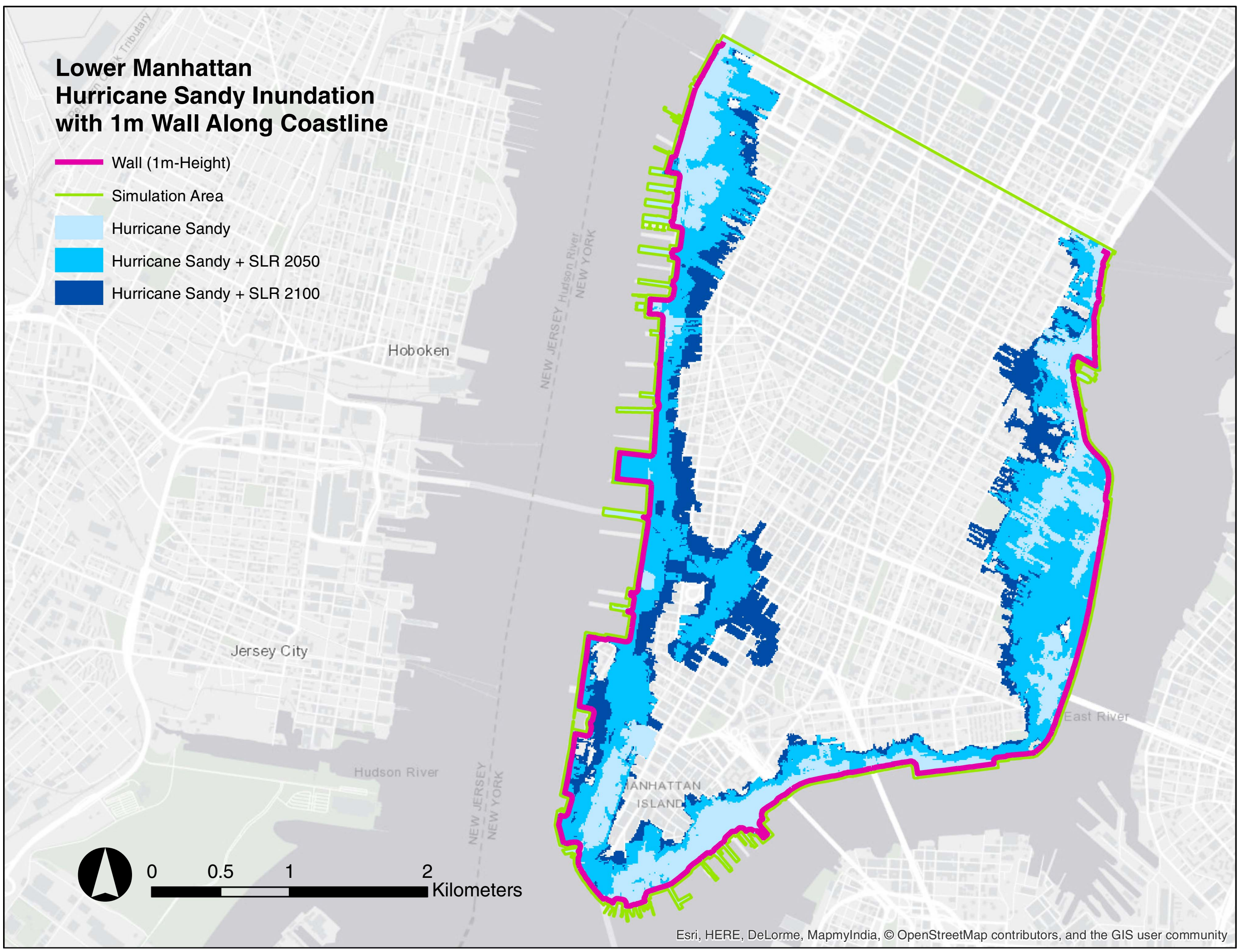

Fig. 14. Results for extent of flooding obtained using proposed GISSR methodology for following three scenarios: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. The following protective measure is considered: seawall of height 1 m along entire length of coastline of Lower Manhattan (bold line on map). (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

seawall since cascading floodwater around the edges of the seawall cannot travel all the way to the middle of it. There is also some modest flooding reduction away from the middle of the seawall, as shown in Tables 6 and 7. Consequently, the building of Compartments C1–C3 produces some limited reduction to the extent of flooding.

The flooding results shown in Figs. 12 and 13 and Tables 6 and 7 indicate that building only Compartment C1 or Compartments C1–C3 of the Big U project provides limited or no reduction at all to the extent of the inundation area compared to the case of no protective measures. The logical conclusion is that a seawall needs to be built around the entire length of the coastline of Lower Manhattan. This is examined in the next section.

Flood Simulations Involving Seawall around Entire Length of Lower Manhattan

As indicated by the bold lines in Figs. 14 and 15, a seawall around the entire length of Lower Manhattan is considered now (such a wall will be present when the entire Big U project is completed, although its height has not yet been decided at every point along the coastline). Because the Big U project will eventually extend beyond the two northern edges of the bold lines in Figs. 14 and 15, it is assumed that floodwater cannot cascade around these two edges. Two cases are considered with a uniform seawall height along the entire length of the coastline: 1 and 2 m [if the uniform wall height is 4.57 m (15 ft) as in the current design of Compartments C1–C3, then there will be no flooding at all as the combined height of the coastline elevation plus the wall height is larger than the Hurricane Sandy maximum storm surge and corresponding tide, plus any middle estimate SLR up to 2100].

Fig. 14 displays the extent of flooding for the case of the 1-m seawall, and Fig. 15 the extent of flooding for the 2-m wall. Fig. 14 indicates that a 1-m seawall offers only limited protection, especially when SLR occurs. The 2-m-high wall provides better overall protection, and only the 2100 SLR results in limited flooding, as also indicated in Tables 6 and 7.

Fig. 16 provides the evolution of the floodwater height at the three locations in Lower Manhattan for the case of a 1-m-high seawall built along the entire length of the coastline in Lower Manhattan (bold line in Fig. 2). Comparison of Figs. 16 and 10 indicates that the 1-m-high seawall reduces the flood heights for

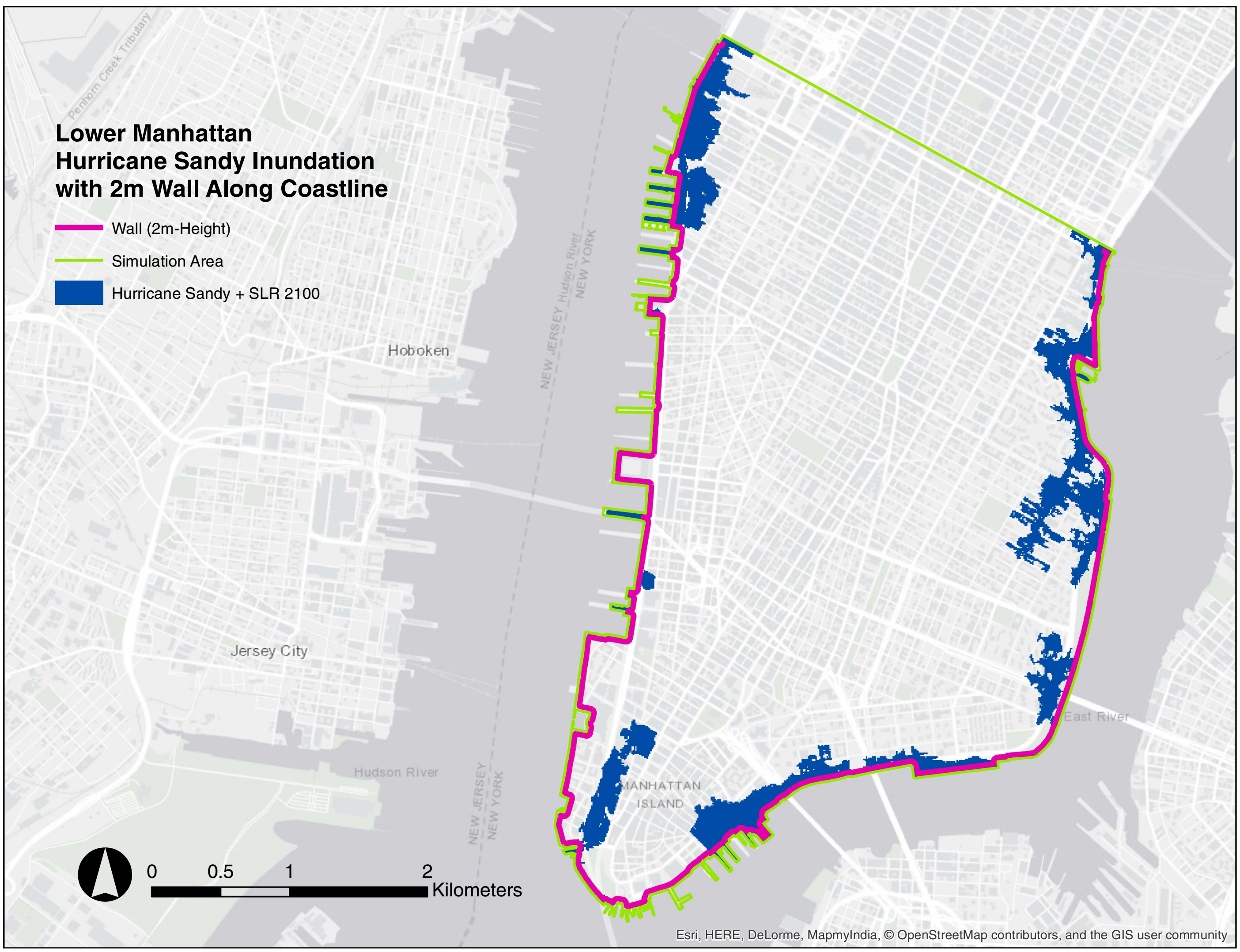

Fig. 15. Results for extent of flooding obtained using proposed flood simulation methodology for following three scenarios: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. The following protective measure is considered: seawall of height 2 m along entire length of coastline of Lower Manhattan (bold line on map). (Base map by Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.)

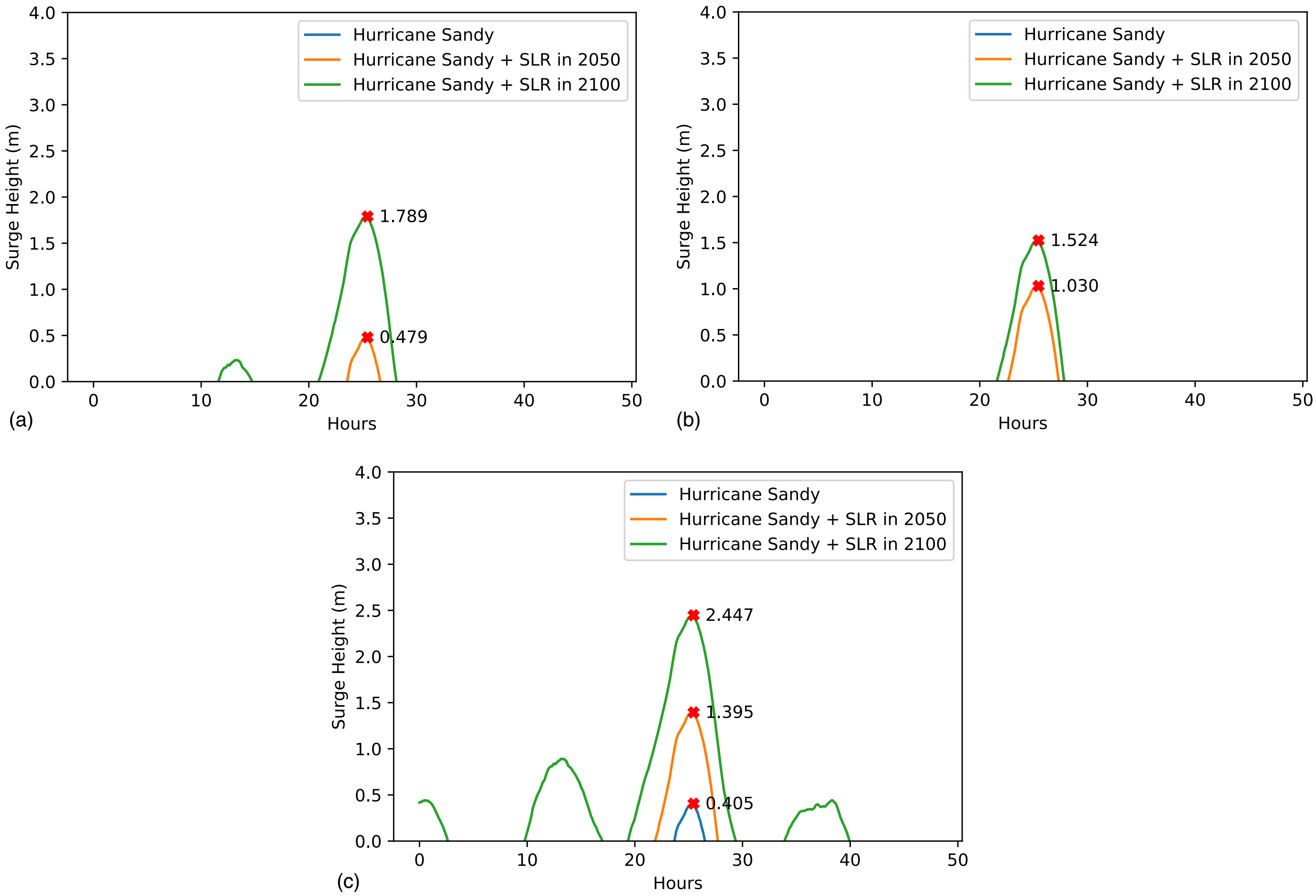

Fig. 16. Time histories of floodwater height at the three locations. At each location, three scenarios are considered: Hurricane Sandy, Hurricane Sandy plus SLR middle estimate in 2050s, and Hurricane Sandy plus SLR middle estimate in 2100. The following protective measure is considered: seawall of height 1 m along entire length of coastline of Lower Manhattan: (a) South Ferry subway station; (b) Canal Street subway station; and (c) Con Edison Plant at 14th St.

the scenario of Hurricane Sandy without any SLR but has minimal or no effect for the scenarios of Hurricane Sandy with the middle SLR estimate in the 2050s and 2100.

Comparison of the results in Figs. 12 and 13 and Figs. 14 and 15 and Tables 6 and 7 reveals that only a seawall along the entire length of the coastline of Lower Manhattan (full-length wall) can provide effective protection against flooding caused by Hurricane Sandy and different scenarios of SLR [taking also into account that a 4.57-m (15-ft) high full-length wall results in zero flooding].

Cost-Benefit Analysis Considerations

Any protective measure must be, of course, cost effective, in the sense that its overall design and construction cost must be lower than the ensuing reduction in flooding losses (compared to the case of doing nothing). The overall cost estimate for the Lower East Side (LES) segment of the Big U project provided by Rebuild By Design (2015) is $418 million for Compartment C1 and over $1 billion for Compartments C1–C3. These estimates include flood protection structures, landscape and architectural features, utilities, wet feet, new buildings, contingencies and escalation, and soft costs. Consequently, in order for the LES segment to be financially meaningful (if built independently of the rest of the Big U project), it must reduce anticipated flood losses (compared to the scenario of doing nothing) by more than its own costs. Based on Figs. 12 and 13 and Tables 6 and 7, this appears to be unlikely.

Flood losses are considered in general over an extended period of time (e.g., 50 or 100 years) that can involve multiple catastrophic storms. The ultimate objective is to determine the optimal protective strategy for a prescribed budget (the optimal protective strategy corresponds to the maximum reduction in flooding losses). The optimal protective strategy involves, in general, different protective measures (i.e., not only seawalls) implemented at different geographical locations and at different time instants.

The GISSR methodology constitutes an indispensable tool in determining the aforementioned optimal protective strategy since it can estimate inundated areas with high computational efficiency.

Conclusions

A storm surge–induced flood simulation methodology has been proposed for coastal urban environments. The methodology, called the GIS-based subdivision-redistribution (GISSR) methodology, combines GIS with Manning's equation to first calculate the volume of water flowing into the geographical area under consideration and then to redistribute it appropriately over that area. It uses detailed topographical features, such as elevation, slope, and surface roughness, as well as the time histories of the storm surge and tide heights along the coastline. It is capable of incorporating a variety of protective measures along the coastline, such as seawalls. For flood simulations in the future, it is straightforward to account for a prescribed value of SLR.

The methodology is extremely efficient from a computational point of view, requiring only 0.01 s to simulate a specific storm over Lower Manhattan, NYC, on an Intel Xeon X5650 CPU at 2.67 GHz (single processor) with 48 GB RAM. Larger geographical areas will require larger computational times, but the increase is expected to be mostly linear.

The accuracy of the methodology is assessed by comparing its results to the extent of flooding observed during Hurricane Sandy. Although several simplifying assumptions are involved, the accuracy is sufficiently high. Several examples are provided involving different protective measures in Lower Manhattan. The methodology is ideal for determining the optimal protective strategy for a coastal city because of its high computational efficiency (in general, such optimization requires a very large number of flood simulations).

Data Availability Statement

- Some or all data, models, or code generated or used during this study are available in a repository online, in accordance with funder data retention policies:
    1. Miura, Y. (2020). "High-speed GIS flood simulation. GitHub repository." Accessed December 2020. https://github.com/ym2540/GIS_FloodSimulation.git DOI: 10.5281/zenodo.3971004.
    2. Department of Information Technology & Telecommunications (2018). "Building footprints." Accessed December 2020. https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh.
    3. Department of Environmental Protection and Department of Information Technology and Telecommunications (2018). "1 foot digital elevation model (DEM)." Accessed December 2020. https://data.cityofnewyork.us/City-Government/1-foot-Digital-492Elevation-Model-DEM-/dpc8-z3jc.
    4. Department of Homeland Security, Federal Emergency Management Agency (2018). "Hazus." Accessed December 2020. https://www.fema.gov/hazus.
    5. National Oceanic and Atmospheric Administration (2012). "Water level—Observed water level at 5188518750, the battery, NY from 2012/10/29 00:00 GMT to 2012/10/30 23:59 GMT." Accessed December 2020. https://tidesandcurrents.noaa.gov/waterlevels.html?id=8518750&units=metric&bdate=20121029&edate=20121030&timezone=GMT&datum=MSL&interval=6&action=.
    6. Department of Small Business Services (2015). "Sandy inundation zone." Accessed December 2020. https://data.cityofnewyork.us/Environment/Sandy-Inundation-Zone/uyj8-7rv5
    7. United States Census Bureau (2010). "Public use microdata areas (pumas)." Cambridge Texts in Applied Mathematics. Cambridge University Press. Accessed December 2020. https://www.census.gov/programs-536surveys/geography/guidance/geo-areas/pumas.html.
    8. ESRI (2020). "Surface volume arcmap 10.8." Accessed December 2020. https://desktop.arcgis.com/en/arcmap/latest/tools/3d-analyst-toolbox/surface-volume.htm.
    9. Department of City Planning (DCP) (2018) "Borough Boundaries." Accessed December 2020. https://data.cityofnewyork.us/City-Government/Borough-Boundaries/qefp-jxjk.
    10. New York City Department of City Planning (2018). "MapPLUTO." Accessed December 2020. https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-pluto-mappluto.page.

Acknowledgments

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References

Arcement, G. J., and V. R. Schneider. 1989. *Guide for selecting Manning's roughness coefficients for natural channels and flood plains*. Washington, DC: US Government Printing Office.

Berger, M. J., D. L. George, R. J. LeVeque, and K. T. Mandli. 2011. "The GeoClaw software for depth-averaged flows with adaptive refinement." *Adv. Water Res.* 34 (1): 1195–1206.

Chow, V. T. 1959. *Open-channel hydraulics*. Caldwell, NJ: Blackburn.

Department of Environmental Protection and Department of Information Technology and Telecommunications. 2018. "1 foot digital elevation model (DEM)." Accessed September 1, 2019. https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc.

Department of Homeland Security, Federal Emergency Management Agency. 2018. "Hazus." Accessed August 21, 2019. https://www.fema.gov/hazus.

Department of Small Business Services. 2018. "Sandy inundation zone." Accessed July 1, 2018. https://data.cityofnewyork.us/Environment/Sandy-Inundation-Zone/uyj8-7rv5.

Dorn, H., M. Vetter, and B. Höfle. 2014. "GIS-based roughness derivation for flood simulations: A comparison of orthophotos, lidar and crowd-sourced geodata." *Remote Sens.* 6 (2): 1739–1759. https://doi.org/10.3390/rs6021739.

ESRI (Environmental Systems Research Institute). 2020. "Surface volume ARCMAP 10.8." Accessed July 10, 2020. https://desktop.arcgis.com/en/arcmap/latest/tools/3d-analyst-toolbox/surface-volume.htm.

Gornitz, V., M. Oppenheimer, R. Kopp, P. Orton, M. Buchanan, N. Lin, R. Horton, and D. Bader. 2019. "New York City panel on climate change 2019 report chapter 3: Sea level rise." *Ann. N. Y. Acad. Sci.* 1439 (1): 71–94. https://doi.org/10.1111/nyas.14006.

Horton, R., C. Little, V. Gornitz, D. Bader, and M. Oppenheimer. 2015. "New York City panel on climate change 2015 report chapter 2: Sea level rise and coastal storms." *Ann. N. Y. Acad. Sci.* 1336 (1): 36–44. https://doi.org/10.1111/nyas.12593.

Lopeman, M., G. Deodatis, and G. Franco. 2015. "Extreme storm surge hazard estimation in lower manhattan." *Nat. Hazards* 78 (1): 355–391. https://doi.org/10.1007/s11069-015-1718-6.

Miura, Y., H. Qureshi, C. Ryoo, P. C. Dinenis, J. Li, K. T. Mandli, G. Deodatis, D. Bienstock, H. Lazrus, and R. Morss. 2021. "A methodological framework for determining an optimal coastal protection strategy against storm surges and sea level rise." *Nat. Hazards*. 1–23. https://doi.org/10.1007/s11069-021-04661-5.

National Oceanic and Atmospheric Administration. 2012. *Water level—Observed water level at 8518750, the Battery, NY from 2012/10/29 00:00 GMT to 2012/10/30 23:59 GMT*. Washington, DC: National Oceanic and Atmospheric Administration.

Nobre, A., L. Cuartas, M. Hodnett, C. Rennó, G. Rodrigues, A. Silveira, M. Waterloo, and S. Saleska. 2011. "Height above the nearest drainage—A hydrologically relevant new terrain model." *J. Hydrol.* 404 (1–2): 13–29. https://doi.org/10.1016/j.jhydrol.2011.03.051.

Rebuild By Design. 2015. "The Big U." Accessed August 25, 2020. http://www.rebuildbydesign.org/our-work/all-proposals/winning-projects/big-u.

Swamee, P. K. 1988. "Generalized rectangular weir equations." *J. Hydraul. Eng.* 114 (8): 945–949. https://doi.org/10.1061/(ASCE)0733-9429(1988)114:8(945).

Syme, W. 2008. "Flooding in urban areas—2D modelling approaches for buildings and fences." In *Proc., 9th National Conf. on Hydraulics in Water Engineering: Hydraulics 2008*, 25–32. Barton, ACT, Australia: Engineers Australia.

United States Census Bureau. 2010. "Public use microdata areas (PUMAs)." Accessed September 1, 2019. https://www.census.gov/programs-surveys/geography/guidance/geo-areas/pumas.html.