Impacts of Sea Level Rise and Storms on Manhattan

—by Monika Calef

Introduction

Problem

Throughout the twentieth century, the rise of sea level contributed to increased coastal inundation, erosion, and ecosystem losses, but with considerable local and regional variation due to other factors. According to the most recent report by the Intergovernmental Panel on Climate Change (IPCC 2007), coastal areas will be even more vulnerable in the near future, with continuing rise in sea level, more frequent and larger storms, increased storm surges, and more.

One influential and densely populated city in the North American coastal zone is New York City, with a population of nearly 8.5 million. Surrounded by water and experiencing a major hurricane about every 75 years (Naparstek 2005), the city has cause for alarm.

In 1893, a hurricane devastated New York City. What would be the impact of a major hurricane today?

Further, what does a projected continuing rise in sea level mean to a city whose highest point is 80 m above sea level? How much of one borough, Manhattan, could be underwater in the year 2100 due strictly to rising sea levels?

Location

Manhattan, New York, USA

Time to complete the lab

45 minutes

Prerequisites

Intermediate to advanced geographic information system (GIS) experience; knowledge of ArcGIS®
10.0 and Spatial Analyst extension.

Data used in this lab

- Data source: US Geological Survey national map server at
  `http://cumulus.cr.usgs.gov/webappcontent/neddownloadtool`
  `/NEDDownloadToolDMS.html` (unprojected file)
- Provided shapefile *Manh_outline* (the boundary for the county of New York) originally
  downloaded from the US Census Bureau at
  `http://www.census.gov/geo/www/cob/co2000.html`, the file was then projected to
  universal transverse Mercator (UTM) NAD 1983 Zone 18N and clipped to New York
  County (FIPS = '061')

Student activity

Imagine Hurricane Katrina striking New York City. The city is located in the vulnerable coastal zone
and has been in the path of powerful hurricanes before—on average, once every 75 years
(Naparstek 2005). In 1821, a major hurricane caused tremendous destruction in Manhattan. A
hurricane in 1893 removed the mile-long barrier Hog Island off the southern coast of the
Rockaways (a peninsula jutting into the ocean between Brooklyn and Long Island) while also razing
southern Brooklyn and Queens via a 10-meter (m) storm surge.

Currently, New York City is home to nearly 8.5 million people, nearly 1.6 million of whom live on
the island of Manhattan. The attack of September 11, 2001, on the World Trade Center accounted
for almost 3,000 lost lives and managed to stall the economy nationwide, if not globally. But are
there other, natural catastrophes looming that could eclipse that loss of life and property? Several
years after Hurricane Katrina, New Orleans, with a population of 1.2 million, still has not fully
recovered from its devastating impacts.

Global climate change has raised sea levels worldwide during the twentieth century at a rate of
roughly 1.7 millimeters (mm) per year (Church and White 2006), a trend that will continue for
many more decades, as it is essentially unstoppable. More alarming, the rate of sea level rise is
accelerating. Recent satellite data shows sea level rise at an annual rate of 3.19 mm since 1993
(`http://climate.nasa.gov/keyIndicators/`).

Sea-level rise is caused by three major factors:

- *Total ocean water volume*—Ocean volume increases as water currently locked up in
  frozen soils and land glaciers melts and flows into the ocean.

- *Ocean temperature*—Warmer water expands, so a warmer ocean will require more space than a cooler ocean. Ocean temperature, in turn, is a function of atmospheric greenhouse gas concentrations, as well as how well the ecosphere can remove greenhouse gases from the atmosphere.
- *Sinking coastlines*—Land can sink for a variety of reasons. For example, the Louisiana coastline is sinking due to subsidence of soft marsh soils combined with coastal erosion. This process is accelerated by resource extraction and the removal of wetlands. Melting land glaciers cause rebounding of the land mass, which can lead to a sinking on the other side of the geologic plate, as is happening along the northern coast of central Europe as Scandinavia is lifting.

Global climate change is increasing the vulnerability of coastal areas to flooding and intense storms. While impacts will vary regionally, global rise of sea level is expected to contribute to increased coastal inundation, erosion, and ecosystem losses and will be accompanied by a further rise in sea surface temperatures of up to 3°C, an intensification of tropical and extratropical cyclones (storms), larger extreme waves and storm surges, altered precipitation and runoff, and ocean acidification (IPCC 2007).

According to the IPCC 2007, global sea level rise relative to 1980–1999 will range from 0.28 m to 0.43 m by the end of the twenty-first century depending on future greenhouse gas concentrations.

Storms are the result of unstable atmospheric conditions. A general rule is that warmer air and warmer oceans contain more energy and are thus more likely to form violent storms. This leads many scientists to caution that continued global warming accompanied by ocean warming seems to be responsible for an increase in more severe storms observed in the Atlantic Ocean during the past 30 years. However, the data record is not long enough and contains a lot of natural variability, which is why scientists are divided on this issue (for example, Environmental Protection Agency, Intergovernmental Panel on Climate Change, and World Meteorological Organization cited at `http://www.epa.gov/climatechange/science/recentpsc.html#ref`).

Project overview

This exercise determines the area of Manhattan subject to flooding under two sea level rise scenarios (best case and worst case) and a major hurricane. The specific questions you want to answer with this project are as follows:

Question 1: *How much of Manhattan will be inundated by rising sea levels by 2100?*

Question 2: *How much of Manhattan is at risk of a 10 m (30-foot) storm surge?*

To answer your research questions, you need to determine land elevations, land areas inundated under projected sea level rise, and land areas at risk of flooding by a 10 m storm surge.

Land elevations can easily be derived from a digital elevation model (DEM), which is available for free from the United States Geological Survey (USGS). The problem with these DEMs are their lack of accuracy. Depending on data product, vertical accuracy can be off by several meters, which

would render the data useless for this exercise. However, in the absence of better data, you are going to assume that the accuracy for low-relief Manhattan is sufficient for this application. This exercise will use the National Elevation Dataset (NED) at 1-arc-second resolution, which approximates 30 m pixel sizes (each cell is 30 by 30 m). Higher resolution is available (1/3 arc second and for some areas even 1/9 arc second), but they require too much time to download and process.

The exact degree of sea level rise by 2100 is unclear, but two extreme ends of the prediction scale suggest sea level rise of 0.28 m to 0.43 m with a range of 0.19 m to 0.58 m depending on statistical confidence interval and scenario (IPCC 2007 AR4 WGII Ch. 6, Table 6.3, p. 323; also from Meehl et al. 2007). If recently observed increases in ice discharge from the Greenland and Antarctic ice sheets are considered, this would add another 0.05 m to 0.11 m rise for the worst-case scenario (IPCC 2007; Meehl et al. 2007). You will choose the two most extreme values for your projection: 0.28 m and 1.12 m (0.43 m + 0.58 m margin of error + 0.11 m rise due to glacial melt).

Since a 10 m storm surge has been observed during a hurricane in the past, you will use this value.

This project consists of three parts representing the datasets you need to process: (1) land elevations, (2) flooded areas due to two scenarios for sea level rise, and (3) flooded areas due to a storm surge.

COLLECT AND PROCESS DATA

LAND ELEVATIONS

1   Go to the USGS National Seamless Map Server at `http://cumulus.cr.usgs.gov/webappcontent/neddownloadtool /NEDDownloadToolDMS.html`. If you are having problems downloading data, use the two files provided with this exercise, and skip to Step 6.

2   Check to define the area of interest by state and/or county and select *New York State* and *New York County*. Click *Submit*.

   This data request will tell you the coordinates for your area of interest:

   Top = 40.8785777730601   Bottom = 40.7002827728948
   Left = -74.0270157323376   Right = -73.9104847322291

   It will also provide several files.

3   Choose the two files at 1-arc-second resolution in ArcGrid™ format and download them.

   If you have problems with downloading, make sure your pop-up blocker is turned off. Depending on your Internet connection, this should take about a minute per file.

4   The downloaded folder contains metadata information, a shapefile, an info folder, and the actual elevation grid (e.g., *grdn41w074_1* in the *n41w074* folder). In Windows 7, you can simply double-click each layer until you reach the two grids which are stored in folders (*grdn41w075_1* and *grdn41w074_1)*. If double-clicking does not work, you need to unzip the two downloaded files.

Note: a grid is a raster dataset based on the ArcInfo raster data model which must be in a *workspace* that has an *info* subfolder.

5   Create a subfolder under your c:/student folder and call it *SeaLevel*. Copy the folders named *grdn41075_1* and *grdn41074_1* to this *SeaLevel* folder using either Windows Explorer or ArcCatalog .

6   Go into ArcGIS and make sure your Spatial Analyst extension is checked (*Customize » Extensions*).

7   Add the *Manh_outline* shapefile to your map and then add the two grids (*grdn41075_1* and *grdn41074_1)*. This sets your Layers data frame properties to UTM meters.

  If you add the data to your map in the reverse order, you can change the projection manually to UTM under *Layers » Properties*.

  When you add both grids to your map, you see that *grdn41w075_1* ranges from -18.625 to 401.459 m in elevation, while *grdn41w074_1* ranges from -2.454 to 167.410 m in elevation and they do not appear to match seamlessly; you will fix this later. These two grids have floating point values (their values have decimal places) in latitude-longitude.

  > If your grids show a value range from -3.40282e+038 to 3.40282e+038, you need to create the statistics first. Right-click the first grid, go to *Properties » Symbology*, select Classified, and agree to create a histogram. Repeat this for the second grid.

  First, you need to project the elevation data to match the *Manh_outline* layer*.*

8   Go to *ArcToolbox » Data Management Tools » Projections and Transformations » Raster » Project Raster*.

9   Select the *grdn41w075_1* layer*.* The input coordinate system should default to *GCS_North_American_1983*.

10   Select your *SeaLevel* folder as the output folder and name the output grid *n41w75_utm*.

11   For the output coordinate system, import the coordinate information from the *Manh_outline* layer, set the output cell size to *30 m* and use *bilinear interpolation* as the *Resampling Technique*. Click *OK*.

12 Repeat this for the other grid and name it *n41w74_utm*

Click *ArcToolbox » Data Management Tools » Raster » Raster Processing » Clip*. Use the newly

If you are having problems handling the data size, you can also clip the grid before projecting it.

Next, the two grids (*n41w74_utm* and *n41w75_utm*) need to be clipped to the outline of Manhattan, which will reduce the overall data you have to view and process.

13 Click *ArcToolbox » Data Management Tools » Raster » Raster Processing » Clip*. Use the newly projected grids (*n41w74_utm* and *n41w75_utm*) one at a time as the input raster and the *Manh_outline layer* for the output extent, and check *Use Input Features for Clipping Geometry*.

14 Name the new grids *n41w75_utm_c* and *n41w74_utm_c*, respectively.

Now you are going to merge the two grids into one manageable grid.

15 Go to *ArcToolbox » Data Management Tools » Raster » Raster Dataset » Mosaic To New Raster*.

16 Add your two projected and clipped grids from the previous step as inputs (*n41w75_utm_c* and *n41w74_utm_c*).

17 Set the output location to an existing folder, name the new grid *dem* (no extension), set the number of bands to *1*, and keep the rest as default.
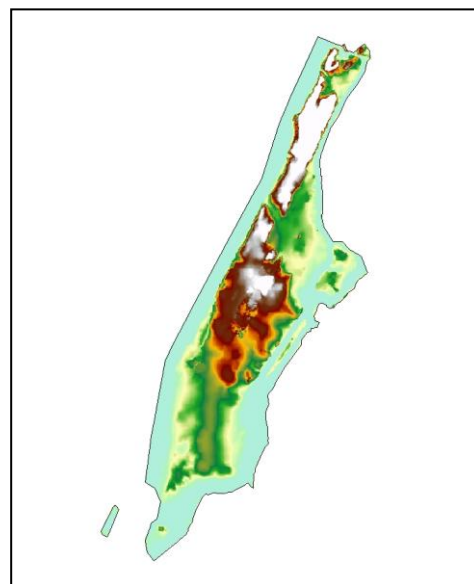

Figure 1. Elevations for Manhattan.

18 If you forgot to set the cell size to 30 m earlier, you can do that here as well.

You might need to turn off all layers, then check the *manh_outline* layer and the *dem* layer to make them visible; then zoom to the *dem* layer. Your resulting image should be clipped to the outline of the Manhattan layer, along with a little 'island' to its southwest, and range in elevation from -0.168574 to 79.6759 m. If you set the cell size to 30 in step 11, your values might be slightly different; the same applies if you clipped the grid before projecting it or forgot to check *bilinear interpolation* for the Resampling Technique. Don't worry about it if your values are off merely by a few decimals.

19 Go to the *dem*'s layer properties, click the *Symbology* tab, right-click the color ramp box, uncheck *Graphic View*, and select *Elevation #1* for your color scheme.

With the border of Manhattan displayed as a black outline only, your resultant image should now look like figure 1. Note that the census boundary includes land underwater.

Now that you have your base elevation raster dataset, you need to identify areas that are affected by each of your scenarios. To be specific, you need to know

- Which land is already underwater (elevation ≤ 0 m)
- Which areas will flood under your best-case scenario (BCS) (≤ 0.28 m)
- Which will flood under the worst-case scenario (WCS) (≤ 1.12 m)
- Which will flood under an extreme storm surge (≤ 10 m)
- Which is safe from flooding under all scenarios (> 10 m)

To tag areas that fall under each of these conditions, you will assign unique identifiers so that you can merge all grids in the final processing step: best-case scenario (value = 1), worst-case scenario (value = 3), flooded by storm surge (value = 5), area currently underwater (value = 0), and land currently above sea level (value = 7). Odd numbers are chosen so that their sums will not add up to any of the individual numbers (this should become clearer when evaluating the data in Table 1).

FLOODING FROM SEA LEVEL RISE

First, you want to separate area currently underwater (which will not count toward area lost to rising sea level) from area currently above water and thus potentially at risk from sea level rise. You will accomplish this using a conditional statement.

1   Go to *ArcToolbox » Spatial Analyst Tools » Conditional » Con*.

2   Select the *dem* layer that resulted from the *Mosaic To New Raster* geoprocessing tool, as your input conditional raster, use the expression *"VALUE" <= 0*, and use *0* as *the input true raster or constant value* and *7* as the *input false raster or constant value*.

3   Name the output raster (or grid) *land.*

If elevation is less than or equal to 0, cell value is set to *0* (water); if elevation is not greater than 0, the value is set to *7* (land). Check it. The table of contents should list only two possible values for your new grid (or layer): *0* and *7*.

4   Right-click the *land* layer in the table of contents, choose *Properties*, and click the *Symbology* tab. Change the color for value *0* to blue and value *7* to green. Your result should look similar to figure 2.

Figure 2. Elevations for Manhattan, using blue to represent all values below current sea level and green for all areas above.

5   Open *land*'s attribute table. It should show 69,530 cells with a value of *7* (land) and 25,683 cells with a value of *0* (currently underwater).
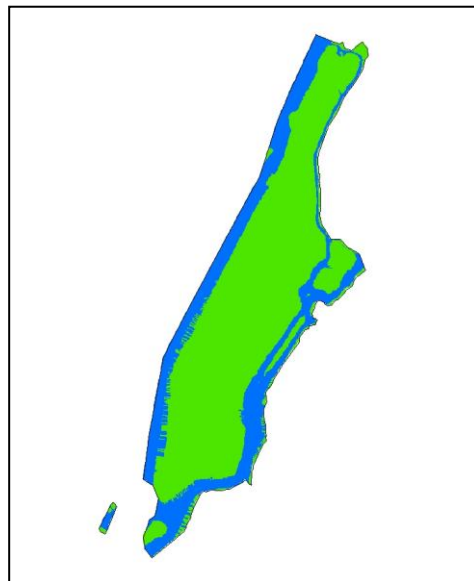
Next, identify all areas flooded under the best-case scenario.

6   Using the *dem* layer as your input conditional raster again, your conditional expression must
       now read *"VALUE" > 0 and "VALUE" <= 0.28*.

7   Use *1* as *input true raster* and *0* as *input false raster*.

8   Name the output raster (or grid) *flood_BCS*.

       The result should show a light ring of cells around the island that are subject to flooding. The
       attribute table should indicate that 91,675 cells have the value *0* and 3,538 cells have the
       value *1*; that is, they meet the condition you were looking for and will flood under the best-case
       scenario.

9   Repeat the last three steps for the worst-case scenario using *"VALUE" > 0 and "VALUE" < = 1.12* in
       the conditional expression (see step 6 above), assign *3* to all true values, and *0* to input false
       raster (see step 7 above). Name the output grid *flood_WCS*. The attribute table should indicate
       88,874 cells with a value of *0* and 6,339 cells with a value of *3*.

STORM SURGE

Now add the 10 m storm surge.

1   Use the same input raster (*dem*) and the conditional
       statement *"VALUE" > 0 and "VALUE" <= 10,* but assign *5* to
       all areas meeting the condition, *0* to *input false raster*,
       and name the grid *flood_storm*.

       Your resultant attribute table for the *flood_storm* layer
       should show 37,102 cells meeting the criteria to flood
       under a 10 m storm surge (*value = 5*).

2   Overlay the *flood_storm* layer with the original *dem* in
       the *Elevation #1* color scheme. Set the *0* value of
       flood_storm to *no color* and change the cells with a value
       of *5* to *red* (figure 3).

You have now created all the rasters or layers necessary to
determine the answer to your geographic problem.

Figure 3. The color red indicates all land areas
currently above water that are subject to
flooding under a 10 m storm surge.

Since the area of interest under each of your scenarios has a
unique identifier, you can add all the rasters or layers
together into one final grid using the Raster Calculator
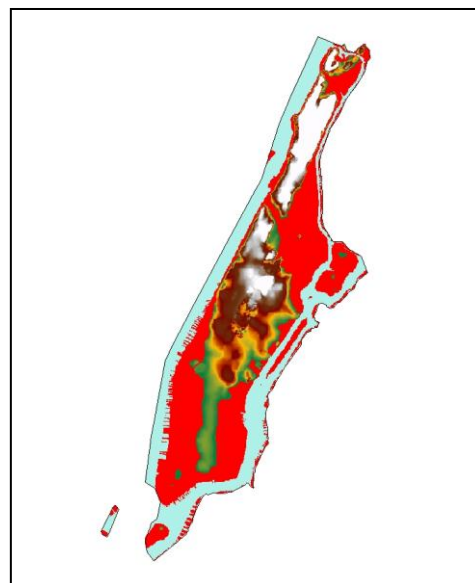geoprocessing tool. The only thing to keep in mind now is simple math, since all areas that flood

during the WCS also flood during the BCS; thus, the values for these cells would become *3 + 1 = 4*. Likewise, areas that flood under a 10 m storm surge, will of course flood during either sea-level rise scenario.

3   Go to *Spatial Analyst Tools » Map Algebra » Raster Calculator* and add all your flood grids together so that the expression reads

```
"flood_storm" + "flood_BCS" + "flood_WCS" + "land".
```

4   Save the output raster as *dem_final.*

Your result should match Table 1.

VALUE	COUNT
0	25,683
7	32,428
12	30,763
15	2,801
16	3,538

Table 1: values and count for the
final raster layer or grid created during this exercise

What do the cell values mean? Based on your unique identifiers, you can deduce what each cell value represents. A value of *0* is land that is currently underwater. A value of *7* represents dry land for all scenarios. A value of *12* is the sum of 7 + 5, thus current land (*value = 7*) that floods only under a storm surge (*value = 5*). A value of *15* is the combination of 7 + 5 + 3, thus land that floods under the worst-case scenario as well. Finally, a value of *16* represents current land that will flood under all three scenarios (7 + 5 + 3 + 1).

The results should resemble figure 4 (if you edit the colors and descriptions).

5   Export your attribute table for the *dem_final* layer into e.g. excel (as dbf) and you can then calculate area to answer your geographic questions. Since our cell sizes were 30 m by 30 m, each cell extends over 900 m^2. Thus, multiply the cell count by 900 to get m^2 which you can then divide by 1000 x 1000 to yield km^2. Current land area is given in the *land* grid (count = 69,530) or is the sum of all rows with values > 0 in table 1. Use that to calculate current land area endangered by flooding and your results should match table 2.
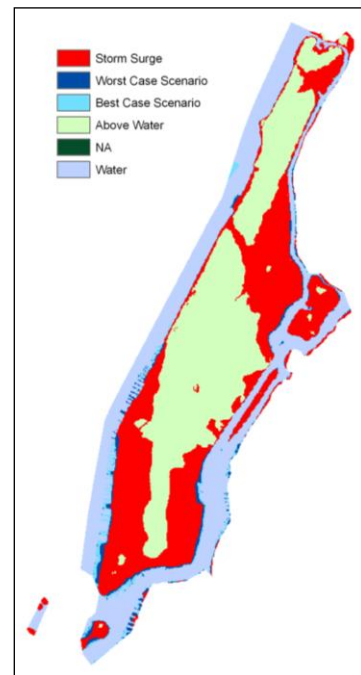

Figure 4: Areas subject to flooding due to a hurricane storm surge or two climate change scenarios.

Scenario	Value	Number of cells	Area (one cell = 900 m^2)	Percentage of current land area
Land currently underwater	0	25,683	23.11 km^2	N/A
Land always above water	7	32,428	29.19 km^2	46.64%
Land flooded by a storm surge	12	30,763	27.69 km^2	44.24%
Land flooded under the best-case scenario	15	2,801	2.52 km^2	4.03%
Land flooded under the worst-case scenario	16	3,538	3.18 km^2	5.09%

Table 2: Summary of land currently above water and land inundated by sea level rise under the best-case scenario, the worst-case scenario, and a storm surge

You are now able to answer your research questions:

Question 1: *How much of the current land area of Manhattan will be inundated by rising sea levels by 2100?*

Answer: As calculated in table 2, 4.03 percent of Manhattan, or roughly 2.52 square kilometers (km^2) will be inundated under the best-case scenario for sea level rise due to climate change, compared to 5.09 percent, or 3.18 km^2, under the worst-case scenario.

Question 2: *How much of Manhattan will be inundated by a 10 m (30-foot) storm surge?*

Answer: A 10 m storm surge as caused by a hurricane will inundate 44.24 percent of Manhattan, or roughly 27.69 km^2, and pose a very serious threat.

How might you go about answering the next important questions: How many people are at risk from a storm surge? and How many will be at risk from rising sea levels in the future?

You can also repeat this exercise using data for the other boroughs of New York City or any other coastal US city.

References

Church, J. A., and N. J. White. "A 20th Century Acceleration in Global Sea Level Rise." *Geophys. Res. Lett.* 33 (2006): L01602, doi:10.1029/2005GL024826.

Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe. "Coastal Systems and Low-Lying Areas," in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the*

Intergovernmental Panel on Climate Change, edited by Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, 315–356. Cambridge, UK: Cambridge University Press, 2007. (The entire IPCC 2007 report can be viewed and downloaded online. Most helpful was the report by working group II, *Impacts, Adaptation and Vulnerability*.) (`http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html`).

Meehl, G. A., et al. "Global Climate Projections," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge, UK, and New York, NY: Cambridge University Press, 2007.

Naparstek, A. (2005) Storm Tracker. Available from `http://nymag.com/nymetro/news/people/columns/intelligencer/12908/`.

For information on sinking land masses, do a Google search for *Louisiana sinking*, and you will get several easily readable articles.

For more information on hurricanes and the consequences of rising ocean temperatures, see `http://www.ucsusa.org/global_warming/science_and_impacts/science/hurricanes-and-climate-change.html`.

Another interesting site is `http://flood.firetree.net/`, which allows you to set sea level rise from 0 to 60 m for the entire planet (click *North America* at the top).

Climate change information is available at lots of sites; browse the official ones by NASA, NOAA, USGS, EPA, Union of Concerned Scientists, and IPCC.

Credits

Sources of supplied data

grdn41w074_1.lyr, data courtesy of the U.S. Geological Survey, Department of the Interior/USGS
grdn41w075_1.lyr, data courtesy of the U.S. Geological Survey, Department of the Interior/USGS

Instructor resources

Updates for 2013

This exercise was revised extensively from the previous version:

- The DEMs used for this exercise seemed to be no longer available from the USGS sites so they are now included.
- Bilinear interpolation technique is now used for the conversions which changes all the results from the previous version of this exercise.
- Tables 1 and 2 were revised completely to reflect the new results and to be more helpful.

Additional information

This exercise is one of three complementary exercises. *Population Mapping and Modeling for* Manhattan estimates the current population of Manhattan and the population for the year 2100. *Impacts of Sea Level Rise and Storms on Manhattan* estimates the land area threatened to flood from climate change-induced sea level rise as well as a hurricane-induced storm surge. *People of Manhattan at Risk* estimates the number of people at risk from hurricane-induced floods and sea level rise now and in 2100.