Calculation Example: Impacts of Coastal Flooding on Stormwater Infrastructure – City of Charleston, South Carolina

Data Summary and Assumptions

Introduction

The example will demonstrate the method for analyzing design scenarios described in the Analyze Stormwater Systems section. The example first defines the scenarios to be assessed, the location of study, important properties of the outfall location such as elevation, and various other modeling parameters. Then the example demonstrates computing each of the scenarios using both the basic and intermediate methods.

For this case study, we focus on the Southern Peninsula of Charleston, South Carolina. The peninsula is highly urbanized with many historic structures. Several outfalls spread around the perimeter of the peninsula serve to drain stormwater from the central portions of the city. We will focus on the Calhoun West service area. This area includes the Marina service area, which is 46.6 acres and drains through the 4-foot diameter Marina Lake outfall culvert to the southwestern side of the peninsula near the Charleston City Marina, and the Calhoun Street West service area, which is 275.6 acres and drains through a 6 feet by 4 feet closed rectangular structure to the southwestern side of the peninsula near the James Island Expressway bridge.

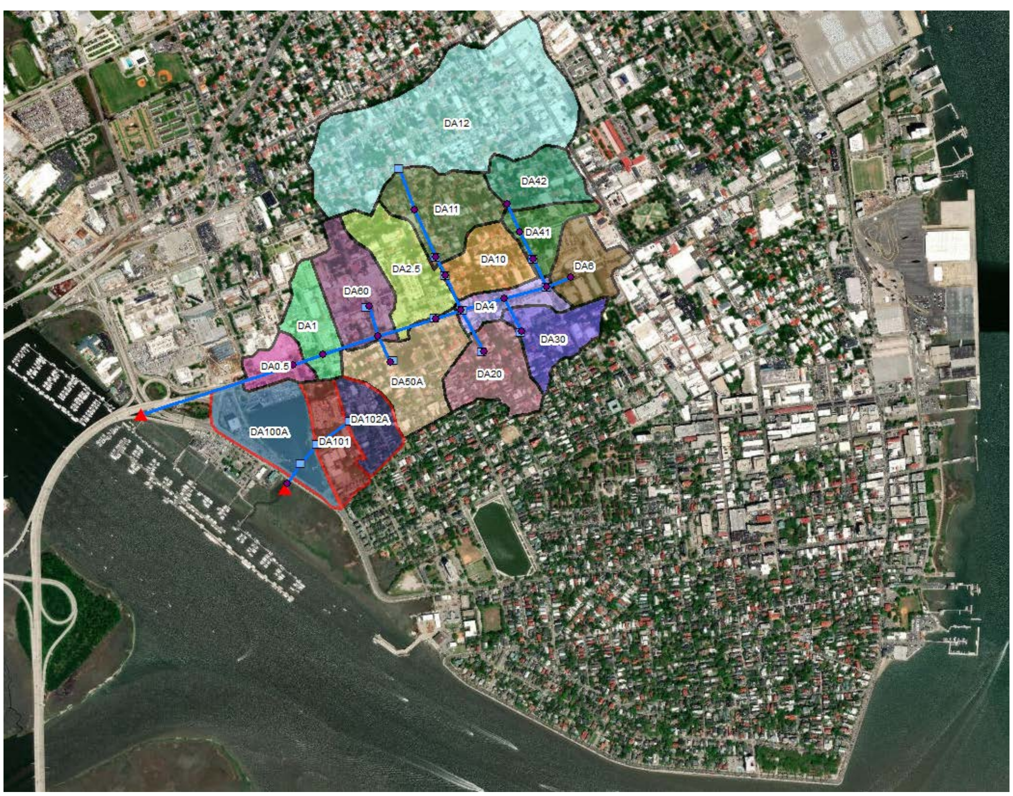


Figure 1: The example will focus on the Calhoun West service area, which drains to two outfalls on the southwestern side of the Charleston peninsula.

Notes about this analysis:

- *The analysis will focus on the Calhoun West service area alone, and assumes that stormwater generated within this area is entirely drained through the Calhoun Street West and Marina systems.*
    - *An existing Environmental Protection Agency (EPA) Stormwater Management Model (SWMM) for the Calhoun Street West and Marina systems is utilized in this analysis. Note that if you do not have a similar model, a basic analysis is still possible if you have a general knowledge of your stormwater system and can sketch the service areas draining to each outfall.*
- *To do a comprehensive analysis of the city, you would need to repeat the process laid out below for all services areas on the peninsula and surrounding coastal areas within Charleston.*

Defining Design Scenarios and Design Flood Elevations

Four scenarios representing combined effects (coastal and stormwater) are considered here. The scenarios were selected to represent the range of extreme combined flooding conditions that are likely to occur at this location. The scenarios range from conditions currently occurring to conditions that are only likely to occur in the future. A 25-year design life is assumed for these combined-effects design scenarios.

<u>Scenario 1</u>

Scenario 1 is defined to look at the effects of extremely high tides—the so-called king tides—on present-day Charleston. We use the highest astronomical tide (HAT) metric as a proxy for king tides. HAT is a metric reported in NOAA's tide gage database, which is available online for gages around the country. In the scenario, we assume

- *Current sea level*
- *Highest astronomical high tide (HAT)*
- *Seasonal and regional tide variations are at peak*
- *No tidal backflow valves are installed*

<u>Scenario 2</u>

In scenario 2, we look to the future. We'll assume mean high water as the tide level, as we are interested in everyday conditions. We'll forecast a situation 25 years from present (2043), where the sea level has risen and the stormwater system is hit with a 10-year storm. The system in Charleston was originally designed for the 10-year storm, so the results of this scenario will isolate for us the effect of 25 years of sea level rise (SLR). Finally, we'll include an adaptation action—tidal backflow valves—which will allow the system to continue to operate as tides rise above the outfall elevations. Scenario 2 assumptions:

- *A 25-year design life*
- *Design scenario of 25-year (2043) SLR*

- *Mean high water*
- *Seasonal and regional tide variations are at peak*
- *A 10-year inland precipitation event (current stormwater design storm).*
- *Tidal backflow valves are installed*

Scenario 3

In scenario 3, we're interested in the impact of sunny-day king-tide flooding in the future. Again, we look at 25 years from the present (2043) and include HAT to represent the king tide event. We'll assume backflow valves are present, since the City of Charleston is currently adding dozens of valves to its system and will have completely protected the system with them within a few years. Scenario 3 assumptions:

- *A 25-year design life*
- *Design scenario of 25-year SLR*
- *Highest astronomical high tide (HAT)*
- *Seasonal and regional tide variations are at peak*
- *Tidal backflow valves are installed*

Scenario 4

In scenario 4, we look at the impact of storm surge. We assume 25 years of SLR (2043), plus a 25-year storm surge. To evaluate the worst case, we use the extreme SLR forecast from NOAA, which is significantly higher in 2043 than the intermediate forecast and which was used in scenarios 1, 2, and 3. We also include seasonal and geographic variations, and a coincident 2-year, 24-hour rain event. Again, we assume tidal backflow valves protect the system. Scenario 4 assumptions:

- *A 25-year design life*
- *25-year SLR*
- *25-year storm surge elevation*
- *Seasonal and regional tide variations are at peak*
- *A coincident 2-year, 24-hour precipitation event due to storm*
- *Tidal backflow valves are installed*

Note: The 25-year storm surge could result from a hurricane or a strong non-tropical storm. The height of the storm surge itself is a function of the strength of the storm and the direction and speed in which it approaches Charleston.

Determine other modeling parameters that will be used throughout the analysis

- **Storm drain system outfall locations and elevations**
  Location = South side of peninsula
  *Outfall pipe invert = **-2.95 feet,** North American Vertical Datum of 1988 (NAVD88) – based on data in the SWMM model for the Calhoun West service area*

Note: If you don't have a SWMM model, you can find the invert elevation from as-built plans you may have for your system, or by conducting a simple survey.

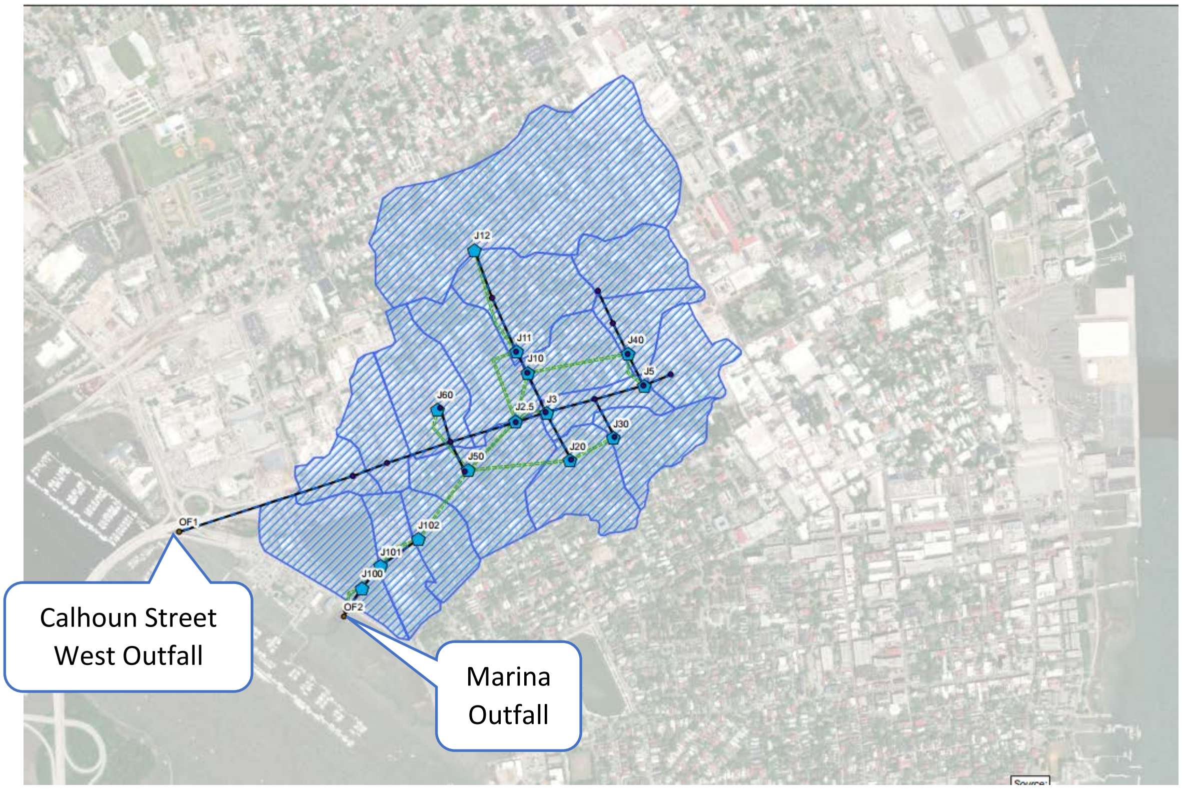


Figure 2: Existing SWMM model provides the location of outfalls for Charleston's West Calhoun service area.

- **Coastal flood overtopping locations and elevations**
  Location = Lockwood Drive along southwestern side of peninsula
  *Average grade elevation = **8.7 feet**, NAVD88 – determined from a recent survey of the area*
  *Length of peninsula in Calhoun West service area along lowest grade elevation = **1600 feet** (this is the length of a weir that would be formed when overtopping occurs)*
  *Weir coefficient for computing storm surge overtopping rate = **2.65** (broad crested barrier wall)*

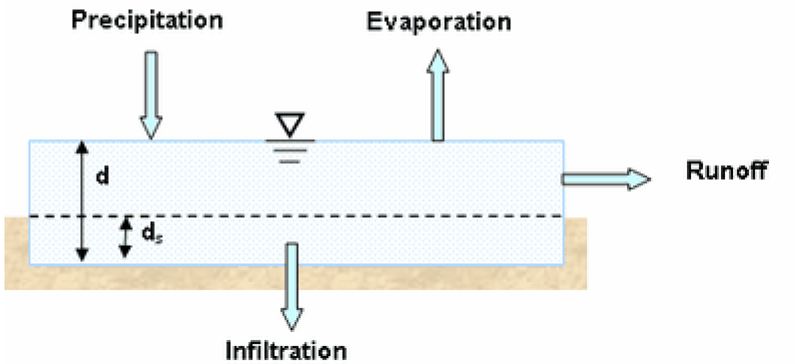
- **Determine rainfall-runoff parameters**

  In the basic analysis, the rainfall runoff is estimated using the rational formula, Q = CIA, where Q is the stormwater flow rate caused by rain at intensity, I, over an area A. The runoff coefficient, C, is determined by the type of land cover, where higher coefficients imply impervious areas such as inner cities and lower coefficients imply high degrees of perviousness such as rural areas.

  For the intermediate analysis, rainfall-runoff will be simulated using the existing EPA SWMM model for the Calhoun West service area, which also uses the Horton method on a sub-basin scale. The Horton method is summarized in the diagram below.

Surface Runoff

The conceptual view of surface runoff used by SWMM is illustrated in the figure below.



Each subcatchment surface is treated as a nonlinear reservoir. Inflow comes from precipitation and the runoff from any designated upstream subcatchments. Outflows consist of infiltration, evaporation, and surface runoff. The capacity of this "reservoir" is the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting, and interception. Surface runoff, **Q**, occurs only when the depth of water **d** in the "reservoir" exceeds the maximum depression storage, $\mathbf{d_s}$, in which case the outflow is given by Manning's equation. Depth of water over the subcatchment (**d**) is continuously updated with time by solving numerically a water balance equation over the subcatchment.

Figure 3: Rainfall runoff method used in the EPA SWMM model[1]

Rainfall Intensity (I)

Both analyses require rainfall intensities for *Charleston,* which can be found from the NOAA ATLAS 14 website at the link below.

2 year – 24 hour Rainfall Depth = 4.23 in/hr
10 year – 24 hour Rainfall Depth = 6.47 in/hr
25 year – 24 hour Rainfall Depth = 7.89 in/hr

https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=sc

Catchment Area (A)

For the basic calculation, it is sufficient to just get a single estimate of the entire service area. In an intermediate analysis, the catchment area is defined by the sub-basins that make up the total service area.

[1] **Citation:**
Rossman, L., and W. Huber. *Storm Water Management Model Reference Manual Volume I,Hydrology.* Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development. EPA/600/R-15/162A, 2015.

For the basic analysis, we use the City of Charleston's basin GIS layer, which the city makes available through its online GIS portal, to determine that the area is **322.2 acres**. This GIS layer was created when Charleston used a LIDAR-flown digital elevation model (DEM) as a basis for defining drainage areas.

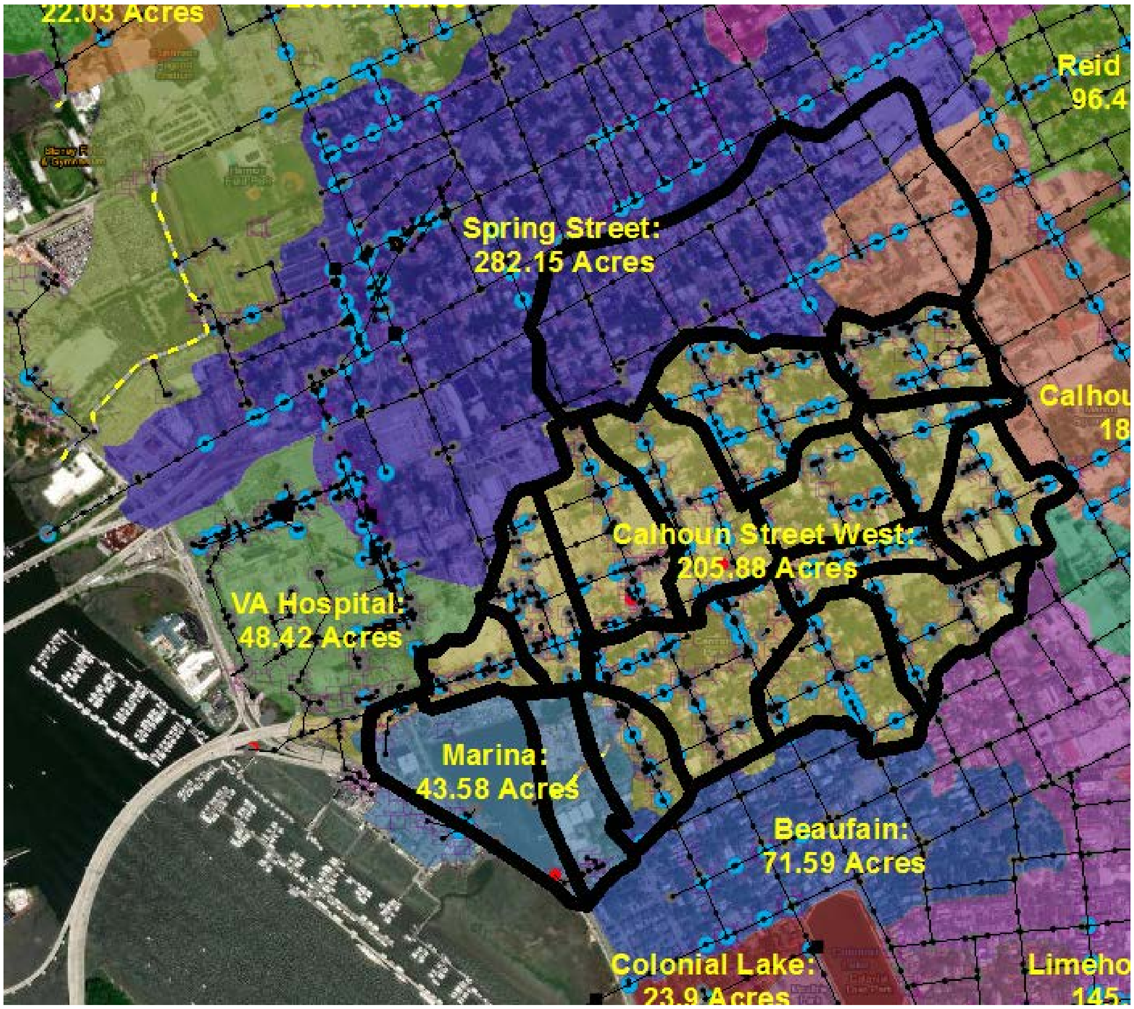


Figure 4: The catchment for the Calhoun Street West service area

Knowledge of the Stormwater System is important

Note that the 322.2-acre area is larger than the catchment area for Calhoun Street West, which is 205.88 acres (see figure 4). We only know this through some knowledge of the stormwater system, which reveals that the service area consists of the catchment area for Calhoun Street West (205 acres), plus parts of the Marina, the Calhoun Street East, and the Spring Street catchments (see figure 3 below).

A disparity between catchment area and service area is common, and is caused by the stormwater system transferring runoff from one catchment to another through pipe connections and pumping. In general, detailed knowledge of your stormwater system and its operation are essential in correctly defining the service area for both the basic and intermediate methods.

Intermediate Method

For the intermediate method, more detail is required. Figure 5 below shows some of the data required. Typically, a model like EPA SWMM is used. It simulates the system running over a period of several days with the concurrent events included in the design scenario. For this case study, the simulation period is 72 hours. Data needed include the following:

- GIS sub-basins that drain to specific intakes in the underground stormwater system.
- GIS-based estimates of sub-basin runoff coefficient for each sub-basin, derived from land use and soil GIS layers.
- GIS Links – the pipes, channels, etc. that transport water.
- GIS Nodes – manholes, intakes, outfalls, pumps, etc. that connect links.
- Tidal time series – this is an hour-by-hour estimate of the tide level over the period of the model run. This is where we can incorporate the coastal total water level developed in step 1 as the high point of the tide over the simulation period.
- Rainfall time series – this is an hour-by-hour rain time series, which can range from a constant intensity, to a more realistic event that varies with time. In the case of scenario 1, where this is no rain event, we set the rain to zero over the 72 hours.

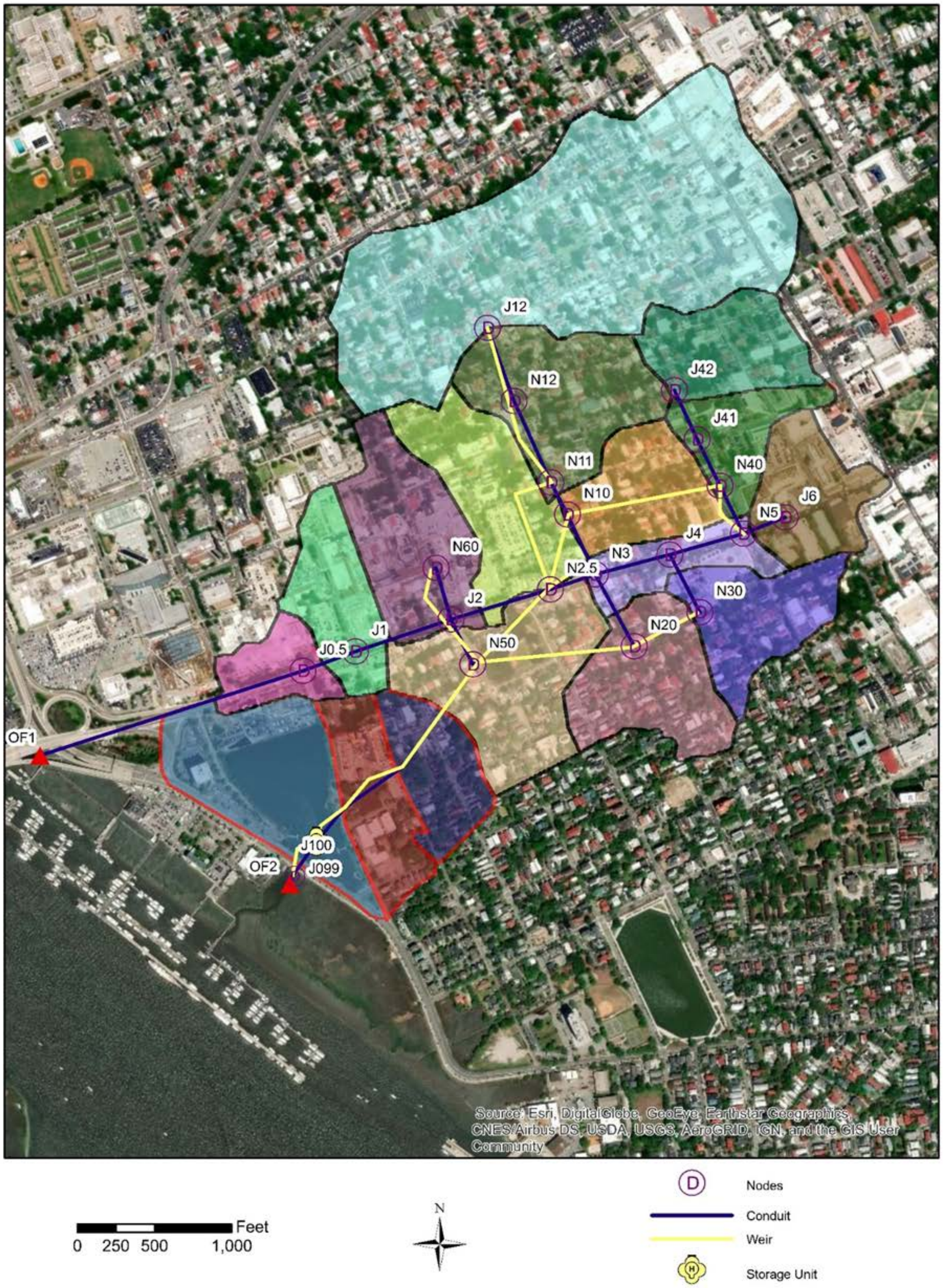


Figure 5: Stormwater system used in intermediate method model. The system includes sub-basins, intakes, links (pipes), and nodes (manholes, intakes, outfalls, pumps, etc.).

With the scenarios defined and the modeling parameters found, we are ready to assess each scenario using the five-step process outlined in the tool.

Calculation Steps

SCENARIO 1 – CURRENT SEA LEVEL + HIGHEST ASTRONOMICAL HIGH TIDE (HAT) + SEASONAL VARIATIONS; TIDAL BACKFLOW VALVE **NOT** PRESENT

Scenario 1 is defined to look at the effects of extremely high tides—the so-called king tides—on present-day Charleston. We use the highest astronomical tide metric as a proxy for king tides.

Step 1: Compute Total Water Level at the Coastline

Step 1 is the same for the basic and intermediate methods, as it consists of estimating the ocean-side coastal total water level.

a. *Estimate current mean higher high water (MHHW) elevation at location:*

The table below is provided on the NOAA station page for the Charleston, South Carolina, tide gage (station number 8665530). Values in this table can be used to calculate the conversion factor between the various datums. (Note: the epoch for data datums below is 1983-2001.)

Elevations on Mean Lower Low Water

Station: 8665530, Charleston, Cooper River Entrance, SC — **T.M.:** 0
Status: Accepted (Apr 17 2003) — **Epoch:** 1983-2001
Units: Meters — **Datum:** MLLW

Datum	Value	Description
MHHW	1.757	Mean Higher-High Water
MHW	1.648	Mean High Water
MTL	0.852	Mean Tide Level
MSL	0.890	Mean Sea Level
DTL	0.878	Mean Diurnal Tide Level
MLW	0.057	Mean Low Water
MLLW	0.000	Mean Lower-Low Water
NAVD88	0.957	North American Vertical Datum of 1988
STND	-0.843	Station Datum
GT	1.757	Great Diurnal Range
MN	1.591	Mean Range of Tide
DHQ	0.109	Mean Diurnal High Water Inequality
DLQ	0.057	Mean Diurnal Low Water Inequality
HWI	0.410	Greenwich High Water Interval (in hours)
LWI	6.630	Greenwich Low Water Interval (in hours)
Max Tide	3.817	Highest Observed Tide
Max Tide Date & Time	09/21/1989 23:42	Highest Observed Tide Date & Time
Min Tide	-1.245	Lowest Observed Tide
Min Tide Date & Time	03/13/1993 19:24	Lowest Observed Tide Date & Time
HAT	2.213	Highest Astronomical Tide
HAT Date & Time	10/16/1993 13:06	HAT Date and Time
LAT	-0.462	Lowest Astronomical Tide
LAT Date & Time	02/09/2001 07:24	LAT Date and Time

Figure 6: NOAA tide station table for the nearest tide gage

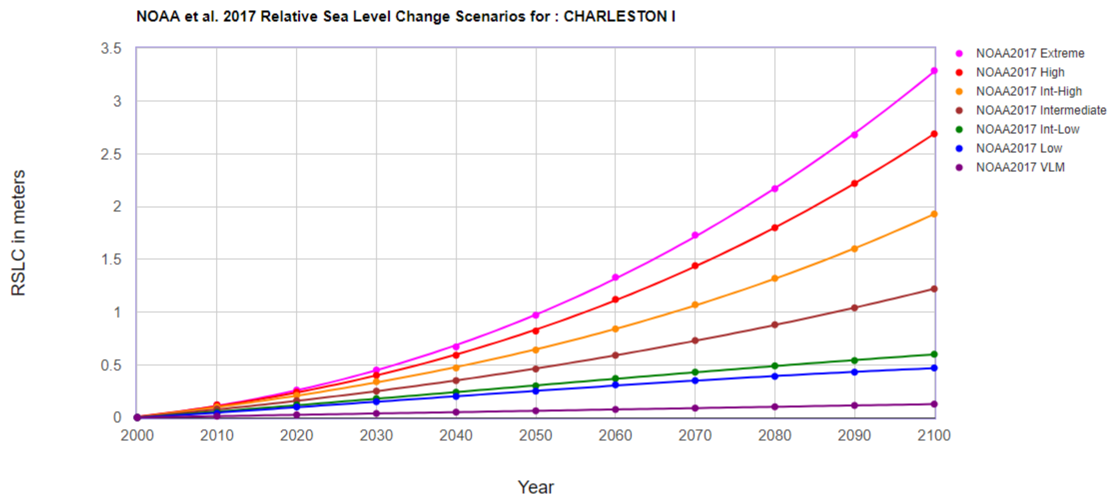
https://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=8665530&name=Charleston%2C+Cooper+River+Entrance&state=SC

b. Convert MHHW elevation to NAVD88:

Based on the table shown in part (a), subtract the NAVD88 value from the MHHW value to determine the datum conversion, i.e., 1.757 m minus 0.957 m = 0.8 m (x 3.281 ft/m = ***2.62 ft,*** *NAVD88)*

c. Calculate current sea level (2018):

The base year in this table is 2000. The current year (2018) sea level rise (assuming intermediate curve), from interpolation, is 0.14 m = ***0.46 ft***



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Enter Project Name
Scenarios for CHARLESTON I
NOAA2017 VLM: 0.00127 meters/yr
All values are expressed in meters

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.01	0.04	0.05	0.08	0.10	0.12	0.12
2020	0.03	0.10	0.12	0.16	0.21	0.24	0.26
2030	0.04	0.15	0.18	0.25	0.34	0.40	0.45
2040	0.05	0.20	0.24	0.35	0.47	0.59	0.67
2050	0.06	0.25	0.30	0.46	0.64	0.82	0.97
2060	0.08	0.31	0.37	0.59	0.84	1.12	1.33
2070	0.09	0.35	0.43	0.73	1.07	1.44	1.73
2080	0.10	0.39	0.49	0.88	1.32	1.80	2.17
2090	0.11	0.43	0.54	1.04	1.60	2.22	2.68
2100	0.13	0.47	0.60	1.22	1.93	2.69	3.29

http://www.corpsclimate.us/ccaceslcurves.cfm

Figure 7: NOAA SLR projections

d. Calculate highest astronomical high tide elevation (use tide gage statistics):

From table in part (a); HAT = 2.213m + MLLW or 0.456m + MHHW

*Convert to NAVD88 using the conversion factor from part (b); HAT= 0.456 m + MHHW (0.8 m) = 1.256 m NAVD88 (**4.12 ft NAVD88**)*

e. Consider adding wave setup if not already included:
Wave setup is not applicable because we are not considering a storm surge situation.

f. Consider need for adding variations in water levels due to regional oceanographic conditions:

*For stormwater analysis and design purposes, the greatest increase in coastal water levels associated with seasonal variations can be assumed. In this case, that's 0.153 m **(0.5 ft).***

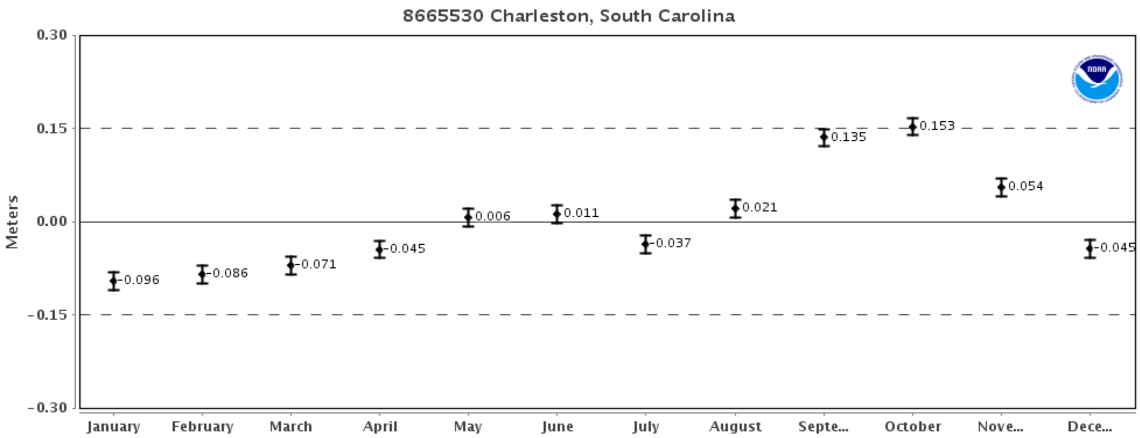

Figure 8: Variations in tide due to regional oceanographic conditions over the year at Charleston

https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8665530

g. Compute maximum stillwater elevation:
*Maximum Stillwater Elevation = SRL [answer to part (c)] + HAT [answer to part (d)] + + seasonal variations [answer to part (f)]; 0.46 ft + 4.12 ft NAVD88 + 0.5 ft = **5.08 ft NAVD88.***

h. Compute wave runup if applicable:
Multiply maximum stillwater elevation by a factor of 1.1 to account for runup
⇨ *Total water level = 1.1*5.08 = **5.59 ft NAVD88***

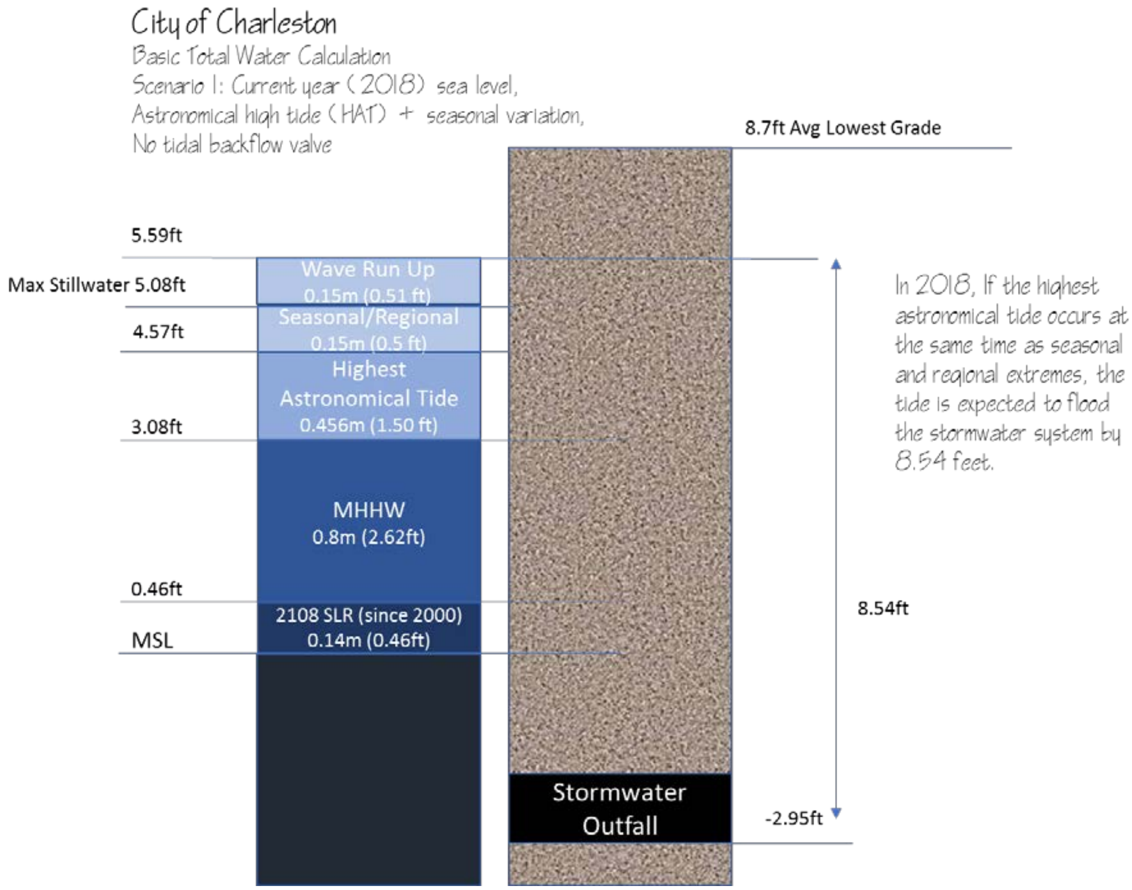

Figure 9: Coastal total water level for scenario 1. The results show that present-day sunny-day extreme tides overwhelm the stormwater system, but do not overtop the peninsula wall.

i. *Use computed coastal total water level at the coastline as a boundary condition at the outfall within the SWMM model:*

***Step 2*: Compute Overtopping Flow Using the Weir Equation (Q = CLH^1.5); where Q is the peak flow in cubic feet per second (cfs), C is the weir coefficient, L is the overtopping length in feet and H is the overtopping head in feet**

This step is not applicable because there is no overtopping.

***Step 3*: Compute Coincident Rainfall Runoff**

This step is not applicable because there is no rainfall event in scenario 1.

***Step 4*: Compute Flow from Other Sources**

This step is no applicable because we are not considering dam or levee breach.

***Step 5*: Compare Total Flow from Combined Events to Stormwater System Capacity**

Basic Method: *Because there are no tidal backflow valves, we can expect the system to be overwhelmed during high tide events. We also found that there is no overtopping. Given that we were focused on sunny-day conditions, we didn't include a rainfall event in the scenario, and so we expect no coincident flows into the stormwater system during the scenario. The flowchart below shows the path we've taken with our calculation.*

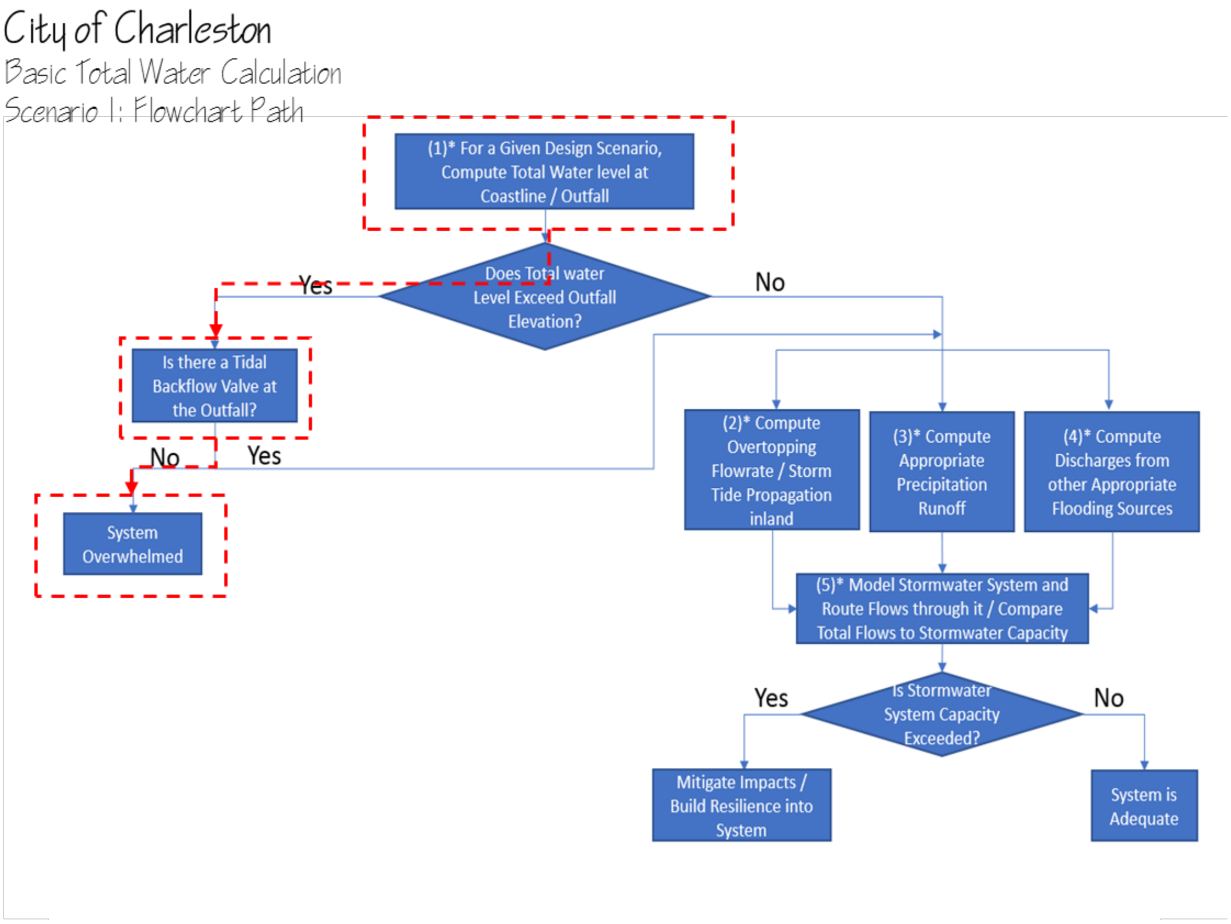

Figure 10: Flowchart showing calculation path for scenario 1

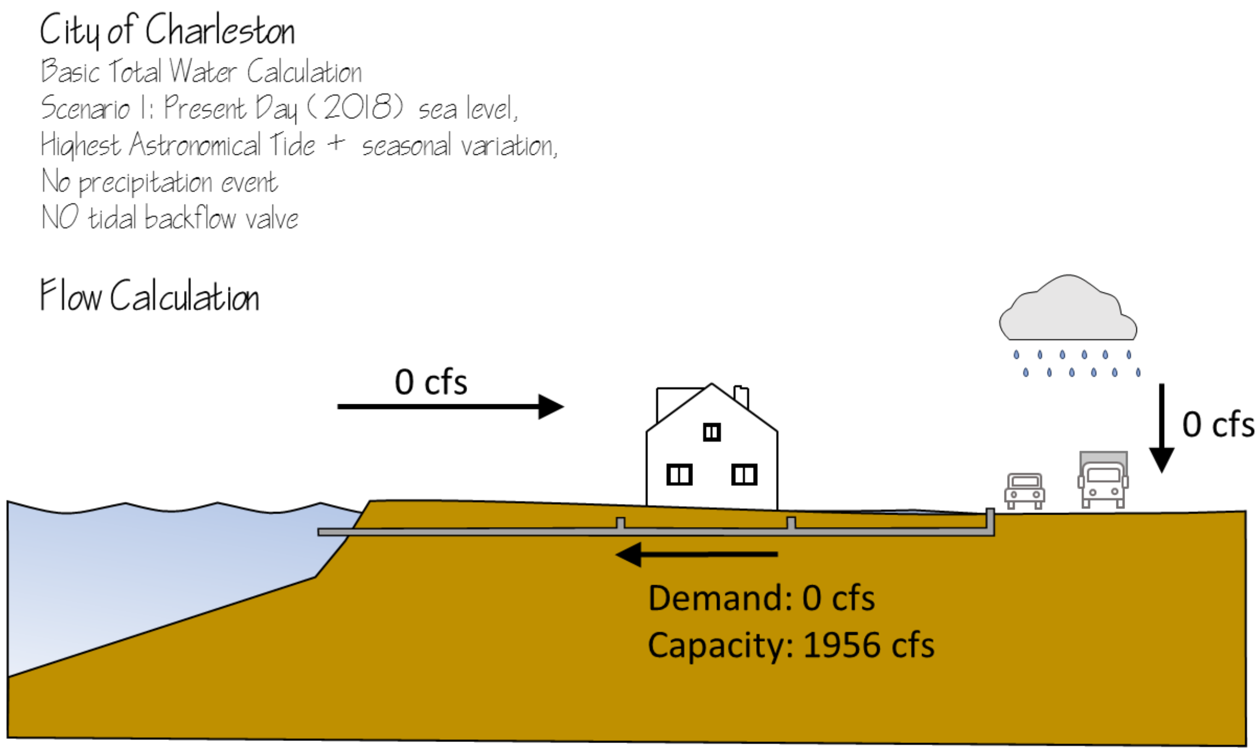

Figure 11: Schematic showing flows through the stormwater system for scenario 1. Note: refer to scenario 2 for an example of calculating the capacity flow of the stormwater system.

Intermediate Method*: The table below shows the results for scenario 1 from the EPA SWMM model. The model has been set to run over a period of 72 hours, and includes combined effects of tide and flood from rain. The tide has been set to peak at the maximum level derived in step 1.*

The first column lists the nodes in the system, as shown in the map in figure 5. The second column shows the hours of surcharge—when the pipes that connect to the node are completely full and running at pressure. The third column gives the hours the node is flooded—where the water level is above the level of the group. The fourth column gives the maximum depth of flooding.

As the table reveals, there is some flooding for this scenario in some of the sub-basins. For example, node N2.5 floods for 14 hours over the course of the 72-hour event.

EPA SWMM Model Results for Scenario 1

	Hours Surcharged	Hours Flooded	Maximum Ponded Depth (Hr)
Node	Scenario 1	Scenario 1	Scenario 1
J0.5	16.01	6	0.469
J1	12.1	6.49	0.497
J2	39.77	4.85	0.11
J4	20.62		

J41			
J42			
J6	18		
N10	19.62	16.24	0.516
N11	19.05	15.1	0.365
N12	16.83	13.93	0.27
N2.5	22.79	14.01	0.31
N20	19.38		
N3	20.89		
N30	18.81		
N40			
N5			
N50	43.3	43.11	1.041
N60	24.84	15.84	0.516
J12			

Basic vs. Intermediate: *This result illustrates the value of the intermediate method relative to the basic. If you'll remember, the basic analysis could only be used to conclude that that system would be overwhelmed and that no overtopping would occur, but it didn't tell us if sunny-day flooding would occur, where it would be, and how severe it would be. The intermediate analysis goes into greater detail, estimating that even with today's conditions, sunny-day flooding is a concern. In our interview with the city engineer of Charleston, these concerns were corroborated.*

SCENARIO 2 – 25-YR SLR + MEAN HIGH WATER + SEASONAL VARIATIONS + 10-YR PRECIPITATION EVENT; ASSUME TIDAL BACKFLOW VALVE IS PRESENT

In scenario 2, we look to the future. We'll assume mean high water as the tide level, as we are interested in everyday conditions. We'll forecast a situation 25 years from the present (2043), where the sea level has risen and the stormwater system is hit with a 10-year storm. The system in Charleston was originally designed for the 10-year storm, so the results of this scenario will isolate for us the effect of 25 years of SLR. Finally, we'll include an adaptation action—tidal backflow valves—which will allow the system to continue to operate as tides rise above the outfall elevations.

***Step 1*: Compute Total Water Level at the Coastline**

As with scenario 1, computing coastal total water level is the same for basic and intermediate analyses.

- *Estimate current mean high water (MHW) elevation at location:*
  Table below is provided on the NOAA station page for the Charleston, South Carolina, tide gage (station number 8665530). Values in this table can be used to calculate the conversion factor between the various datums. (Note: the epoch for data datums below is 1983-2001.)

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Units: Meters — **Datum:** MLLW

Datum	Value	Description
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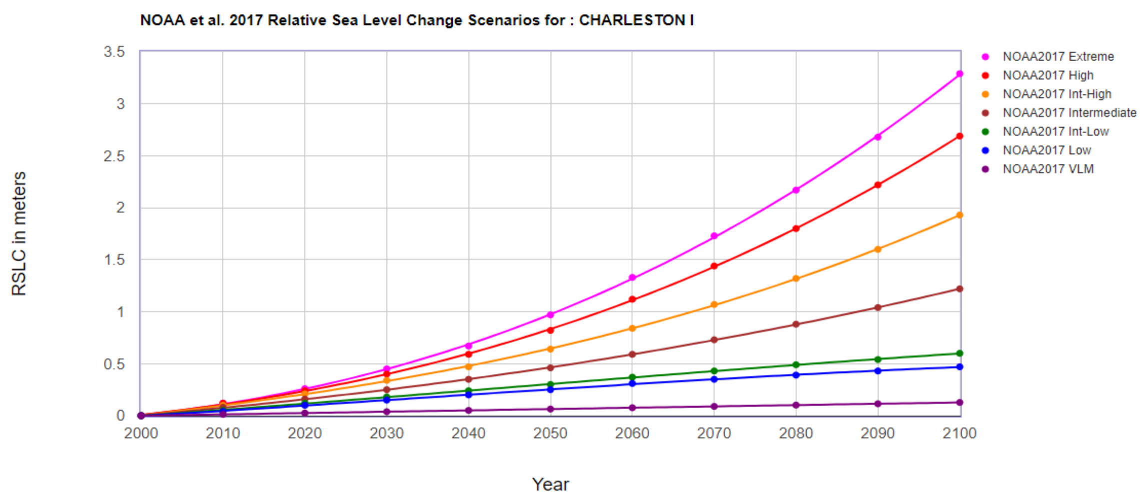
LAT Date & Time	02/09/2001 07:24	LAT Date and Time

  https://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=8665530&name=Charleston%2C+Cooper+River+Entrance&state=SC

- *Convert MHW elevation to NAVD88:*
  Based on the table shown in part (a), subtract the NAVD88 value from the MHW value to determine the datum conversion, i.e., 1.646 m minus 0.957 m = 0.69 m (x 3.281 ft/m = <u>2.26 ft, NAVD88)</u>

- *Calculated projected 25-year sea level rise:*

  The base year in the table is 2000. The current year is 2018. Determine the sea level rise at the 25-yr design life (year = 2018 + 25 = 2043). Through interpolation on the intermediate curve, this number is 0.38 m <u>(1.25 ft)</u>



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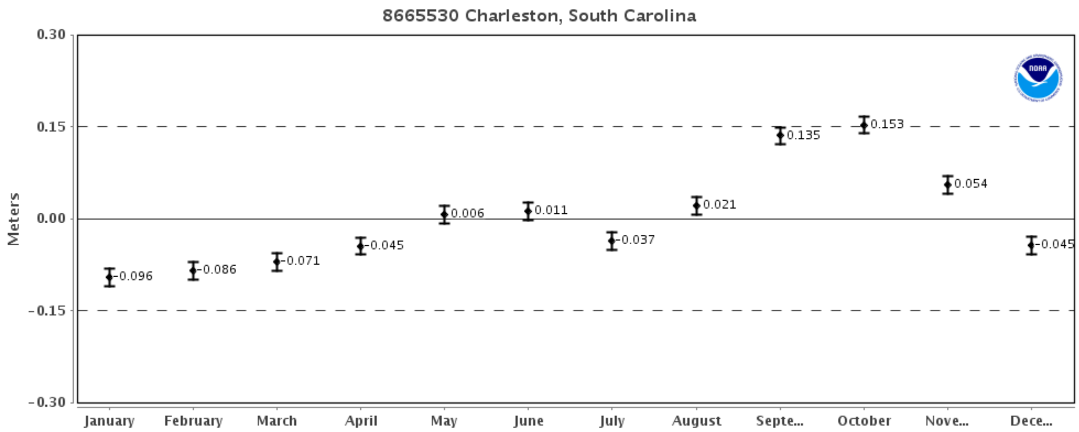
Enter Project Name
Scenarios for CHARLESTON I
NOAA2017 VLM: 0.00127 meters/yr
All values are expressed in meters

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.01	0.04	0.05	0.08	0.10	0.12	0.12
2020	0.03	0.10	0.12	0.16	0.21	0.24	0.26
2030	0.04	0.15	0.18	0.25	0.34	0.40	0.45
2040	0.05	0.20	0.24	0.35	0.47	0.59	0.67
2050	0.06	0.25	0.30	0.46	0.64	0.82	0.97
2060	0.08	0.31	0.37	0.59	0.84	1.12	1.33
2070	0.09	0.35	0.43	0.73	1.07	1.44	1.73
2080	0.10	0.39	0.49	0.88	1.32	1.80	2.17
2090	0.11	0.43	0.54	1.04	1.60	2.22	2.68
2100	0.13	0.47	0.60	1.22	1.93	2.69	3.29

http://www.corpsclimate.us/ccaceslcurves.cfm

- *Consider adding wave setup if not already included:*
  N/A

- *Consider need for adding variations in water levels due to regional oceanographic conditions:*



https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8665530

For stormwater analysis and design purposes, the greatest increase in coastal water levels associated with seasonal variations can be assumed. In this case, that's 0.153 m (<u>0.5 ft</u>).

- *Compute maximum stillwater elevation:*
  Maximum Stillwater Elevation = MHW [answer to part (b)] + SLR [answer to part (c)] + seasonal variations [answer to part (f)]; 2.26 ft, NAVD88 + 1.25 ft, NAVD88 + 0.5 ft = ***<u>4.01 ft NAVD88.</u>***

- *Compute wave runup if applicable:*
  Multiply maximum stillwater elevation by a factor of 1.1 to account for runup.
  ⇨ *Total water level = 1.1*4.01 =* ***<u>4.41 ft NAVD88</u>***

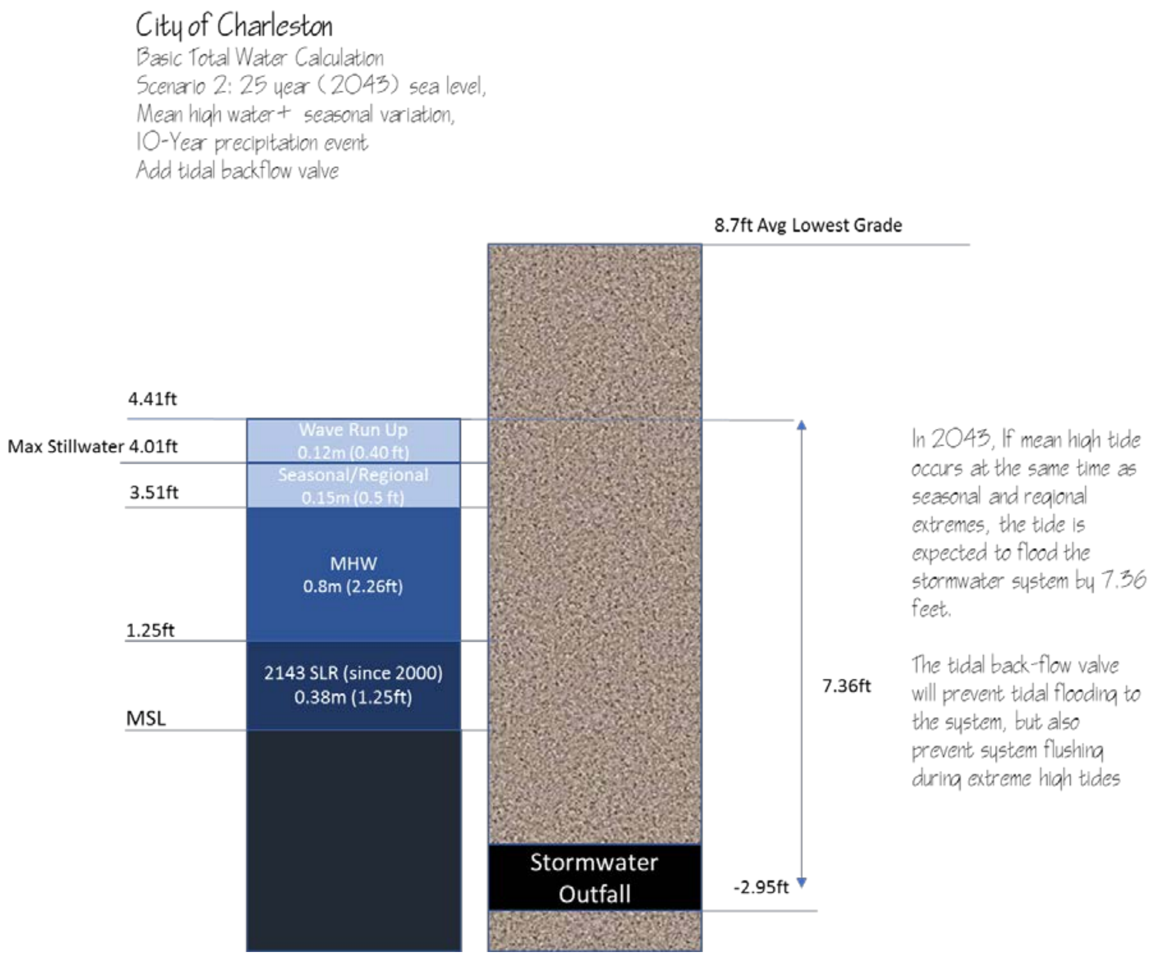


Figure 12: Coastal total water level for scenario 2

You'll note that the coastal total water level is lower than the level we found in scenario 1. This is because we used the mean high water elevation as opposed to the highest astronomical tide (HAT) elevation. Mean high water is more reflective of everyday conditions, while HAT is more representative of the extreme tides that occur once every few years.

***Step 2**: Compute Overtopping Flow Using the Weir Equation (Q = CLH^1.5); where Q is the peak flow in cfs, C is the weir coefficient, L is the overtopping length in feet and H is the overtopping head in feet*

N/A

***Step 3**: Compute Coincident Rainfall Runoff Using EPA SWMM Model*

Basic Method:** Using the modeling parameters, we derived previously,* *Runoff = CIA = 0.8*7.59 in/hr *322.2 acres=* ***<u>1956.4 cfs</u>

Intermediate Method: *The calculation of rainfall will be done within the distributed model. In our case, the EPA SWMM model uses land use and soil GIS data to evaluate the runoff coefficient for each sub-basin, and evaluate the runoff at the sub-basin scale.*

<u>Step 4</u>: Compute Flow from Other Sources

N/A

<u>Step 5</u>: Compare Total Flow from Combined Events to Stormwater System Capacity

Basic Method: *The introduction of backflow valves means that even though the outfall is topped by the tide, no saltwater enters the system. The 10-year rain event generates 1,956 cfs, which the stormwater system is designed for. The blockage of the outfall, however, will mean that during high tide, the system cannot drain the stormwater entering it from the rainstorm. As a result, flooding may still occur, and will take significant time to clear, because it can only drain during periods where the tide is low enough to allow outflow. Because there are no tidal backflow valves, we can expect the system to be overwhelmed during high. The flowchart below shows the path we've taken with our calculation. The flow schematic figure shows the total flows through the system.*

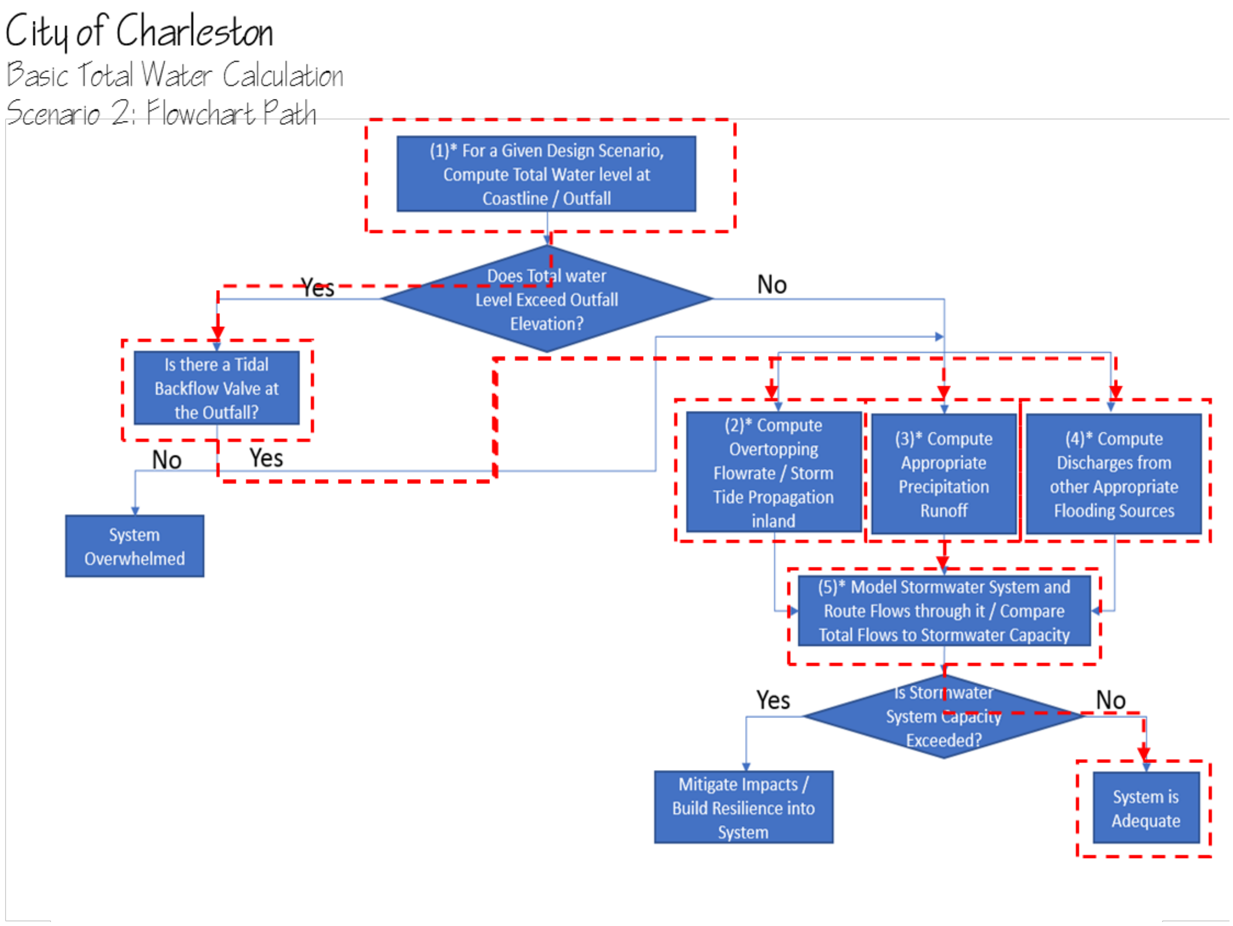


Figure 13: Flowchart showing calculation path for scenario 2

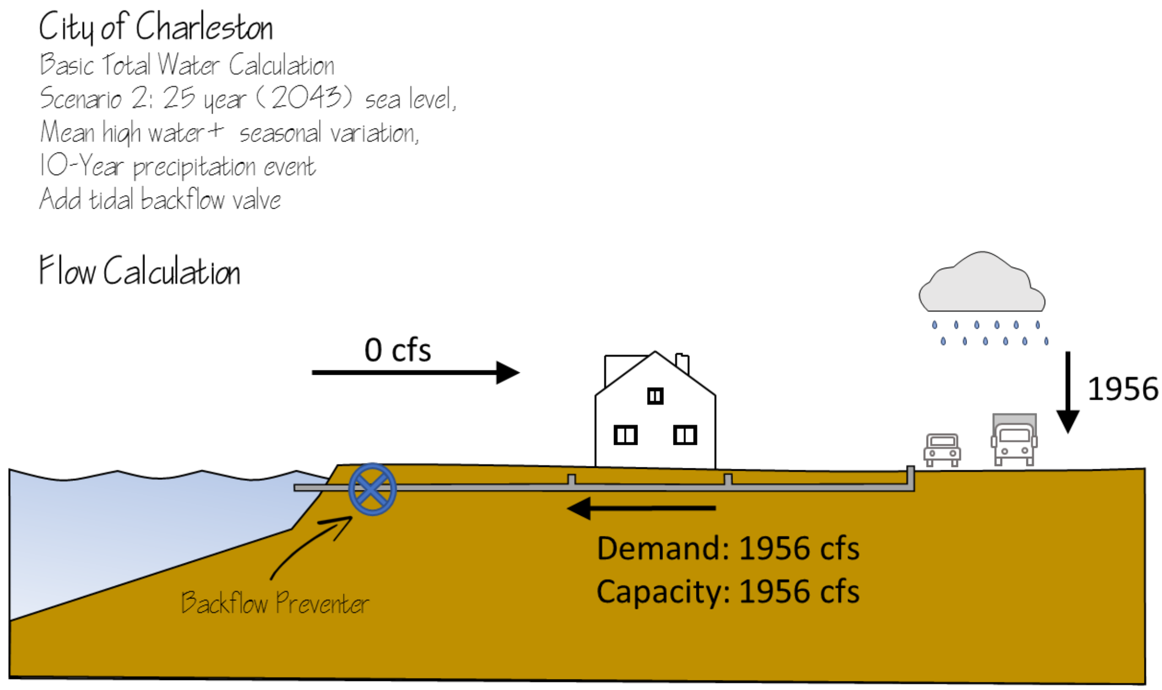


Figure 14: Schematic showing flows through the stormwater system for scenario 2

Intermediate Method*: The table below shows the results for scenario 2 from the EPA SWMM model. The model has been set to run over a period of 72 hours, and includes combined effects of tide and flood from rain. The tide has been set to peak at the maximum level derived in step 1.*

The first column lists the nodes in the system, as shown in the map in figure 5. The second column shows the hours of surcharge—when the pipes that connect to the node are completely full and running at pressure. The third column gives the hours the node is flooded—where the water level is above the level of the ground. The fourth column gives the maximum depth of flooding.

As the table reveals, there is some flooding for this scenario in many of the sub-basins. For example, node N2.5 floods for 4.48 hours over the course of the 72-hour event.

EPA SWMM Model Results for Scenario 2

	Hours Surcharged	Hours Flooded	Maximum Ponded Depth (Hr)
Node	Scenario 2	Scenario 2	Scenario 2
J0.5	0.76	0.05	0.006
J1	0.49	0.29	0.215
J2	11.37	2.01	0.487
J4	5.11		
J41	0.73	0.01	0
J42	0.68	0.01	0
J6	4.63		
N10	5	4.88	2.203
N11	5.01	4.9	2.026
N12	5.01	5	2.575
N2.5	6.06	4.48	1.751
N20	4.73	0.59	0.53
N3	5.26	2.5	1.335
N30	4.68	0.57	0.537
N40	0.95	0.6	1.023
N5	1.34		
N50	14.43	14.43	2.279
N60	7.43	5.79	1.464
J12	0.36		

Basic vs. Intermediate: *As with scenario 1, this result illustrates the value of the intermediate method relative to the basic. The basic analysis showed the system would be able to handle the flow, but since it could not drain at high tide, it would be ineffective in draining the stormwater quickly. The intermediate analysis goes into greater detail, showing that the majority of the sub-basins would flood regularly when even smaller rainfall events occur.*

SCENARIO 3 – 25-YR SLR + HIGHEST ASTRONOMICAL HIGH TIDE (HAT) + SEASONAL VARIATIONS; ASSUME TIDAL BACKFLOW VALVE IS PRESENT

In scenario 3, we're interested in the impact of sunny-day king-tide-like flooding in the future. Again, we look at 25 years from present (2043) and include HAT to represent the king tide event. We'll assume backflow valves are present, since the City of Charleston is currently adding dozens of valves to its system and will have completely protected the system with them within a few years.

***Step 1*: Compute Total Water Level at the Coastline**

As with scenarios 1 and 2, the coastal total water level calculation is the same for basic and intermediate calculations.

a. Estimate current MHHW elevation at location:

Table below is provided on the NOAA station page for the Charleston, South Carolina, tide gage (station number 8665530). Values in this table can be used to calculate the conversion factor between the various datums. (Note: the epoch for data datums below is 1983-2001.)

Elevations on Mean Lower Low Water

Station: 8665530, Charleston, Cooper River Entrance, SC — **T.M.:** 0
Status: Accepted (Apr 17 2003) — **Epoch:** 1983-2001
Units: Meters — **Datum:** MLLW

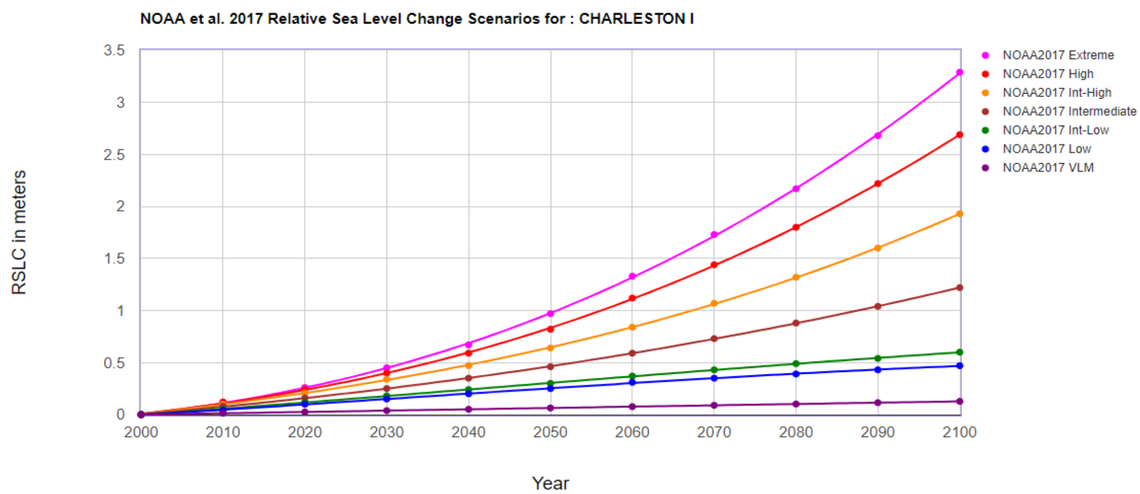
Datum	Value	Description
MHHW	1.757	Mean Higher-High Water
MHW	1.648	Mean High Water
MTL	0.852	Mean Tide Level
MSL	0.890	Mean Sea Level
DTL	0.878	Mean Diurnal Tide Level
MLW	0.057	Mean Low Water
MLLW	0.000	Mean Lower-Low Water
NAVD88	0.957	North American Vertical Datum of 1988
STND	-0.843	Station Datum
GT	1.757	Great Diurnal Range
MN	1.591	Mean Range of Tide
DHQ	0.109	Mean Diurnal High Water Inequality
DLQ	0.057	Mean Diurnal Low Water Inequality
HWI	0.410	Greenwich High Water Interval (in hours)
LWI	6.630	Greenwich Low Water Interval (in hours)
Max Tide	3.817	Highest Observed Tide
Max Tide Date & Time	09/21/1989 23:42	Highest Observed Tide Date & Time
Min Tide	-1.245	Lowest Observed Tide
Min Tide Date & Time	03/13/1993 19:24	Lowest Observed Tide Date & Time
HAT	2.213	Highest Astronomical Tide
HAT Date & Time	10/16/1993 13:06	HAT Date and Time
LAT	-0.462	Lowest Astronomical Tide
LAT Date & Time	02/09/2001 07:24	LAT Date and Time

https://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=8665530&name=Charleston%2C+Cooper+River+Entrance&state=SC

b. Convert MHHW elevation to NAVD88:

Based on the table shown in part (a), subtract the NAVD88 value from the MHHW value to determine the datum conversion, i.e., 1.757 m minus 0.957 m = 0.8 m (x 3.281 ft/m = 2.62 ft, NAVD88) *c. Calculate project 25-year sea level rise:*

The base year in the table is 2000. The current year is 2018. Determine the sea level rise at the of the 25-yr design life (year = 2018 + 25 = 2043). Via interpolation on the intermediate curve, this number is 0.38 m *<u>(1.25 ft)</u>*



http://www.corpsclimate.us/ccaceslcurves.cfm

Enter Project Name
Scenarios for CHARLESTON I
NOAA2017 VLM: 0.00127 meters/yr
All values are expressed in meters

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.01	0.04	0.05	0.08	0.10	0.12	0.12
2020	0.03	0.10	0.12	0.16	0.21	0.24	0.26
2030	0.04	0.15	0.18	0.25	0.34	0.40	0.45
2040	0.05	0.20	0.24	0.35	0.47	0.59	0.67
2050	0.06	0.25	0.30	0.46	0.64	0.82	0.97
2060	0.08	0.31	0.37	0.59	0.84	1.12	1.33
2070	0.09	0.35	0.43	0.73	1.07	1.44	1.73
2080	0.10	0.39	0.49	0.88	1.32	1.80	2.17
2090	0.11	0.43	0.54	1.04	1.60	2.22	2.68
2100	0.13	0.47	0.60	1.22	1.93	2.69	3.29

http://www.corpsclimate.us/ccaceslcurves.cfm

d. Calculate highest astronomical high tide elevation (use tide gage statistics):

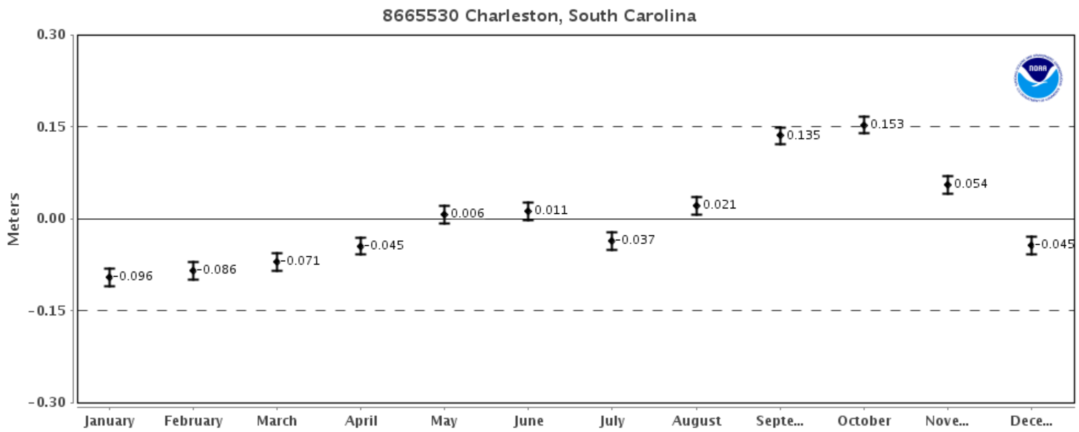
From table in part (a); HAT = 2.213 m + MLLW or 0.456 + MHHW

Convert to NAVD88 using the conversion factor from part (b); HAT= 0.456 m + 0.8 m = 1.256 m NAVD88 *<u>(4.12 ft NAVD88)</u>*

e. Consider adding wave setup if not already included:

N/A

f. Consider need for adding variations in water levels due to regional oceanographic conditions:



https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8665530

For stormwater analysis and design purposes, the greatest increase in coastal water levels associated with seasonal variations can be assumed. In this case, that's 0.153 m (<u>0.5 ft</u>).

g. Compute maximum stillwater elevation:

Maximum stillwater elevation = SLR [answer to part (c)] + HAT [answer to part (d)] + seasonal variations [answer to part (f)]; 1.25 ft + 4.12 ft, NAVD88 + 0.5 ft = ***<u>5.87 ft NAVD88.</u>***

h. Compute wave runup if applicable:

Multiply maximum stillwater elevation by a factor of 1.1 to account for runup.

⇨ *Total water level = 1.1*5.87 =* ***<u>6.46 ft NAVD88</u>***

i. Use computed coastal total water level at the coastline as a boundary condition at the outfall within the SWMM model:

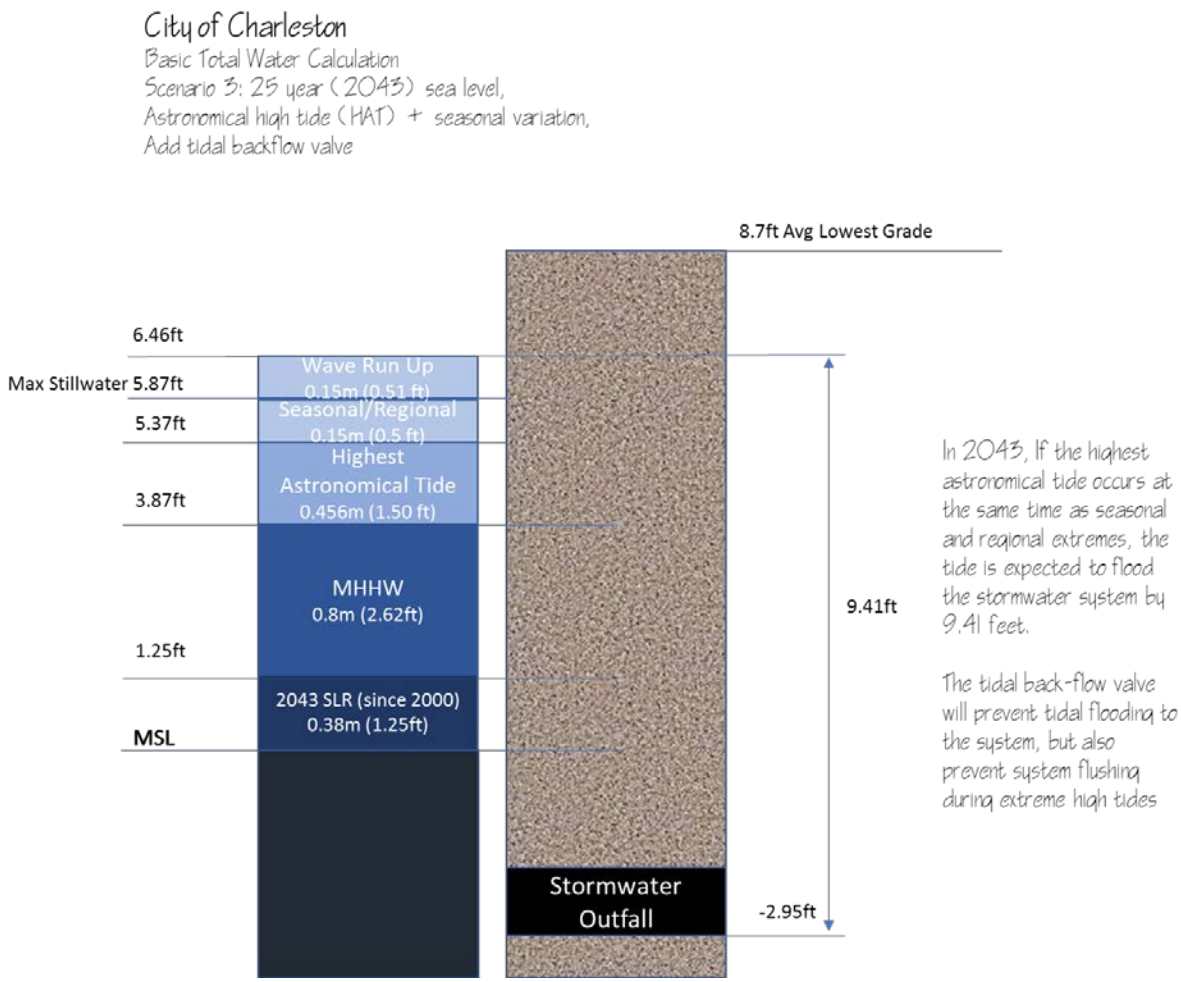


Figure 15: Coastal total stormwater level for scenario 3

<u>Step 2</u>: Compute Overtopping Flow Using the Weir Equation (Q = CLH^1.5); where Q is the peak flow in cfs, C is the weir coefficient, L is the overtopping length in feet and H is the overtopping head in feet

N/A

<u>Step 3</u>: Compute Coincident Rainfall Runoff Using EPA SWMM Model

N/A

<u>Step 4</u>: Compute Flow from Other Sources

N/A

***Step 5**: Compare Total Flow from Combined Events to Stormwater System Capacity*

***Basic Method:** the basic method shows that scenario 3 is like scenario 1, in that the sunny-day king-tide situation will result in the system outfall being overtopped. Using the NOAA intermediate SLR forecast, the coastal total water level is at 6.46 feet, 2.2 feet lower than the peninsula wall, so no overtopping occurs. The tidal backflow valves again will do the job of preventing inflows from the sea side.*

The flowchart below shows the path we've taken with our calculation. The flow schematic figure shows the total flows through the system.

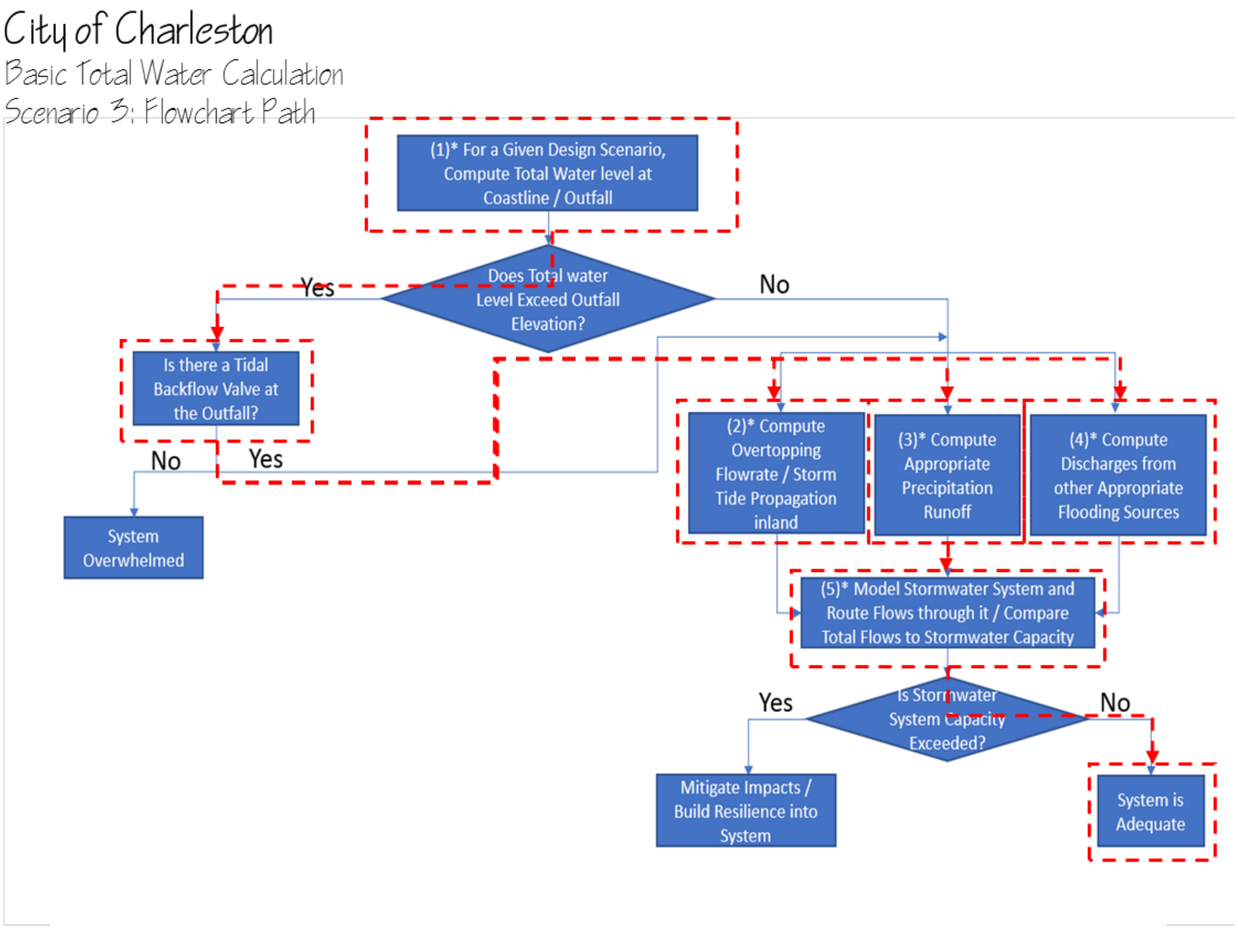


Figure 16: Flowchart showing calculation path for scenario 3

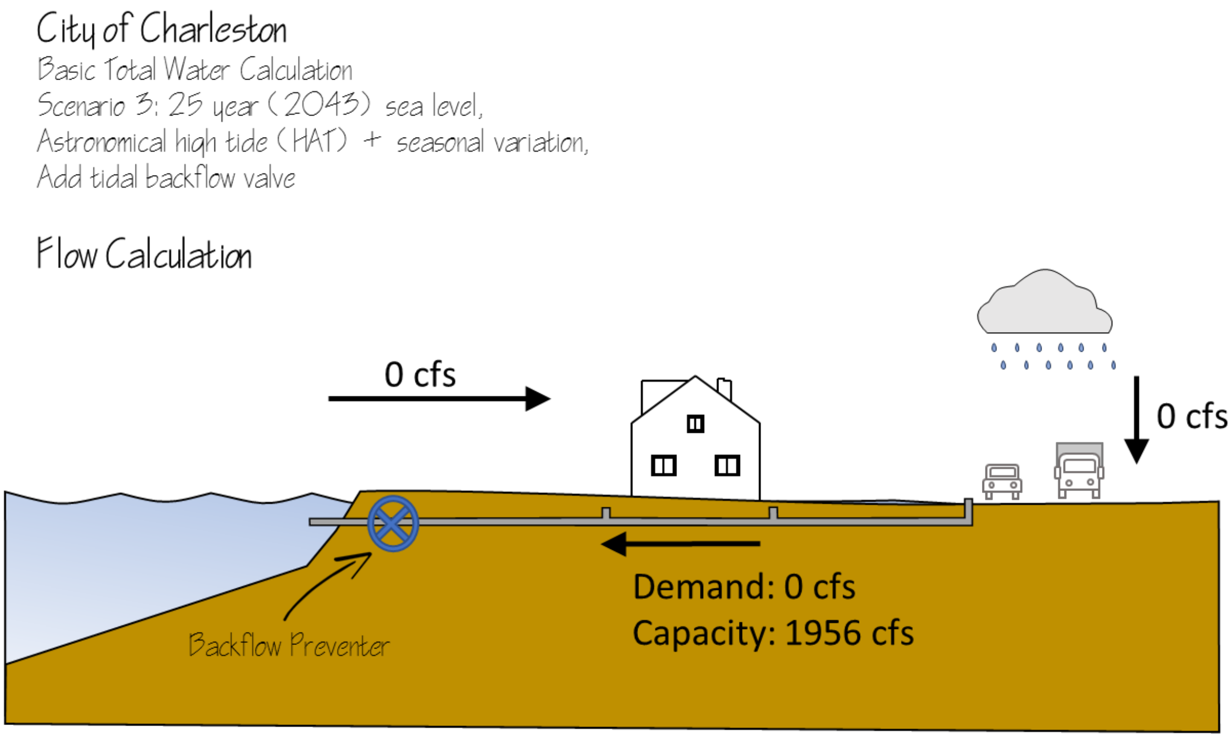


Figure 17: Flow schematic for scenario 3

Intermediate Method*: The table below shows the results for scenario 3 from the EPA SWMM model. The model has been set to run over a period of 72 hours, and includes combined effects of tide and flood from rain. The tide has been set to peak at the maximum level derived in step 1.*

As expected, since we've blocked tidal flows, there is no overtopping, and there is no rain event, the EPA SWMM model finds no flow through the system.

EPA SWMM Model Results for Scenario 3

Node	Hours Surcharged Scenario 3	Hours Flooded Scenario 3	Maximum Ponded Depth (Hr) Scenario 3
J0.5	No nodes were surcharged	No Nodes were flooded	No nodes were flooded
J1			
J2			
J4			
J41			
J42			
J6			
N10			
N11			
N12			
N2.5			
N20			
N3			
N30			
N40			
N5			
N50			
N60			
J12			

Basic vs. Intermediate: *Both the basic and intermediate models agree that if adaptation actions are taken—installing tidal backflow valves—that 25 years in the future, sunny-day king tides will not be at a level that they cause overtopping at the Charleston peninsula wall. However, given the considerable uncertainty in the sea level rise forecast, and uncertainty in the frequency and intensity of rainfall events in Charleston, additional design scenarios should be evaluated that reflect the worst cases of these two flooding sources.*

SCENARIO 4 – 25-YR SLR + 25-YR STORM SURGE + SEASONAL VARIATIONS; COINCIDENT 2-YEAR, 24-HOUR PRECIPITATION EVENT + ASSUME TIDAL BACKFLOW VALVE IS PRESENT

In scenario 4, we look at the impact of storm surge. We assume 25 years of SLR (2043), plus a 25-year storm surge. To evaluate the worst case, we use the extreme SLR forecast from NOAA, which is significantly higher in 2043 than the intermediate forecast and which was used in scenarios 1, 2, and 3. We also include seasonal and geographic variations, and a coincident 2-year, 24-hour rain event. Again, we assume tidal backflow valves protect the system.

***Step 1*: Compute Total Water Level at the Coastline**

a. Estimate current MHHW elevation at location:

Table below is provided on the NOAA station page for the Charleston, South Carolina, tide gage (station number 8665530). Values in this table can be used to calculate the conversion factor between the various datums. (Note: the epoch for data datums below is 1983-2001).

Elevations on Mean Lower Low Water

Station: 8665530, Charleston, Cooper River Entrance, SC — **T.M.:** 0
Status: Accepted (Apr 17 2003) — **Epoch:** 1983-2001
Units: Meters — **Datum:** MLLW

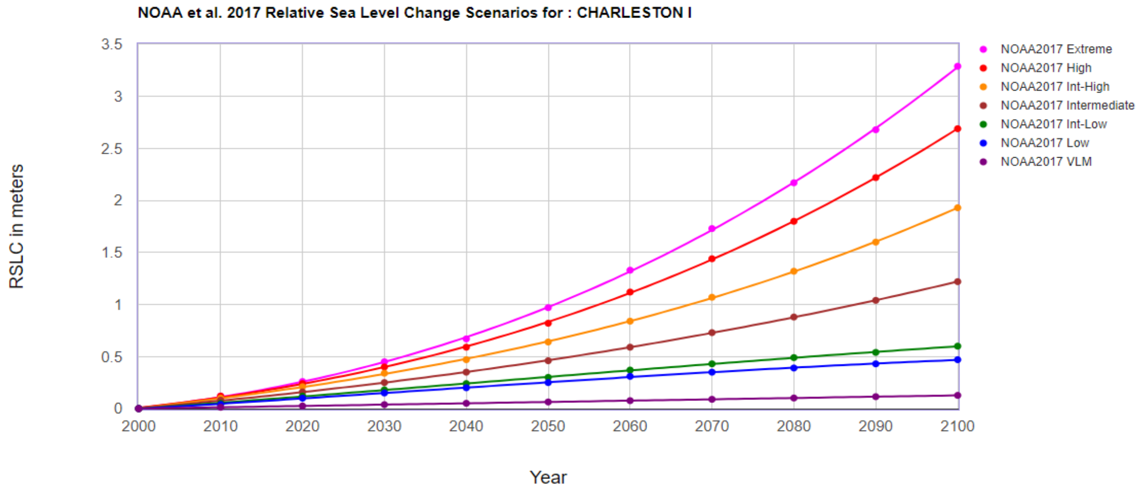
Datum	Value	Description
MHHW	1.757	Mean Higher-High Water
MHW	1.648	Mean High Water
MTL	0.852	Mean Tide Level
MSL	0.890	Mean Sea Level
DTL	0.878	Mean Diurnal Tide Level
MLW	0.057	Mean Low Water
MLLW	0.000	Mean Lower-Low Water
NAVD88	0.957	North American Vertical Datum of 1988
STND	-0.843	Station Datum
GT	1.757	Great Diurnal Range
MN	1.591	Mean Range of Tide
DHQ	0.109	Mean Diurnal High Water Inequality
DLQ	0.057	Mean Diurnal Low Water Inequality
HWI	0.410	Greenwich High Water Interval (in hours)
LWI	6.630	Greenwich Low Water Interval (in hours)
Max Tide	3.817	Highest Observed Tide
Max Tide Date & Time	09/21/1989 23:42	Highest Observed Tide Date & Time
Min Tide	-1.245	Lowest Observed Tide
Min Tide Date & Time	03/13/1993 19:24	Lowest Observed Tide Date & Time
HAT	2.213	Highest Astronomical Tide
HAT Date & Time	10/16/1993 13:06	HAT Date and Time
LAT	-0.462	Lowest Astronomical Tide
LAT Date & Time	02/09/2001 07:24	LAT Date and Time

https://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=8665530&name=Charleston%2C+Cooper+River+Entrance&state=SC

b. Convert MHHW elevation to NAVD88:

Based on the table shown in part (a), subtract the NAVD88 value from the MHHW value to determine the datum conversion, i.e. 1.757 m minus 0.957 m = 0.8 m (x 3.281 ft/m = 2.62 ft)

c. Calculate project 25-year Sea Level Rise:



http://www.corpsclimate.us/ccaceslcurves.cfm

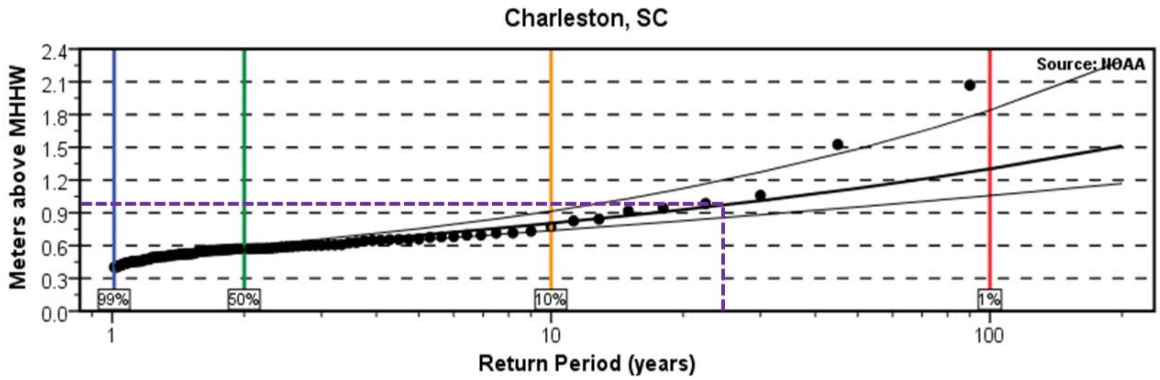
Enter Project Name
Scenarios for CHARLESTON I
NOAA2017 VLM: 0.00127 meters/yr
All values are expressed in meters

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.01	0.04	0.05	0.08	0.10	0.12	0.12
2020	0.03	0.10	0.12	0.16	0.21	0.24	0.26
2030	0.04	0.15	0.18	0.25	0.34	0.40	0.45
2040	0.05	0.20	0.24	0.35	0.47	0.59	0.67
2050	0.06	0.25	0.30	0.46	0.64	0.82	0.97
2060	0.08	0.31	0.37	0.59	0.84	1.12	1.33
2070	0.09	0.35	0.43	0.73	1.07	1.44	1.73
2080	0.10	0.39	0.49	0.88	1.32	1.80	2.17
2090	0.11	0.43	0.54	1.04	1.60	2.22	2.68
2100	0.13	0.47	0.60	1.22	1.93	2.69	3.29

http://www.corpsclimate.us/ccaceslcurves.cfm

The base year in this table is 2000. First, the current year is 2018. Determine the sea level rise of the 25-yr design life (year = 2018 + 25 = 2043). Through interpolation for the intermediate curve, this number is 0.38 m (1.25 ft). In comparison, the projected SLR for the extreme curve is 0.76 m (2.49 ft).

d. Calculate 25-year storm surge elevation (use tide gage statistics):

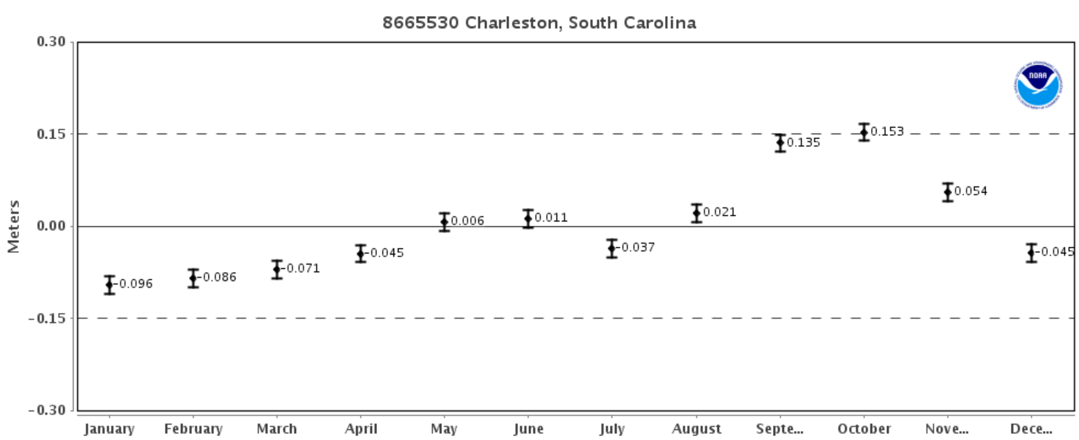


https://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8665530

The 25-year water level (dashed purple line) is estimated from the return period curve at the tide gage; 1.0 m MHHW.
Convert to NAVD88 using the conversion factor from part (b); 25-yr storm surge = 1.0 m MHHW + 0.8 m = <u>1.8 m NAVD88 (5.9 ft NAVD88)</u>

e. Consider adding wave setup if not already included in 25-year storm surge elevation:
Wave setup is already included in the answer to part (d) since tide gage data was directly used to determine the extreme water levels.

f. Consider need for adding variations in water levels due to regional oceanographic conditions:



https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8665530

For stormwater analysis and design purposes, the greatest increase in coastal water levels associated with seasonal variations can be assumed. In this case, that's 0.153 m (0.5 ft).

g. Compute maximum stillwater elevation:
Maximum stillwater elevation = 25-yr storm surge [answer to part (d)] + SLR [answer to part (c)] + seasonal variations [answer to part (f)]; 5.9 ft NAVD88 + 1.25 ft + 0.5 ft = ***<u>7.65 ft NAVD88</u>***

For extreme SLR: Maximum stillwater elevation = 25-yr storm surge [answer to part (d)] + SLR [answer to part (c)] + seasonal variations [answer to part (f)]; 5.9 ft NAVD88 + 2.49 ft + 0.5 ft = ***<u>8.89 ft NAVD88</u>***

h. Compute wave runup if applicable:

*For intermediate SLR: Multiply maximum stillwater elevation by a factor of 1.1 to account for runup. Total water level = 1.1*7.65 =* ***<u>8.41 ft NAVD88</u>***

For extreme SLR: Runup is not expected since the maximum stillwater elevation number exceeds the overtopping elevation (answer to step 3); 8.89 ft NAVD88 - 8.7 ft NAVD88 = 0.19 ft

i. Use computed coastal total water level at the coastline as a boundary condition at the outfall within the SWMM model:

The extreme SLR results were used as the downstream boundary condition for this scenario, since that results in overtopping and flow progression inland from the coast.

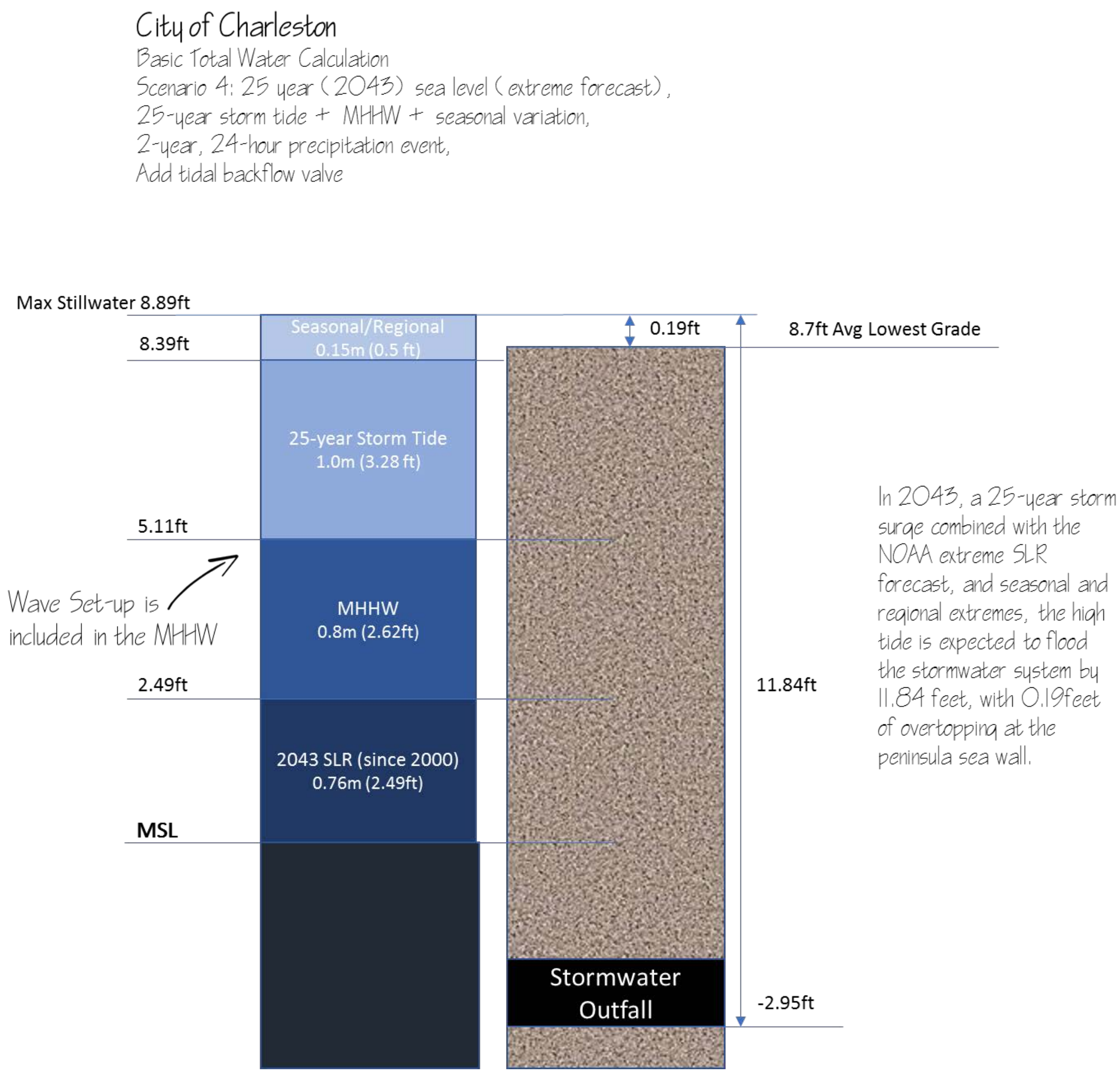


Figure 18: Coastal total water level for Scenario 4351

***Step 2**: Compute Overtopping Flow Using the Weir Equation (Q = CLH^1.5); where Q is the peak flow in cfs, C is the weir coefficient, L is the overtopping length in feet and H is the overtopping head in feet*

Overtopping flow (Q cfs) = CLH^1.5

*Assuming a weir coefficient of 2.65, Q = 2.65*1600*0.19^1.5 = **351.2 cfs***

Apply overtopping flowrate as an inflow at the weir node in the EPA SWMM model.

<u>Step 3</u>: Compute Coincident Rainfall Runoff

Basic Method: *Using the modeling parameters we derived previously,*

*Runoff = CIA = 0.8*5.82 in/hr *322.2 acres=* ***<u>1500.2 cfs</u>***

Intermediate Method: *The calculation of rainfall will be done within the distributed model. In our case, the EPA SWMM model uses land use and soil GIS data to evaluate the runoff coefficient for each sub-basin, and evaluate the runoff at the sub-basin scale.*

<u>Step 4</u>: Compute Flow from Other Sources

N/A

<u>Step 5</u>: Compare Total Flow from Combined Events to Stormwater System Capacity

Basic Method*: The basic method shows that scenario 4 will overtop the peninsula wall if the worst case SLR forecast is used. However, if we assume the system has been designed for a 10-year 24-hour storm (see scenario 2), then the sum of the overtopping flow (352 cfs) and the flow from the 2-year 24-hour storm included in the scenario will not exceed the 1,956 cfs design flow rate of the system. As a result, the stormwater system should be able to handle the additional overtopping flow. That said, with the coastal total water level as high as it is during the storm, the backflow valves will be activated, and the stormwater system will be ineffective in draining the excess water until the sea level lowers with tide.*

The flowchart below shows the path we've taken with our calculation. The flow schematic figure shows the total flows through the system.

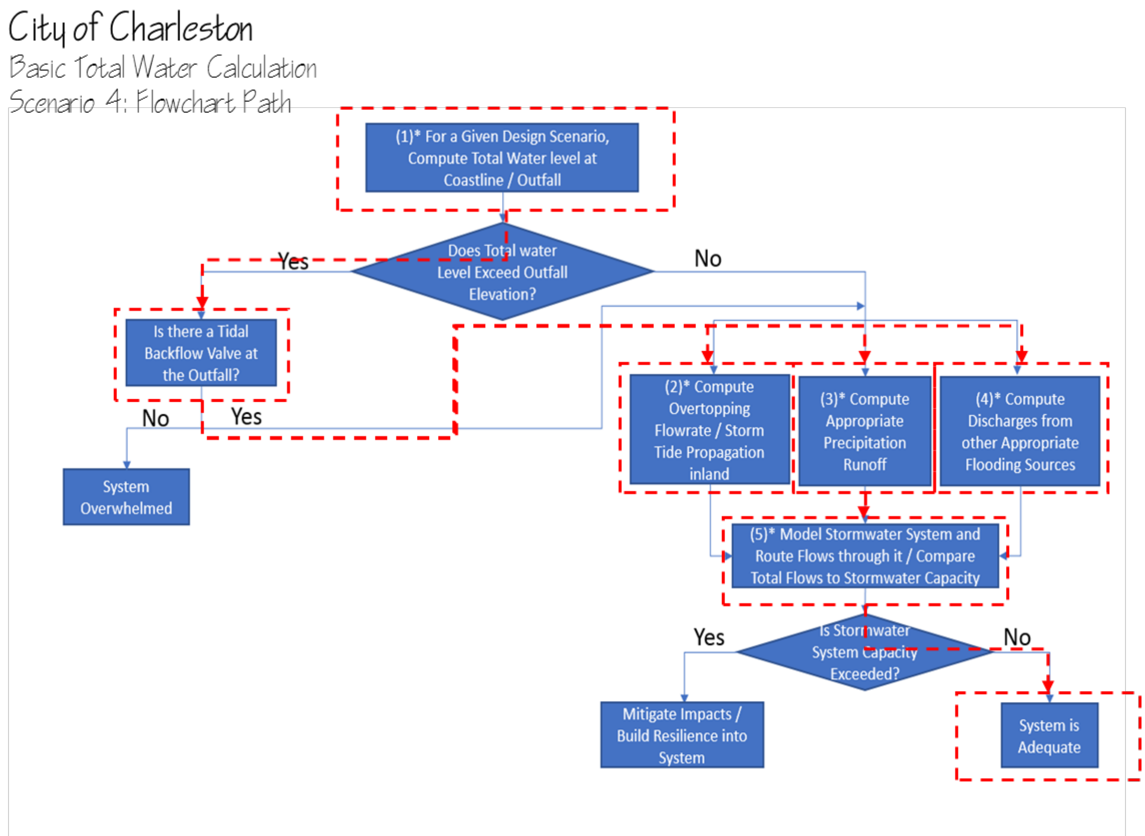


Figure 19: Flowchart showing calculation path for scenario 4

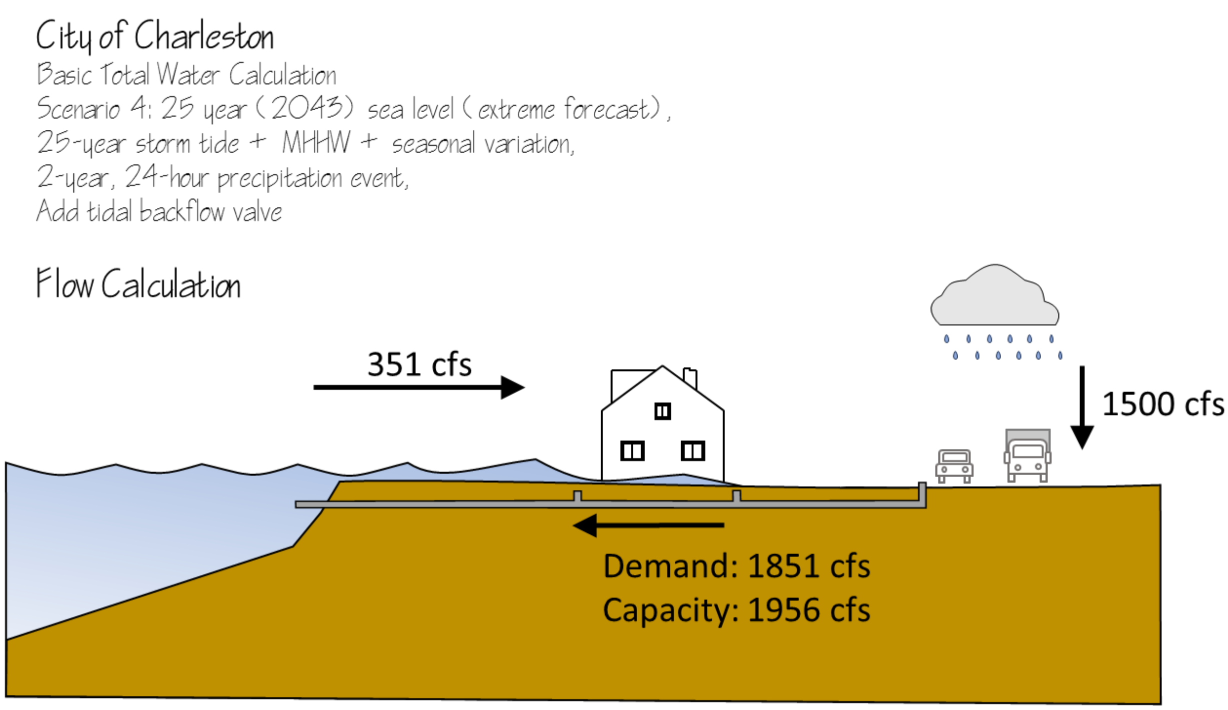


Figure 20: Flow schematic for scenario 4

Intermediate Method*: The table below shows the results for scenario 4 from the EPA SWMM model. The model has been set to run over a period of 72 hours, and includes combined effects of tide and flood from rain. The tide has been set to peak at the maximum level derived in step 1.*

There is significant flooding across the service area in this run, with maximum flood time at around 60 hours of the 72-hour simulation time. This is due to the high flow rates within the system coupled with a high coastal total water level consisting of high tide, storm surge, and extreme sea level rise, among other contributions.

EPA SWMM Model Results for Scenario 4

	Hours Surcharged	Hours Flooded	Maximum Ponded Depth (Hr)
Node	Scenario 4	Scenario 4	Scenario 4
J0.5	15.66	4.48	0.347
J1	13.53	6.52	0.44
J2	53.64	14.81	0.773
J4	35.14		
J41	0.47	0.01	0
J42	0.39	0.01	0
J6	32.9		
N10	34.22	32.64	1.69
N11	33.79	32.19	1.602
N12	32.88	31.97	2.045
N2.5	37.41	31.35	1.322
N20	33.79	0.25	0.136
N3	35.46	7.74	1.096
N30	33.48	0.28	0.301
N40	0.48	0.31	0.795
N5	0.51		
N50	60.82	60.82	2.378
N60	37.73	27.44	1.204
J12			

Basic vs. Intermediate: *As with the other scenarios, the intermediate analysis gives a lot more detail about the location and severity of flooding in this scenario, detail that can be used to pinpoint where adaptation actions would be taken.*

There is an interested discrepancy between the basic and intermediate analyses as well. Where the basic analysis forecast that in a basins-wide sense, the stormwater system would be able to handle the combined flows of overtopping and rain-driven flooding, the intermediate model reveals significant flooding across the service area. This could be due to the high sea water level taking a significantly long time to abate after the storm surge, but it could also mean that the capacity of the stormwater system is *not as high as the 1,956 cfs we estimate in scenario 2. Using the intermediate model, we can assess the capacity flow rate more accurately, another advantage of the intermediate method.*

The table and figure below show a summary of the scenario results presented in this example, along with a quick reference of the location nodes listed in the table. Please use it for reference to understand the differences between the scenarios.

SUMMARY OF RESULTS

Node	Hours Surcharged				Hours Flooded				Maximum Ponded Depth (Hr)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
J0.5	16.01	0.76		15.66	6	0.05		4.48	0.469	0.006		0.347
J1	12.1	0.49		13.53	6.49	0.29		6.52	0.497	0.215		0.44
J2	39.77	11.37		53.64	4.85	2.01		14.81	0.11	0.487		0.773
J4	20.62	5.11		35.14								
J41		0.73		0.47		0.01		0.01		0		0
J42		0.68		0.39		0.01		0.01		0		0
J6	18	4.63		32.9								
N10	19.62	5		34.22	16.24	4.88		32.64	0.516	2.203		1.69
N11	19.05	5.01	No nodes were surcharged	33.79	15.1	4.9	No Nodes were flooded	32.19	0.365	2.026	No nodes were flooded	1.602
N12	16.83	5.01		32.88	13.93	5		31.97	0.27	2.575		2.045
N2.5	22.79	6.06		37.41	14.01	4.48		31.35	0.31	1.751		1.322
N20	19.38	4.73		33.79		0.59		0.25		0.53		0.136
N3	20.89	5.26		35.46		2.5		7.74		1.335		1.096
N30	18.81	4.68		33.48		0.57		0.28		0.537		0.301
N40		0.95		0.48		0.6		0.31		1.023		0.795
N5		1.34		0.51								
N50	43.3	14.43		60.82	43.11	14.43		60.82	1.041	2.279		2.378
N60	24.84	7.43		37.73	15.84	5.79		27.44	0.516	1.464		1.204
J12		0.36										

Scenario (1): a. Assumes Current Sea Level; b. Assumes Design Scenario of Astronomical High Tide (HAT) + Seasonal Variations; c. No Tidal Backflow Valve

Scenario (2): a. Assume 25-year Design Life; b. Assume Design Scenario of 25-yr (2043) SLR + Mean High Water + Seasonal Variations + 10-year inland precipitation (current stormwater design storm); c. Assume Tidal Backflow Valve

Scenario (3): a. Assume 25-year design life; b. Assume Design Scenario of 25-yr SLR + Highest Astronomical High Tide (HAT) + Seasonal Variations; c. Assume Tidal Backflow Valve

Scenario (4): a. Assume 25-year design life; b. Assume Coastal Design Scenario of 25-yr SLR + 25-year Storm Surge Elevation + Seasonal Variations; c. Assume a coincident 2-year, 24-hour precipitation event due to storm; d. Assume Tidal Backflow Valve