

Retrofitting Storm Sewers to Reduce the Frequency of Erosive Discharges to Streams:

A Project Screening & Cursory Design Methodology

By

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1.0 Introduction

1.1 The Problem

A primary symptom of the “*urban stream syndrome*” is a flashy flow regime characterized by elevated frequency of erosive flows.¹ Flows capable of mobilizing streambed substrates have been identified as a predictable driver of biological disturbance in streams². The increased frequency of streambed mobilization in urban streams has been linked to reductions in biological diversity^{3,4} as well as stream enlargement (both vertical incision and horizontal widening)⁵ and associated damage to public and private property⁶. In addition to direct disturbance of in-stream biota from streambed substrate mobilization, the sediment pollution created from stream destabilization degrades benthic habitat. Sedimentation/siltation has been consistently identified as the leading cause of biologic impairment of streams in Ohio⁷ and nationally⁸.

Mitigating the in-stream impacts of this urban hydrologic alteration, in previously developed watersheds, will require significant effort to better manage stormwater throughout these watersheds. Such efforts will require multiple approaches and the more “tools in the box” the better. This document establishes a methodology for assessing opportunities to apply one tool to mitigate urban hydrologic alteration – storm sewer retrofits.

1.2 Storm Sewer Retrofitting

What if there were untapped stormwater detention infrastructure buried beneath our feet? Utilizing existing storm sewer pipes to detain relatively small runoff events that are capable of producing erosive stream flows, might be an important tool for mitigating the impacts of flashy urban flow regimes at the watershed-scale. Potential benefits of this approach would include:

- Efficiency of managing the stormwater where it is already being routed
- Complementarity with on-site practices – Potential for a “treatment train” approach
- Cost effective – No earth movement or property acquisition required
- Could be designed to facilitate water quality treatment and spill containment

¹ Walsh, C. J. et al. 2005. The urban stream syndrome: current knowledge and the search for a cure. J. North Am. Benthol. Soc. 24, 706–723.

² Poff, N.L., 1992. Why disturbances can be predictable: a perspective on the definition of disturbance in streams. Journal of the North American Benthological Society. 11(1), 86–92.

³ Townsend, C.R., Scarsbrook, M.R., Doledec, S., 1997. Quantifying disturbance in streams: alternative measures of disturbance in relation to macroinvertebrate species traits and species richness. Journal of the North American Benthological Society. 16(3), 531–544

⁴ Hawley, R.J., Wooten, M.S., MacMannis, K.R., and Fet, E.V. 2016. When Do Macroinvertebrate Communities of Reference Streams Resemble Urban Streams? The Biological Relevance of Qcritical. Freshwater Science. 35(3):778-794.

⁵ Hawley, R.J., MacMannis, K.R., and Wooten, M.S. 2013. Bed Coarsening, riffle shortening, and channel enlargement in urbanized watersheds, northern Kentucky, USA. Geomorphology 201: 111-126.

⁶ Hawley, R.J., MacMannis, K.R., and Wooten, M.S. 2013. How Poor Stormwater Practices Are Shortening the Life of our Nation’s Infrastructure—Recalibrating Stormwater Management for Stream Channel Stability and Infrastructure Sustainability.

⁷ <https://epa.ohio.gov/dsw/tmdl/OhioIntegratedReport>

⁸ https://ofmpub.epa.gov/waters10/attains_nation_cy.control

Storm sewers are a ubiquitous feature of our developed landscapes providing a huge number of locations at which this approach might be implemented. But how many of these locations are viable options where retrofitting could reduce the frequency for erosive flows without causing flooding problems? The answer is currently unclear.

1.3 Purpose of this Methodology

A major barrier to assessing the viability of storm sewer retrofitting is the lack of established methods for assessing the suitability of candidate retrofit locations, and for designing the retrofits. This methodology was developed, with funding from the Ohio Environmental Education Fund, and technical support from the U.S. Environmental Protection Agency's Center for Environmental Solutions and Emergency Response, for assessing the suitability of candidate storm sewer retrofit locations and cursory designs. The procedures described in this document, used in conjunction with the accompanying spreadsheet tool, will allow the user to answer two critical questions about a candidate retrofit location:

1. Can a retrofit be configured in a way that will NOT result in increased flooding during a specified design storm?
2. Within the parameters facilitating an affirmative answer to question 1, can a retrofit be configured in a way that will result in a decrease in the frequency of "erosive" discharges?

Additionally, the cursory design parameters estimated, using the accompanying spreadsheet tool, will facilitate assessment of the feasibility and cost associated with constructing the retrofit.

This document, and the accompanying spreadsheet tool, are intended to facilitate future investigation to clarify the contexts in which storm sewer retrofitting is likely to be successful.

1.4 Types of Storm Sewer Retrofits

Methods were developed for two types of retrofits: *flap gate retrofits* and *riser retrofits*.

It should be noted that either of these retrofit types, when installed at storm sewer outfalls, have the potential to cause localized erosion problem. Erosion control measures should be implemented in the vicinity of such retrofits as appropriate.

1.4.1 Flap Gate Retrofits

A *flap gate retrofit* consists of a flap gate, with a low flow orifice, installed on the end of a storm sewer pipe and a mechanism to keep the flap gate closed. The low flow orifice can be achieved by simply cutting-off the bottom of the flap gate. The height to which the flap gate is cut off above the bottom of the retrofitted pipe is designed to allow for flow rates just less than that which have been determined "erosive" (See Section 3) when water is backed-up behind the gate to a maximum detention height above which the gate would be pushed open. This maximum detention height of water is designed to detain as much water as possible without causing flooding problems up stream to the retrofit. The maximum detention height of water can be achieved by adjusting the combine forces exerted on the gate by any combination of various mechanisms (e.g. weights, spring latches and/or magnets). Once the maximum height of water is exceeded, the weight of the water becomes sufficient to push the gate open restoring the conveyance capacity of the sewer system. *flap gate retrofits* can be installed on storm sewer outfalls or in storm sewer junctions, (e.g. manholes or catch basins) given sufficient space in the junction box.

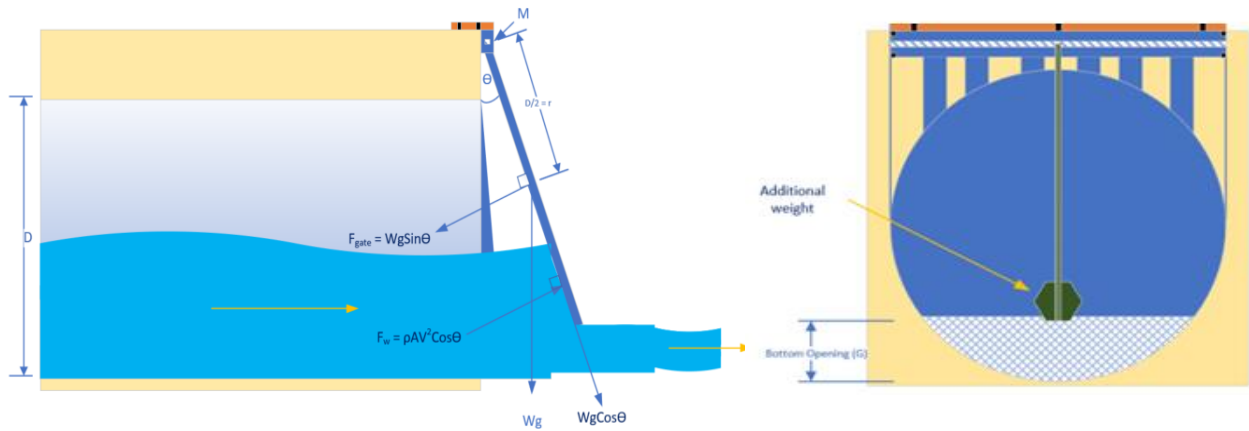


Figure 1.1: Conceptual diagram of a *flap gate retrofit*.

1.4.2 Riser Retrofits

A riser retrofit consists of a riser installed at the end of a storm sewer outfall. This can be imagined as a detention basin riser flowing in reverse. The storm sewer outfall flows into the riser and discharges through a low flow orifice at the bottom. This low flow orifice is designed to allow for flow rates just less than that which have been determined “erosive” (See Section 3) when water is backed-up behind the riser to a maximum detention height above which the riser would begin to discharge through its overflow orifice (as well as the low flow orifice) restoring some conveyance capacity of the sewer system. The maximum detention height in the sewer system is equal to the bottom elevation of the overflow orifice. This maximum detention height of water is designed to detain as much water as possible without causing flooding problems up stream to the retrofit. Note that, unlike *flap gate retrofits*, *riser retrofits* are not suitable for installation in storm sewer junctions (e.g. manholes or catch basins).

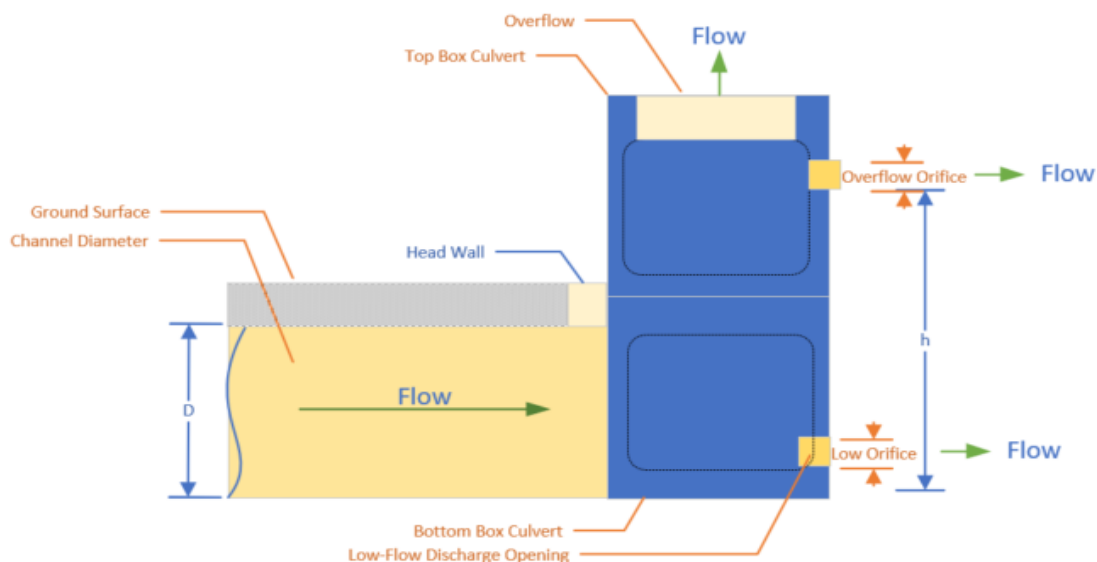


Figure 1.2: Conceptual diagram of a *riser retrofit*.

1.4.3 Some Comparative Notes on Retrofit Types

As noted above, while both retrofit types are generally suitable for installation of storm sewer outfalls, only flap gate retrofits are potentially suitable for installation in storm sewer junctions, (e.g. manholes or catch basins) given sufficient space in the junction box. When assessing the potential to retrofit a storm sewer outfall, the first preference for retrofit type (from a functionality standpoint) would be a *flap gate retrofit*, because a flap gate retrofit is capable of restoring a greater conveyance capacity to the sewer system once the maximum height of water is exceeded. While installation of a *riser retrofit* will constitute a permanent alteration in the hydraulic grade line (HGL) of the system, a flap gate retrofit can be designed to fully restore the sewer systems conveyance capacity if the gate is designed to open fully (90-degrees to vertical). Even if a riser retrofit can be designed to achieve hydrologic objectives (reducing the frequency of “erosive flows”) while not increasing flooding, it is likely that a *flap gate retrofit* will allow for a greater detention volume (greater maximum height of water) compared to a *riser retrofit*, while avoiding increases in flooding.

So, why then would one consider a *riser retrofit*? A typical limiting factor for a *flap gate retrofit* is the amount of force that must be applied to the gate to hold back the desired height of water. The magnitude of this force is a function of the height of water and the diameter and slope of the pipe to be retrofitted. Thus, *flap gate retrofits* will not be feasible in all locations (particularly on large diameter pipes). In contrast, it may be more feasible to hold back the same height of water with a riser structure. In this context, an innovation that could drastically increase the number of feasible storm sewer retrofit applications would be a safe and reliable mechanism to hold the gate of a *flap gate retrofit* closed against high forces from detained water (several thousand to a few tens of thousands of units of pound-force across the gate). It is also critical that such a mechanism can be structurally supported by the pipe or headwall on which the retrofit is installed.

2.0 Overview of Procedures

2.1 A Six-Phase Process

The procedures associated with the methodology described in this document can be broken-down into six-phases:

- A. Determination of the critical discharge – Section 3
- B. Initial project location screening – Section 4
- C. Determination of cursory design parameters for the retrofit device – Section 5
- D. Building a Storm Water Management Models (SWMM) – Section 6
- E. Conducting a flood risk analysis (with SWMM) – Section 7
- F. Conducting a critical discharge frequency analysis (with SWMM) – Section 8

In Section 3, determination of *critical discharge* is discussed. The objective here is to identify a flow rate that represents a threshold above which erosivity is significantly increased. This is the important step of determining the design flow rate of which you would like to reduce the frequency. A storm sewer retrofit device would be designed to discharge at a flow rate less than the *critical discharge*, until and unless the detention capacity of the system is exceeded.

In Section 4, the process for rapidly screening multiple candidate project locations to select the location(s) most likely to meet the criteria of a suitable storm sewer retrofit site is discussed. By conducting the analyses laid-out in this document on the sites most likely to be suitable retrofit sites first, we will minimize the number of analyses conducted for locations that are unsuitable. Section 4 also discusses data requirements for assessing the suitability of a candidate storm sewer retrofit location.

In Section 5, a cursory design spreadsheet tool, created for use with this document is discussed. The spreadsheet tool can be used to generate cursory design parameters necessary for representing the retrofits in a SWMM. The resulting SWMM will be used in the final phases of the process. The parameters provided by the spreadsheet tool can also provide insight into physical and monetary requirements of installing a retrofit in the proposed location (e.g. the force required to detain the required amount of water).

In Section 6, methods for representing the retrofits in a sewershed model using the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) are discussed. Cursory design parameters generated in the previous phase will be used to parameterize the representation of the retrofit in SWMM. A pre- and post-treatment version of the SWMM will be utilized to conduct flood risk and critical discharge frequency analyses in the final two phases of the process.

In Section 7, using the SWMM to conduct a flood risk analysis based on local stormwater regulations is discussed. This analysis will aid in determining if installing the retrofit, using the assumed cursory design parameters, would be permissible.

In Section 8, using the SWMM to conduct a critical discharge frequency analysis is discussed. This analysis will aid in determining the effectiveness of the proposed retrofit at reducing the frequency of *critical discharges*. While the flood risk analysis could be conducted after the critical discharge frequency analysis, it is recommended to proceed in the prescribed order because the flood risk analysis takes less effort and if the flood risk analysis shows that the retrofit, using current cursory design parameters, would NOT be permissible, then there is no reason to conduct the critical discharge frequency analysis.

3.0 Determining the Critical Discharge

3.1 What is a Critical Discharge?

The objective of installing a storm sewer retrofit is to reduce the frequency of “erosive” flows in the receiving stream to a more natural statistical recurrence interval. This raises the questions: how do we define an “erosive” stream flow? In fluvial geomorphology, the erosivity of a flow rate, or discharge, in a stream is often discussed in terms of the bed material that the discharge is capable of moving. For a given discharge, in a given stream reach, there is a maximum streambed substrate particle size that the discharge would be expected to move. A “critical” discharge is defined in terms of the maximum streambed substrate particle size that it can move. A *critical discharge* is often defined in association with the 50th [d_{50}] or 84th [d_{84}] percentile-sized particle found on the streambed. For example, the d_{50} -critical discharge would be expected to have enough power to move a particle equal to the median sized particle found on the streambed, but, theoretically, not a larger particle (say the 75th percentile particle).

3.2 Estimating a *Critical Discharge*

The *critical discharge* for a given stream reach depends on the size of the particles on the streambed, as well as the dimensions/pattern/profile of the channel. *Critical discharges* can be estimated using standard geomorphic survey techniques or by monitoring streambed substrate movement over time via particle painting/tagging with concurrent flow data. A method for estimating *critical discharge* based on geomorphic survey data was described by Hawley & Vietz (2016)⁹.

Critical discharge estimates can be standardized in a scalable manner for a geomorphologically homogenous region to facilitate regional management strategies.¹⁰ Hawley et al. (2017)¹¹ reported that estimated *critical discharge* (d_{50}) at 23 sites in Northern Kentucky were well approximated as 40-percent of the 2-year recurrence interval peak discharge. Beyond facilitating regional management strategies, the ability to define an “erosive” flow rate in terms of the peak flow rate resulting from a standardized storm event facilitates scaling-down of an estimated *critical discharge* for a receiving stream to a smaller site-level *critical discharge* associated with a hydrologic mitigation project (e.g. a storm sewer retrofit). Once a relationship between in-stream *critical discharge* and the peak discharge associated with a standardized storm event is established, one can rapidly estimate a site-level *critical discharge* using available tools including USGS regional curves¹² and the [WinTR-55](https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1042901)¹³ application.

If one has a reliable estimate of the *critical discharge* for the receiving stream of interest, estimating the 1-year or 2-year return interval peak discharge for that same reach (using available tools such as those cited above^{14,15}) will facilitate the conversion of that *critical discharge* to a proportion of the standardized peak discharge ($\text{critical discharge} \div \text{standardized peak discharge}$). One can then estimate the standardized peak discharge for hydrologic mitigation project site and multiply it by the conversion factor to arrive at the scaled-down site-level *critical discharge* estimate. If reliable information does not exist for the *critical discharge* of the receiving stream of interest, or a regional relationship of *critical discharge*-to-a standardized peak discharge, qualified personnel capable of conducting the necessary geomorphic measurements and analyses should be mobilized to estimate the *critical discharge*.

3.3 Which *Critical Discharge* should be Targeted?

While there tends to be a threshold flow at which much of a heterogeneous mixture of stream bed substrate particle sizes mobilize, as opposed to smaller particles moving first followed by larger particles as flows increase (based on laboratory flume studies)¹⁶, the degree to which this varies from stream-to-stream and region-to-region is not clear. So, what is the *critical discharge* that should be targeted for

⁹ Hawley, R.J., and Vietz, G.J. 2016. Addressing the Urban Stream Disturbance Regime. *Freshwater Science*. 35(1): 278-292.

¹⁰ Hawley, R.J., and Vietz, G.J. 2016. Addressing the Urban Stream Disturbance Regime. *Freshwater Science*. 35(1): 278-292.

¹¹ Hawley, R.J., Goodrich, J.A., Korth, N.L., Rust, C.J., Fet, E.V., Frye, C., MacMannis, K.R., Wooten, M.S., Jacobs, M., and Sinha, R. 2017. Detention Outlet Retrofit Improves the Functionality of Existing Detention Basins by Reducing Erosive Flows in Receiving Channels. *Journal of the American Water Resources Association*. 53(5): 1032-1047.

¹² U.S. Geological Survey. 2005. Bankfull Characteristics of Ohio Streams and Their Relation to Peak Streamflows. Scientific Investigations Report 2005-5153

¹³ <https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1042901>

¹⁴ U.S. Geological Survey. 2005. Bankfull Characteristics of Ohio Streams and Their Relation to Peak Streamflows. Scientific Investigations Report 2005-5153

¹⁵ <https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1042901>

¹⁶ Leopold, L.B. 1994. *A View of the River*. Harvard University Press. p 28.

storm sewer retrofit projects (e.g. the d_{50} or the d_{84} *critical discharge*)? The smaller the *critical discharge* used to design a mitigation project, the greater the degree of confidence we can have that our efforts will be effective; however, depending on the storage volume available, it can be more challenging to implement mitigation projects designed to smaller flows.

In streams that are highly impacted by flashy urban flows, it will likely be very challenging, if not impossible, to restore the frequency for *critical discharges* to natural levels; so, designing projects to discharge at less than the *critical discharge* will often be desirable, when sufficient storage is available, to make-up for unmitigated flow in other locations of the watershed. While consideration should be given to maintaining the competence of the stream to convey the sediment load that it receives, this is not likely to be a major concern in urban streams impacted by urban hydrologic alteration. Conversely, if storage above a storm sewer retrofit is not sufficient to fully achieve at target discharge, it may still be worthwhile to implement the project if it helps to move you closer to your in-stream hydrologic objectives.

4.0 Initial Project Location Screening

4.1 Pipe Storage-to-Sewershed Area Ratio

Initial screening of candidate retrofit locations, involves getting a general idea of the storage capacity of the storm sewer system above the candidate retrofit location relative to the amount of storm water that is delivered to it. In this early screening stage this can be assessed in terms of comparing the ratio of *maximum available storage in the pipes-to-sewershed area*. Once this ratio is known for candidate retrofit locations, these locations can be prioritized by potential suitability for retrofitting. Begin by proceeding to subsequent phases of this procedure with the location(s) that have the highest ratios (most relative storage volume). This approach will minimize the number of times that subsequent analyses are conducted on sites that are not suitable of receiving storm sewer retrofits.

4.1.1 How Much Storage is Available?

For the first part of the *maximum available storage in the pipes-to-sewershed area* ratio, maximum available storage in the pipes, the following data will be needed:

- Rim elevations of all junctions, upstream of the candidate retrofit location, through which water could possibly surcharge resulting in flooding
- Length, shape, dimensions, and upstream/downstream invert elevation for each pipe upstream of the candidate retrofit location

The quality and extent to which storm sewer data are available will vary by local jurisdiction. As with many of the procedures discussed in this document, this those associated with this phase will go much more quickly if good GIS-based data exist for the storm sewer system.

The first step is to identify the junction with the lowest rim elevation upstream of the candidate retrofit location. This elevation is the furthest upstream that we can back-up (store) stormwater without causing flooding. Note that the flood risk analysis (Section 7) may show that we cannot actually back-up water that far without causing flooding, but for this cursory screening phase, this is our best estimate. A delineation of potential pipe-storage includes all pipes upstream of the candidate retrofit location that are below the rim elevation of lowest upstream junction. Now that we have delineated the limits of

potential pipe storage, we can calculate the volume of each individual potential storage pipe, and sum those volumes.

4.1.2 Estimating the Sewershed Area

For the second part of the *maximum available storage in the pipes-to-sewershed area* ratio, sewershed area, there are a number of methods and resources available to assist with this. For a site-level candidate retrofit location (i.e. a single property or development) existing drainage design plans may be available from a local regulatory agency or the property owner. These plans will provide the most accurate extent of the drainage area. For large-scale projects, or site-level projects for which no drainage design plans can be obtained, the drainage area can be delineated using publicly available elevation data – either topographic mapping (elevation contours) or a digital elevation model (DEM). While, the most accurate method would involve a hand delineation by and experiences spatial analysis with access to electronic sewer system data, aerial photographs, and high-resolution elevation contours based on LiDAR data, this level of precision is not necessary for this initial screening phase. Note that, depending on the nature of the areas in question, a higher degree of confidence in sewershed (and “Subcatchment”) area(s) will likely be required for the development of the Storm Water Management Model (SWMM) to be utilized to conduct flood risk and critical discharge frequency analyses in the final two phases of the process.

Procedures and tutorials for delineating drainage areas/watershed using topographic mapping are available for many online sources including the [Natural Resources Conservation Service](#)¹⁷. Similarly, there are online sources documenting procedures for delineating watershed using DEMs and ArcGIS. Alternatively, there are also some online tools that will delineate watersheds associated with a point that the user drops on a map (e.g. [USGS’s StreamStats](#)¹⁸; & [WikiWatershed’s Model My Watershed tool](#)¹⁹); however, these delineations are typically based on low-resolution DEMs and should be used with caution for site-level or small-scale projects.

It should also be noted that the proportion to the sewershed that is covered by impervious surface, and the extent to which impervious surface is directly plumbed to the sewer system will impact the amount of water delivered to the sewer. When comparing *maximum available storage in the pipes-to-sewershed area* ratios, consider whether this aspect of the candidate drainage areas is comparable. All other factors being equal, a candidate site with a greater proportion of impervious surface in its sewershed should be considered to have a lower effective *maximum available storage in the pipes-to-sewershed area* ratio.

4.2 Diameter of the Pipe to be Retrofitted

In addition to the *maximum available storage in the pipes-to-sewershed area* ratio, the size of the pipe on which the retrofit is to be installed, is an important factor for *flap gate* retrofits in particular, that could impact the suitability of the location for retrofitting. All other factors being equal, when retrofitting a 6-foot diameter pipe vs. a 3-foot diameter pipe with a *flap gate retrofit*, a much larger force will be required to hold the gate shut for the 6-foot diameter pipe. This is because the surface area of the flap gate, on which the force of the detained water is being applied, is four times greater for a 6-foot diameter flap gate than for a 3-foot diameter flap gate. That produces four times as many inches² to be multiplied by the pressure (lbs./inch²) exerted on the gate based on the height of water to be held back by the flap gate.

¹⁷ https://www.nrcs.usda.gov/wps/portal/nrcs/detail/nh/technical/?cid=nrcs144p2_015680

¹⁸ <https://streamstats.usgs.gov/ss/>

¹⁹ <https://modelmywatershed.org/>

As this example illustrates, the amount of force required to hold a flap gated shut against a given height of water increases exponentially with increasing pipe diameter.

5.0 Estimating Cursory Retrofit Design Parameters

5.1 Summary

In this section we describe how to use the spreadsheet tool that has been created, for use with this document, to estimate cursory design parameters for a candidate retrofit location. The spreadsheet tool includes separate “sheets” for *flap gate retrofits*, and for *riser retrofits*. As the user begins the process of populating (and tweaking) the input parameters of the spreadsheet tool, important information can be gleaned about the design options and physical challenges for the candidate location. This tool can also be used to generate the data needed to model the retrofit in U.S. Environmental Protection Agency’s Storm Water Management Model (SWMM) as described in Section 6.

This phase of the process can be completed largely with the same data requirements discussed in the Section 4, with one addition: pipe material. Knowledge of the material that the pipe is made of will be needed to select an appropriate Manning’s coefficient as discussed in Section 5.3.

5.2 A Narrative Example of How the Spreadsheet Tool Can be Used

When assessing the potential for installing a flap gate retrofit at a candidate location, the user can start by entering the estimated maximum storage height (“height of water”) into the appropriate cell of the “Flap Gate – Inputs and Outputs” sheet of the spreadsheet. The maximum storage height can be estimated as a couple of feet below the lowest manhole of catch basin elevation (lowest potential flood point), upstream of the retrofit, minus the invert elevation at the location of the retrofit. The user can increase the force exerted to hold the gate closed (“additional weight”) until the gate stays shut at the prescribed maximum storage height. Next, the user can change the size of the low flow orifice (“bottom opening”) to attempt to achieve a “flow rate” (a spreadsheet output) of just under the target *critical discharge* for the prescribed maximum storage height. At this point, the user can begin to incrementally decrease the force exerted to hold the gate closed until a force is identified that will continue to hold the gate shut at the prescribed maximum storage height, but will allow the gate to begin to open if the “height of water” is increased by one-inch.

At this point the user can take a very important step in the early site suitability assessment process, assessing the feasibility of holding back the prescribed maximum storage height, based on the amount of force required to do so (the sum of the “Weight of Gate” and “Additional Weight” parameters). The infrastructure on which the flap gate retrofit will be mounted, must be able to support the equipment necessary to exert this amount of force (such equipment might include weights hung on the gate, spring powered latches, or magnets). **Does the amount of force required to hold the gate closed seem feasible?** If not, try any or all of the following approaches:

- increase the angle at which the gate will be mounted on the pipe (initial angle of gate);
- reducing the maximum storage height; or
- increase the target critical discharge (see discussion in Section 3.3).

If the none of those option result in reducing the force required to hold the gate shut to a feasible level, and the candidate retrofit location is an outfall, consider if a *riser retrofit* might be a more appropriate solution.

Through this iterative process of parameter tweaking, the user will close-in-on the optimal cursory design parameter estimates for the candidate retrofit location, if the location is suitable. Keep in mind, that even if the spreadsheet indicates that you can feasibly detain a certain maximum storage height, the flood risk analysis (Section 7), may indicate that the proposed design would result in increased flooding. In that case, try reducing the level of the maximum storage height (tweaking other parameters appropriately) and conduct the flood risk analysis again base on the new resulting cursory design parameters.

5.3 Flap Gate Retrofit Spreadsheet Tool – Inputs

An image of the Input Parameters section of the *flap gate retrofit* spreadsheet tool is provided below.

	A	B	C	D	E	F	G	H
	Input							
1								
2	Pipe Parameters (for the pipe immediately upstream of the flap gate retrofit)							
3	This program is currently only valid for circular pipes.							
4	Pipe Diameter	Enter the channel diameter	D	24.00	inches	2.00	feet	
5	Pipe Radius	The radius is automatically calculated	R	12.00	inches	1.00	feet	
6								
7	Height of water	Enter height to which water is backed-up above the pipe invert (maximum height is 20 feet).	H	48.00	inches	4.00	feet	
9								
10	Pipe Slope	Enter the slope of the pipe	s	1.000%	percent	<5%		
11				0.0100	ft/ft			
12	Manning's Coefficient	Enter the Manning's Roughness Coefficient	n	0.0110				
13								
14	Flap Gate Parameters							
15	Bottom Opening	Enter the height of any opening cut into the gate (height above pipe invert).	G	3.00	inches	0.25	feet	G<R
16	Weight of Gate	Enter the weight of the flap gate	w	250.00	lbs			
17	Additional Weight	Enter any additional weight placed on the gate or the total equivalent weight of the sum of forces applied via other mechanism.	W	2,500.00	lbs			
18	Initial Angle of gate	Enter the initial angle of the gate	θ	5.00	degrees			
19	*Future* Enter the location of the weight from the hinge	Location of Weight (L)	L	Not used	feet from hinge			
20	Bottom Opening Discharge Coeff	Dimensionless number for pressure loss in nozzles and orifices.	0.70					
21								
22								

Figure 5.1: Screen shot of the *flap gate retrofit* spreadsheet tool Inputs Parameters section.

There are two input parameter subsections in the spreadsheet, Pipe Parameters (for the pipe on to which the retrofit would be installed), and Flap Gate Parameters. The light-green cells with bold font, in both of these input subsections, are cells in which the user can input parameters.

The Pipe Parameters to be input into the spreadsheet tool are as follows:

1. Pipe Diameter (D) – Enter the diameter of the pipe in inches (in). The program shows the pipe diameter converted to feet (ft). The radius is also automatically calculated and shown in inches and in feet.
2. Height of Water (H) – Enter the height of water to which water can be backed-up above the invert of the pipe at the retrofit (in). Note that the maximum height of water allowed is 20-feet.
3. Pipe Slope (S) – Enter the slope of the pipe, as a percentage of fall over run. This parameter is actually the slope of the hydraulic curve upstream of the discharge and can be approximated by the slope of a pipe for a distance equal to approximately ten pipe diameters.
4. Manning's Coefficient (n) – Enter the Manning's roughness coefficient for the pipe. The Manning's roughness coefficient should be considered to be dependent upon the depth of flow.

The Flap Gate Parameters to be input into the spreadsheet tool are as follows:

1. Bottom Opening (G) – If a low flow orifice is achieved by cutting off a portion of the bottom of the gate, enter the height of the opening above the invert of the pipe (in).
2. Weight of Gate (w) – enter the weight of the flap gate, in pounds (lbs).
3. Additional Weight (W) – Enter any additional weight placed on the gate or the total equivalent weight in pounds of the sum of forces applied via other mechanisms (e.g. spring latches or magnets), (lbs).
4. Initial Angle of the Gate (Θ) – Enter the initial angle at which the gate is mounted on the pipe in degrees (typically between 5 degrees and 15 degrees from the vertical). This allows the gate to have a horizontal face component to completely seat the gate by gravity. If the gate is not mounted at an angle, enter "0" in this cell.
5. Bottom Opening Discharge Coefficient - The discharge coefficient is a dimensionless number between 0 and 1 used to characterize the flow and pressure loss behavior of nozzles and orifices in fluid systems. This parameter is specific to the geometry of the pipe, the depth of flow, the design of the flap gate and the weight of the flap gate. Use 0.7 as the initial parameter. A higher discharge coefficient indicates lower losses and a higher flow rate and could be used to determine worst-case scenarios.

5.4 Flap Gate Retrofit Spreadsheet Tool – Outputs

An image of the Output section of the *flap gate retrofit* spreadsheet tool is provided below.

	A	B	C	D	E	F
24	Output (specific to input height of water)		48 inches			
25	Flow Rate	Total Flow Rate from the Pipe	Q	35.30	cfs	
26				15,840.68	gpm	
27						
28	Velocity	Velocity of Water from the Pipe	V	11.23	ft/sec	
29						
30	Area of Bottom Opening	Area open to flow through the opening at the bottom of the gate		0.2267	ft^2	
32						
33	Flow Area	Total Equivalent Flow Area (dependent upon angle of gate opening)	A	3.1416	ft^2	
34						
35	Force Required to Keep Gate Shut					
36	Water Force on Gate	This is the force of water on the gate		8,416.45	ft-lb/sec^2	
37	Down Force on Gate	This is the gravitational force on the gate.		7,717.64	ft-lb/sec^2	
38	Status of Gate Opening	Gate is "Open" or "Closed"	Gate is	Open		
39	Additional Pull Force Required	This force represents the additional		698.81	ft-lb/sec^2	
40						
41	Angle of Opening	This is the angle of the gate opening		Fully Open	degrees	
42						
43						
44						
45	Output (data series table for full range of potential water heights)					
46	The output below shows the flow rate, velocity, gate open status, and angle of gate opening for all values of "height of water" upto the maximum height of water (in one-inch increments). This data is also graphed in the charts on the associated sheets.					
47						
48	Height of Water (inches)	Flow (cfs)	Velocity (fps)	Gate Open?	Angle of Gate	Height of water (ft)
49	1	0.09	1.95	Closed	0.00	0.08
50	2	0.38	3.05	Closed	0.00	0.17
51	3	0.64	3.21	Closed	0.00	0.25
52	4	0.74	3.24	Closed	0.00	0.33
53	5	0.82	3.63	Closed	0.00	0.42
54	6	0.90	3.97	Closed	0.00	0.50
55	7	0.97	4.29	Closed	0.00	0.58
56	8	1.04	4.59	Closed	0.00	0.67
57	9	1.10	4.86	Closed	0.00	0.75
58	10	1.16	5.13	Closed	0.00	0.83
59	11	1.22	5.38	Closed	0.00	0.92
60	12	1.27	5.62	Closed	0.00	1.00
	Cover Sheet	Flap Gate - Inputs and Outputs	Flap Gate Chart 1	Flap Gate Chart 2	Riser Inputs and Outputs	

Figure 5.2: Screen shot of the *flap gate retrofit* spreadsheet tool Outputs section.

There are two output subsections in the spreadsheet: outputs specific to the input height of water, and an output data series table for the full range of potential water heights. The output data series table includes height of water between one-inch and the input maximum height of water in increments of one-inch (reported in both inches and feet). The output data series table also reports flow (CFS), velocity (FPS), status of gate (open or closed), and angle of gate (degrees). This table will be utilized to create a tabular "Rating Curve" for SWMM to control the behavior of the retrofit model (Section 6.3.2).

The outputs specific to the input height of water include the following:

- Flow Rate – total flow rate from the pipe, Q in ft³/sec (cfs) and gallons per minute (gpm).

- Velocity – velocity of water from the pipe, V, in ft/sec.
- Area of Bottom Opening – the area open to flow through the opening at the bottom of the gate (corresponds Bottom Opening height input, G), in ft².
- Flow Area - The total flow area that is open to flow. This value varies with the angle to which the gate is pushed open by flow.
- Water Force on Gate – The force of water on the gate (Ft-Lb/sec²).
- Down Force on Gate – The gravitational force of the gate (Ft-Lb/sec²).
- Status of Gate Opening – When the water force is less than the gravitational force, the gate is closed. When the water force is greater than the gravitation force, the gate opens to an angle where the two forces are equal. This output is displayed as “Open” or “Closed”.
- Additional Pull Force Required – The additional pull force required to keep the gate closed. This represents the force that must be exerted in a horizontal direction to overcome the opening force that water is exerting on the gate. This could be applied using various mechanisms (or a combination of mechanisms) including weights, spring latches and/or magnets.
- Angle of Gate Opening – The angle of the partially open flap gate in degrees. When the gate is fully open (i.e., at 90 degrees), this field displays “Fully Open”. When the Gate is fully closed, the field displays “-”.

5.5 Riser Retrofit Spreadsheet Tool – Inputs

An image of the Input Parameters section of the *riser retrofit* spreadsheet tool is provided below.

	A	B	C	D	E	F	G	H
1	Input							
2	Pipe Parameters (for the pipe immediately upstream of the riser retrofit)							
3	Shape	This program is currently only valid for orifice pipes.	Circular	Circular				
4	Pipe Diameter	Enter the pipe diameter	D	24.00	inches	2.00	feet	
5	Radius	The radius is automatically calculated	R	12.00	inches	1.00	feet	
6								
7	Total Height of water	Enter the height of water from the bottom of the channel.	H	48.00	inches	4.00	feet	
8	Pipe Slope	Enter the slope of the pipe	s	1.00%	percent	<5%		
9				0.0100	ft/ft			
10	Manning's Coefficient	Enter the Manning's Roughness Coefficient	n	0.011				
11								
12								
13	Low-Flow Orifice Parameters							
14	Low flow Orifice Diameter	Enter the diameter of the low-flow orifice	d	3.00	inches	0.25	feet	d<D
19	Overflow Orifice Diameter	Enter the diameter of the over-flow orifice	do	24.00	inches	2.00	feet	
20	Height of Overflow Orifice	Enter the height of the overflow orifice above the invert of the pipe	h	48.00	inches	4.00	feet	
21	Bottom Opening Discharge Coeff		0.7					

Figure 5.3: Screen shot of the *riser retrofit* spreadsheet tool Inputs Parameters section.

There are two input parameter subsections in the *riser retrofit* spreadsheet, Pipe Parameters (for the pipe on to which the retrofit would be installed), and Orifice Parameters. The light-green cells with bold font, in both of these input subsections, are cells in which the user can input parameters.

The Pipe Parameters for this spreadsheet tool are the same as those described for the flap gate retrofit spreadsheet tool (Section 5.3).

The Orifice Parameters to be input into the spreadsheet tool are as follows:

- Low Flow Orifice Diameter – Enter the diameter of the circular low flow orifice (in). Note that the spreadsheet tool only supports circular orifices at this time.
- Overflow Orifice Diameter – Enter the diameter of the circular overflow orifice (in). Note that the spreadsheet tool only supports circular orifices at this time.
- Height of Overflow Orifice – Enter the height of the bottom of the overflow orifice above the invert of the pipe (in).
- Bottom Opening Discharge Coefficient - The discharge coefficient is a dimensionless number between 0 and 1 used to characterize the flow and pressure loss behavior of nozzles and orifices in fluid systems. This parameter is specific to the geometry of the pipe, the depth of flow, and the design of the riser. Use 0.7 as the initial parameter. A higher discharge coefficient indicates lower losses and a higher flow rate and could be used to determine worst-case scenarios.

5.6 Riser Retrofit Spreadsheet Tool – Outputs

An image of the Output section of the *riser retrofit* spreadsheet tool is provided below.

There are two output subsections in the spreadsheet: outputs specific to the input height of water, and an output data series table for the full range of potential water heights. The output data series table includes height of water between one-inch and the input maximum height of water in increments of one-inch (reported in both inches and feet). The output data series table also reports flow (CFS) and velocity (FPS). This table will be utilized to create a tabular “Rating Curve” for SWMM to control the behavior of the retrofit model (Section 6.3.2).

The outputs specific to the input height of water include the following:

- Flow Rate from Low Flow Orifice – Q in ft^3/sec (cfs).
- Velocity of Water from the Low Flow Orifice – V , in ft/sec .
- Flow Rate from Overflow Orifice – Q in ft^3/sec (cfs).
- Total Flow Rate – sum of flow rates from both the low flow orifice and the overflow orifice, Q in ft^3/sec (cfs).

	A	B	C	D	E
24	Output (specific to input height of water)			48.00	inches
25	Flow Rate from Lower Orifice	Flow Rate from Lower Orifice	Q	0.55	cfs
26				247.51	gpm
27	Velocity of Water from the Lower Orifice	Velocity from Lower Orifice	V	11.23	ft/sec
28					
29	Flow Rate from Overflow Orifice	Flow Rate from Overflow Orifice	Q	-	cfs
38				-	gpm
47	Total Flow Rate	Sum of Flow Rates from the Lower Orifice and the Overflow Orifice	Q	0.55	cfs
48				247.51	gpm
49					
50	Output (data series table for full range of potential water heights)				
51	The output below shows the flow rate from the Lower and Upper orifice, velocity from the Lower Orifice and Total Flow Rate for all values of "height of water" (in one-inch increments) up to the maximum height of 144 inches (assumed to be two 6-foot culverts stacked).				
52					
53	Height of water (inches)	Flow Rate from Lower Orifice (cfs)	Velocity of Water from the Lower Orifice (fps)	Flow Rate from Overflow Orifice (cfs)	Total Flow Rate (cfs)
54	1	0.03	1.75	0.00	0.03
55	2	0.08	2.36	0.00	0.08
56	3	0.10	2.81	0.00	0.10
57	4	0.16	3.24	0.00	0.16
58	5	0.18	3.63	0.00	0.18
59	6	0.19	3.97	0.00	0.19
60	7	0.21	4.29	0.00	0.21
61	8	0.23	4.59	0.00	0.23
62	9	0.24	4.86	0.00	0.24
63	10	0.25	5.13	0.00	0.25
64	11	0.26	5.38	0.00	0.26
65	12	0.28	5.62	0.00	0.28
66	13	0.29	5.85	0.00	0.29
67	14	0.30	6.07	0.00	0.30
68	15	0.31	6.28	0.00	0.31
69	16	0.32	6.49	0.00	0.32
70	17	0.33	6.69	0.00	0.33
71	18	0.34	6.88	0.00	0.34
72	19	0.35	7.07	0.00	0.35
73	20	0.36	7.25	0.00	0.36
74	21	0.36	7.43	0.00	0.36
	◀ ▶	Cover Sheet	Flap Gate - Inputs and Outputs	Flap Gate Chart 1	Flap Gate Chart 2
					Riser Inputs and Outputs

Figure 5.4: Screen shot of the *riser retrofit* spreadsheet tool Outputs section.

5.7 Technical Documentation for *Flap Gate Retrofit* Calculations

The spreadsheet tool for the *flap gate retrofit* use the following flow equations:

1. Manning equation for open channel flow when the water level is below the height of the bottom opening ($H < G$).

2. Bernoulli's equation in the form of Torricelli's Law when the water height is greater than bottom opening but the gate is fully closed.
3. Manning equation for open channel flow when the water level is above the height of the bottom opening ($H < G$) and the gate is open.
4. Bernoulli's equation when the water height is greater than the pipe diameter and the gate is fully open ($H > D$).

Each flow regime is explained in the sections below.

5.7.1 Manning Equation Open Channel Flow Through the Bottom Opening

When the flow is governed by the slope of the pipe and the roughness coefficient and is approximated by the Manning's equation for open channel flow:

$$Q = \frac{1.49}{n} * A * R_h^{2/3} * S^{1/2}$$

Where:

Q is the flow rate of water, ft³/sec (cfs)

n is the Manning roughness coefficient

A is the flow area, ft²

R_h is hydraulic radius, ft

S is the slope of the pipe in feet/feet

If flow depth (H) < radius, r:

1. Circular segment height, $h = H$
2. Central angle, $\theta = 2 * \cos^{-1}\left(\frac{r-h}{r}\right)$
3. Segment Area, $K = r^2 * \frac{(\theta - \sin \theta)}{2}$
4. Arc Length, $s = r * \theta$
5. Flow Area, $A = K$
6. Wetted Perimeter, $P_w = s$
7. Hydraulic Radius, $R_h = A/P_w$

If flow depth (H) > radius, r:

1. Circular segment height, $h = 2r - d$
2. Central angle, $\theta = 2 * \cos^{-1}(\frac{r-h}{r})$
3. Segment Area, $K = r^2 * \frac{(\theta - \sin \theta)}{2}$
4. Arc Length, $s = r * \theta$
5. Flow Area, $A = \pi r^2 - K$
6. Wetted Perimeter, $P_w = 2\pi r - s$
7. Hydraulic Radius, $R_h = A/P_w$

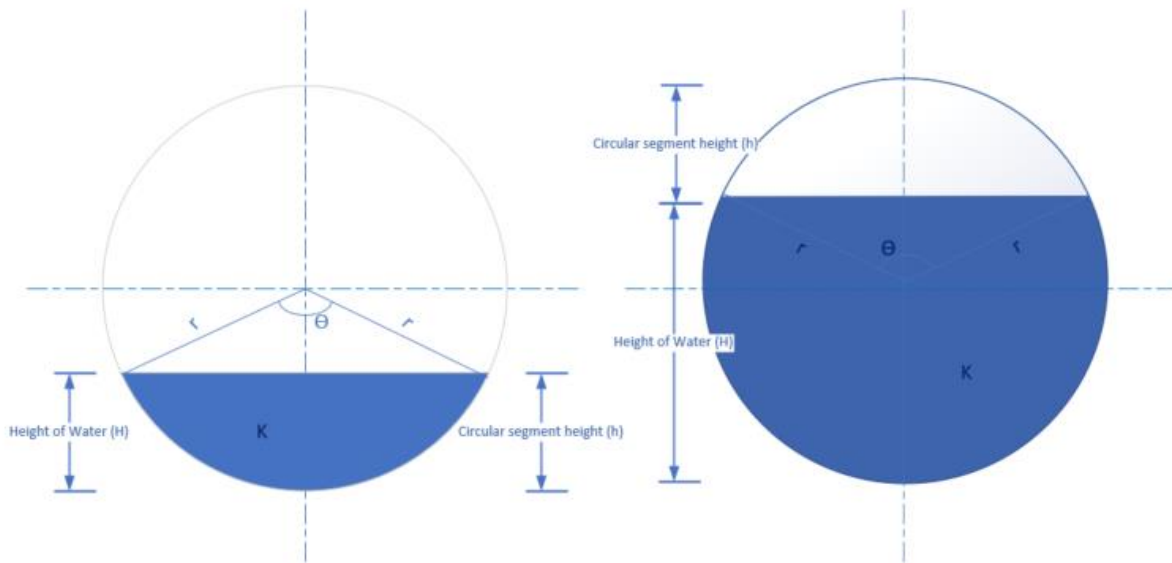


Figure 5.5: Circular measurement reference diagram.

5.7.2 Torricelli's Law (Bernoulli's Equation)

The velocity of fluid flowing out of an orifice under the force of gravity is related to the height of fluid behind the orifice through Torricelli's Law:

$$V = C_d * \sqrt{2gH}$$

$$Q = V * A = C_d * A * \sqrt{2gH}$$

Where:

V is the velocity of flow, ft/sec

A is the area of the flow, ft²

H is the height of fluid behind the orifice, ft

g is the acceleration due to gravity, ft/sec²

C_d is the discharge coefficient, a dimensionless number to characterize the flow and pressure loss behavior of nozzles and orifices in fluid systems

5.7.3 Angle of the Gate Opening

To calculate the angle of opening, the force of the water jet on the flap gate should equal the downward moment of the weight of the flap gate. The pressure force of the water has a resultant force that is 2/3 of the way from the top of the water height. The force of the water and the downward force from the weight of the gate is given by:

$$F_w = \rho * A * V^2 * \cos \theta$$

$$F_{gate} = (W + w) * g * \sin \theta$$

Summing the moments about the hinge point, M, and rearranging:

$$\sin \theta = \frac{\rho * A * V^2}{(W + w) * g}$$

Where:

F_w = net force of water

P = density of water, lb/ft³

A = wetted area, ft²

V = velocity of water, ft/sec

$\sin \theta$, $\cos \theta$ = sine and cosine of the angle of opening of the flap gate

w = weight of the gate, lbs

W = additional weight placed on the gate, lbs

g = acceleration due to gravity, ft/sec²

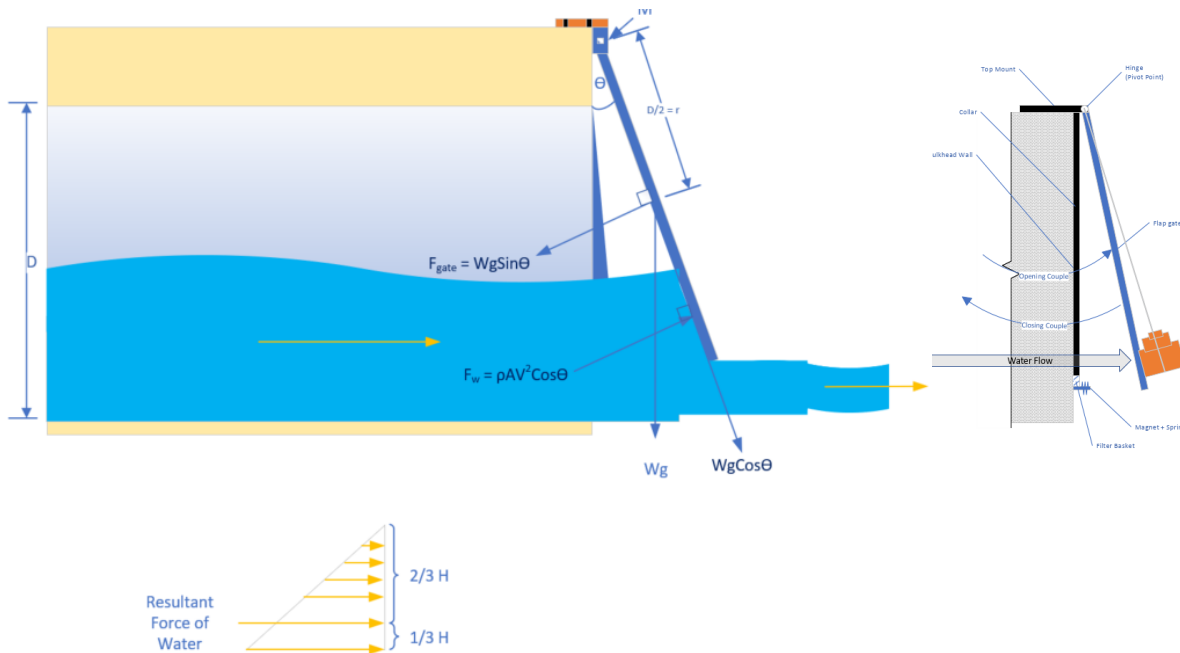


Figure 5.6: Diagram of forces associated with a *flap gate retrofit*.

5.7.4 Flap Gate Retrofit Technical References

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5.8 Technical Documentation for Raiser Retrofit Calculations

The riser retrofit calculations are based on the open pipe flow equations presented in Section 5.7.1 for water heights less than the diameter of the orifice and full-pipe pressure discharge presented in Section 5.7.2 for water heights greater than the diameter of the orifice. The same equations are valid for the Lower and the Upper orifice.

6.0 Representing Retrofits in a Storm Water Management Model (SWMM)

6.1 The Role of SWMM in the Process

Utilization of the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM), will be a critical component of this project screening and cursory design process. Please note that, other modeling platforms may have similar capabilities to SWMM and be suitable to conduct these analyses; however, the methods described in the following three sections have been developed specifically for SWMM 5 version 5.1. Once pre-treatment and post-treatment versions the SWMM are complete, these models will facilitate flood risk analyses (Section 7), as well as critical discharge frequency analyses (Section 8) of the candidate retrofit location. The spreadsheet tool discussed in Section 5 will be utilized to parameterize the post-treatment SWMM. The first step is to build and calibrate a pre-treatment SWMM. This section will discuss how to alter a copy of that pre-treatment SWMM to represent the proposed retrofit for a post-treatment model using SWMM-specific objects and methods.

Data requirements for this phase of the process include all of the data requirements discussed in Sections 4 and 5, in addition to: invert elevations for all junctions, land cover (impervious surface) data, soils data (parameters dependent upon infiltration method selected in SWMM), and elevation data to facilitate delineation of "Subcatchments", (areas draining to each catch basin). See Section 4.1.2 for a discussion of drainage area delineation methods. Rainfall data will also be required to run simulations once the SWMMs are developed. Acquiring appropriate rainfall data for the flood risk analysis and the critical discharge frequency analysis is discussed in Sections 7 and 8 respectively.

6.2 SWMM Resources

The procedures for setting up a sewershed model with SWMM are well document; and therefore, are not discussed here. The reader will need to have a level of familiarity with SWMM to understand and apply the methods presented in this Section as well as Sections 7 and 8. Readers with little or no experience with SWMM (but with a basic understanding of hydrology), are encouraged to start by reviewing the most recent version of the SWMM User's Manual. For analysis of relatively small sewersheds (only several sewer inlets and pipes), the beginning user should be able learn the procedure and build a model with no more that a week or two of focused effort; however, modelling a larger sewershed can be a time-intensive task requiring advanced techniques, for example, to delineate a large number of "Subcatchments".

The most recent version of SWMM can be downloaded at [EPA's SWMM website](https://www.epa.gov/water-research/storm-water-management-model-swmm)²⁰. Also, at this website the User will find a link to download the most recent version of the User's Manual. In addition to the User's Manual the Reference Manuals, Volume I (Hydrology) and Volume II (Hydraulics), will also be necessary resources for understanding the "objects" and methods utilized in the methodology described here. Finally, most watershed modeling projects involve a period of trouble shooting/debugging before

²⁰ <https://www.epa.gov/water-research/storm-water-management-model-swmm>

the model will run as intended. If you find yourself stumped at this phase in the project, the [Open SWMM](#) website and online community²¹ will likely be an invaluable resource.

6.3 Representing Storm Sewer Retrofits in SWMM

The two types of storm sewer retrofits for which methods were developed include *flap gate retrofits* and *riser retrofits*, as described in Section 1.3. While these two types of retrofits are structurally and functionally quite different, the methods for representing them in SWMM are similar. Multiple “visual objects” will be used to represent the retrofit structure and “non-visual objects” will be used to control the manner in which flow is routed through the various “visual objects” to model different flow conditions. See Chapter 3 of the SWMM User’s Manual Version 5.1 for discussion of “visual” vs “non-visual” objects.

6.3.1 Visual Objects Used to Represent Storm Sewer Retrofits in SWMM

While a *riser retrofit* can only be installed at a storm sewer outfall, a *flap gate retrofit* can be installed at either an outfall or within an adequately sized junction (e.g. manhole or catch basin). In either case, the “Node” in SWMM representing the real-world outfall or junction to be retrofitted will be represented in the model as a notational modeling “Junction” (hereafter referred to as Junction Z). When modeling a retrofit to be installed in a manhole or catch basin, Junction Z will remain the same type of “Node” as in the pre-treatment SWMM, a notational “Junction”; however, when modeling a retrofit to be installed on an outfall, the “Node” in the pre-treatment SWMM, a notational “Outfall”, will be converted to a notational “Junction”.

In the case of a *flap gate retrofit* in a manhole or catch basin, Junction Z will discharge through three “Links”, to a single notational “Junction” (Junction Z2) added to the SWMM a short distance below the junction to be retrofitted (Figure 6.1). In the case of retrofitting an outfall, Junction Z will discharge through two or three (depending on retrofit type) “Links”, to two or three notational “Outfalls” (Figures 6.2 and 6.3). Regardless of whether a retrofit is to be modeled at an outfall or in a manhole/catch basin, a *flap gate retrofit* will have three “Links” connected to Junction Z (Figures 6.1 and 6.2) while a *riser retrofit* will have only two “Links” connected to Junction Z (Figure 6.3). The rest of this subsection will describe the modeling method in the context of a *flap gate retrofit* installed on an outfall – reference Figure 6.2 for clarification on how the visual objects discussed connect to each other.

²¹ <https://www.openswmm.org/>

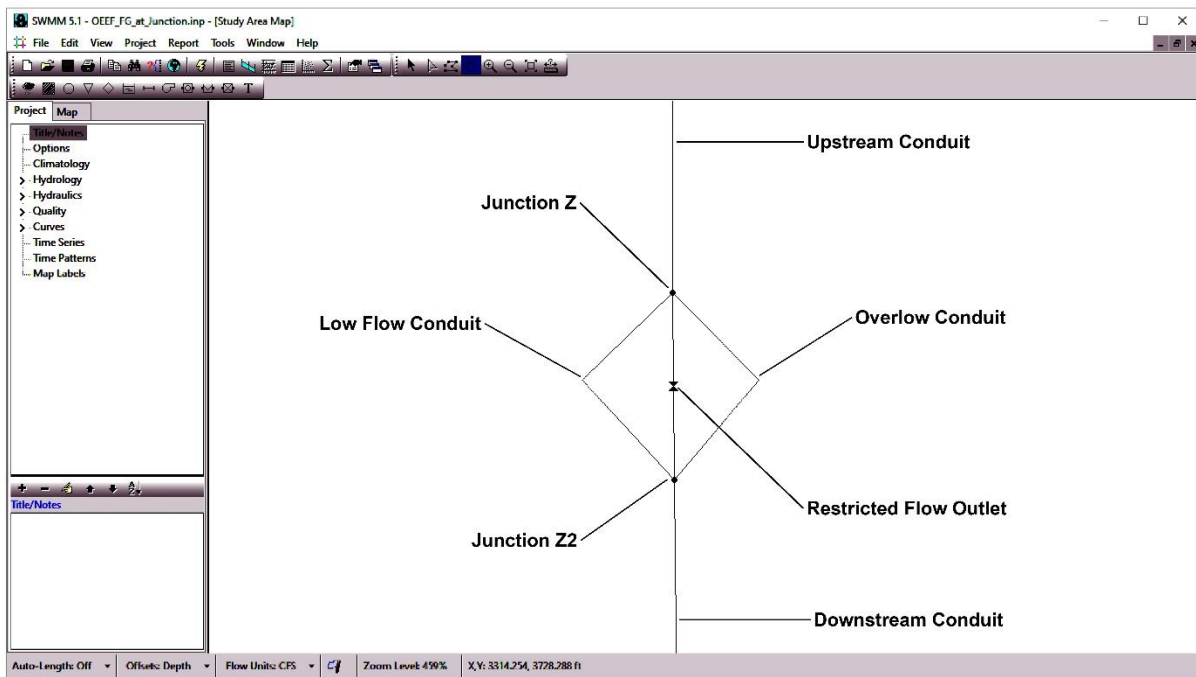


Figure 6.1: “Visual Objects” used to represent a *flap gate retrofit* in a junction (manhole or catch basin) in SWMM.

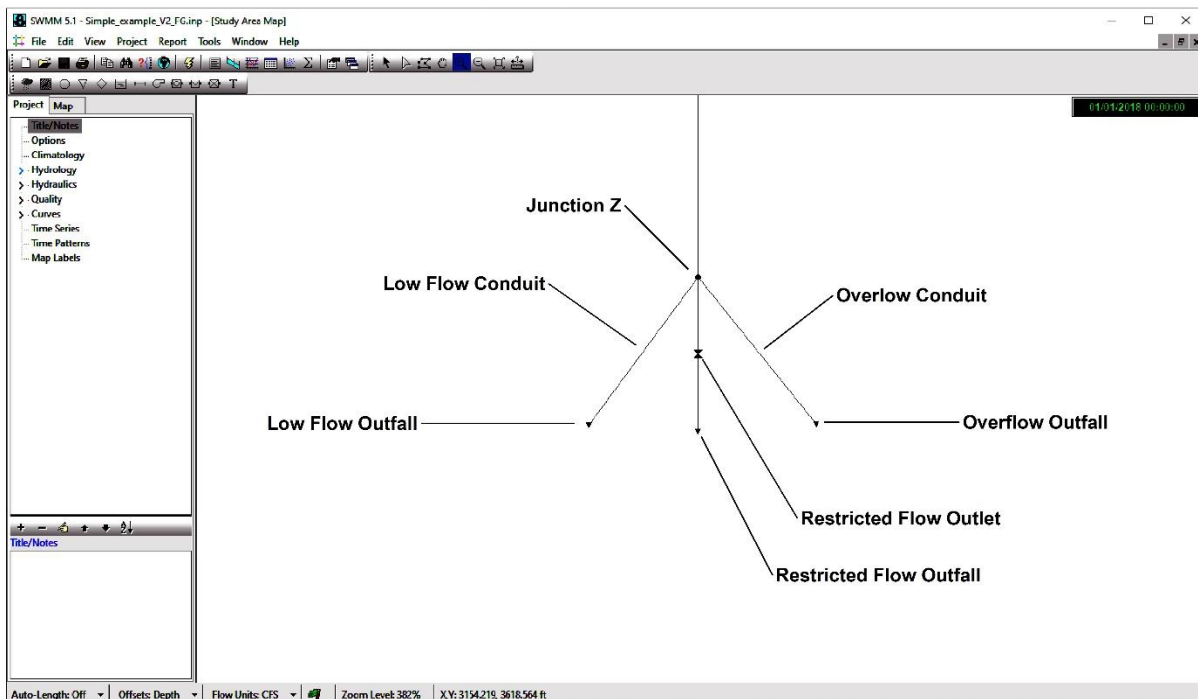


Figure 6.2: “Visual Objects” used to represent a *flap gate retrofit* on an outfall in SWMM.

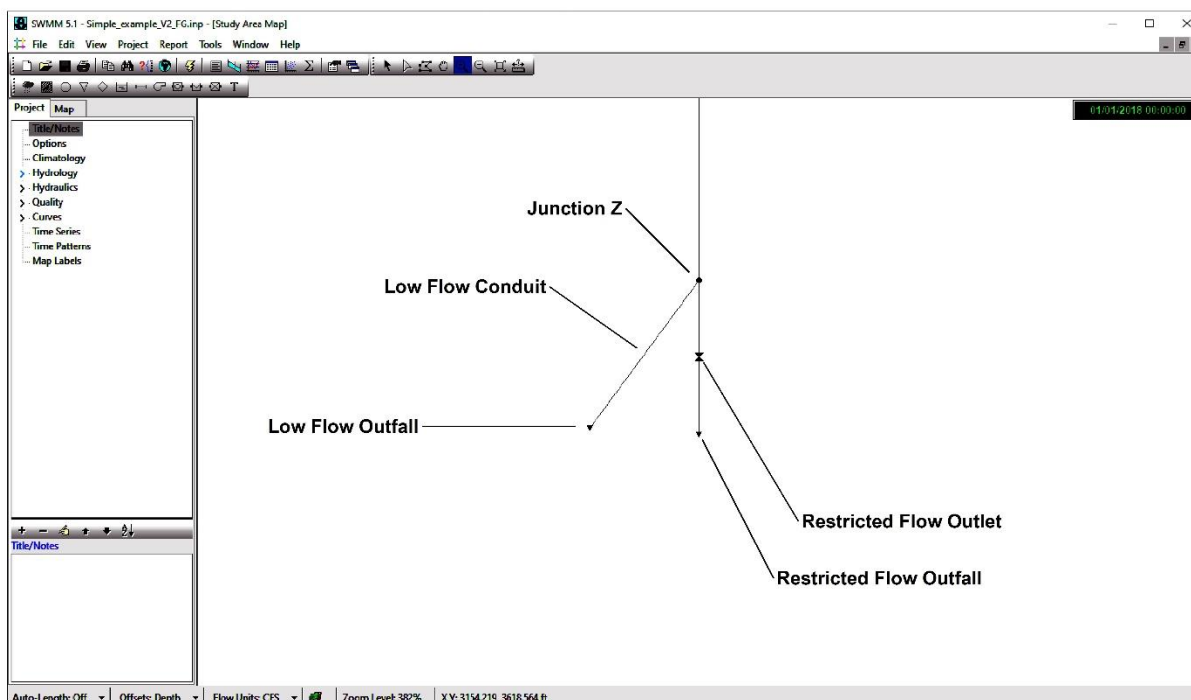


Figure 6.3: "Visual Objects" used to represent a *riser retrofit* on an outfall in SWMM.

Two different types of "Links" will be utilized to connect Junction Z to the notational "Outfalls", "Conduits" and "Outlets". For "Conduit" type "Links", the *Length* property for these "Conduits" will be very short to keep effects of friction minimal since they do not physically exist in the real-world and are purely modeling constructs (5 to 10-feet may be reasonable lengths). The *Invert El.* (invert elevation) property for the "Outfalls" connected to these "Conduits" will be set as appropriate to achieve the same slope as the preceding upstream "Conduit" above Junction Z (based on the "Conduit" *length*). For "Outlet" type "Links", the *Invert El.* of the "Outfall" connected to the "Outlet" will be set to the same *Invert El.* as Junction Z (because "Outlets" do not have *length* properties in SWMM).

The first of the three "Link"-*"Outfall"* pairs added to the post-treatment SWMM, downstream of Junction Z, will be utilized to represent the real-world condition in which flow is discharging through the low flow orifice (of either type of retrofit) in an unrestricted manner (i.e. flow depth \leq the height of the low flow orifice). A "Conduit", hereafter referred to as Low Flow Conduit, will be used to connect the Junction Z to the "Outfall", hereafter be referred to as Low Flow Outfall.

The second "Link"-*"Outfall"* pair will be utilized to represent the real-world condition, for a *flap gate retrofit*, in which flow is discharging through the low flow orifice under pressure due to water backing-up above the elevation of the top of the low flow orifice, but not pushing open the flap gate. In the case of a *riser retrofit*, this "Link"-*"Outfall"* pair will be utilized to represent two real-world conditions: flow is discharging through the low flow orifice under pressure due to water backing up above the elevation of the top of the low flow orifice, but not high enough to discharge through the overflow orifice, and the real-world condition in which there are discharges coming from both the low flow orifice and the overflow orifice of the riser structure. For both *flap gate retrofits* and *riser retrofits*, this second "Link"-*"Outfall"*

pair will consist of an “Outlet” type “Link”, hereafter referred to as Restricted Flow Outlet, connecting Junction Z to an “Outfall”, hereafter be referred to as Restricted Flow Outfall.

The real-world condition in which the flap gate, on a *flap gate retrofit*, has been pushed open will be represented by a third “Link”-“Outfall” pair consisting of a “Conduit”, hereafter referred to as Overflow Conduit, connecting Junction Z to a third “Outfall”, hereafter be referred to as Overflow Outfall. As discussed, this third “Link”-“Outfall” pair will not be utilized for representing *riser retrofits* in SWMM.

To understand why the two types of retrofits are represented differently here, one must understand that flow will be modeled through the Low Flow Conduit and the Overflow Conduit based on unmodified SWMM computations, while flow will be modeled through the Restricted Flow Outlet based on a tabular “Rating Curve” (discussed below in subsection 6.3.2) created using the spreadsheet tool discussed in Section 5. In the case in which a flap gate of a *flap gate retrofit* is pushed fully open (90-degrees from vertical) the flow conveyance capacity of the system is restored to pre-retrofit conditions and a “Rating Curve” is no longer needed to modify the computations of the SWMM; so, flow is routed away from the Restricted Flow Outlet and to the Overflow Conduit. However, in a *riser retrofit*, while the overflow orifice is designed to restore some flow conveyance capacity to the system, the HGL will still be altered; therefore, a “Rating Curve” will still be needed to modify the computations of the SWMM even after the riser begins to overflow. Consequently, flow will continue to be routed to the Restricted Flow Outlet until the water height recedes to a height below the top of the low flow orifice at which time the flow will be routed to the Low Flow Conduit.

Regarding parameterization of Junction Z, the “Max. Depth” must be set to an artificially high level that will be higher than the elevation to which water will be backed up into the system by the retrofit (this is the standard approach to modeling a sealed manhole in SWMM). This is important because, in the case that flow is discharging through the low flow orifice (of either type of retrofit) under pressure due to water backing up above the elevation of the top of the low flow orifice, the depth of water in Junction Z will correspond to the elevation to which water is backed-up in the system. This depth will be utilized in the “Control Rules” (discussed below) to route flow through the various “Link”-“Outfall” pairs discussed above. Additionally, the “Max. Depth” must be set higher than any potential flood point or it could impact the flood risk analysis discussed in Section 7.

The use of a “Rating Curve” is discussed in the following sub-section (this tabular data series will be created using the spreadsheet tool discussed in Section 5), but a couple input properties of the Restricted Flow Outfall will need to be set to utilize that “Rating Curve”. Note that the *Rating Curve* property of the Restricted Flow Outfall, should be set to “TABULAR/HEAD” from the dropdown menu. Once a “Rating Curve” has been created in SWMM, it will be selected from the dropdown menu for the *Curve Name* property under the *Tabular Curve* section of the Restricted Flow Outfall properties dialog window.

6.3.2 Non-Visual Objects Used to Represent Storm Sewer Retrofits in SWMM

6.3.2.1 Applying Control Rules

“Control Rules” will be developed to specify the conditions under which the flow discharging from Junction Z is routed to each of the two or three connected “Links” discussed in the previous sub-section. Below the conditional rules will be described for each type of retrofit installed at an outfall, using the visual object names specified in the previous subsection.

In the case of a *flap gate retrofits* installed on an outfall, the conditional rules will be as follows:

1. Flow will be routed through the Low Flow Conduit when the height of water in Junction Z is \leq the height of the low flow orifice.
2. Flow will be routed through the Restricted Flow Outlet when the height of water in Junction Z is $>$ the height of the low flow orifice, but $<$ the height required to push the flap gate open.
3. Flow will be routed through Overflow Conduit when the height of water in Junction Z is, \geq the elevation required to push the flap gate open.

The following is an example of how these “Control Rules” can be written into SWMM using the visual object names specified above (bold green text) and assuming a low flow orifice height of 0.33-feet, and a 3.1-foot water height required to push the flap gate open.

RULE 1
 IF NODE **JUNCTION Z** DEPTH \leq 0.33
 THEN OUTLET **RESTRICTED FLOW OUTLET** Setting = 0
 AND CONDUIT **OVERFLOW CONDUIT** STATUS = CLOSED

RULE 2
 IF NODE **JUNCTION Z** DEPTH $<$ 3.1
 AND NODE **JUNCTION Z** DEPTH $>$ 0.33
 THEN OUTLET **RESTRICTED FLOW OUTLET** SETTING = 1
 AND CONDUIT **OVERFLOW CONDUIT** STATUS = CLOSED
 AND CONDUIT **LOW FLOW CONDUIT** STATUS = CLOSED

RULE 3
 IF NODE **JUNCTION Z** DEPTH \geq 3.1
 THEN CONDUIT **OVERFLOW CONDUIT** STATUS = OPEN
 AND OUTLET **RESTRICTED FLOW OUTLET** SETTING = 0
 AND CONDUIT **LOW FLOW CONDUIT** STATUS = CLOSED

In the case of a *riser retrofit*, the conditional rules will be as follows:

1. Flow will be routed through the Low Flow Conduit when the height of water in Junction Z is \leq the height of the low flow orifice.
2. Flow will be routed through the Restricted Flow Outlet when the height of water in Junction Z is $>$ the height of the low flow orifice

The following is an example of how these “Control Rules” can be written into SWMM using the visual object names specified above and assuming a low flow orifice height of 0.33-feet.

RULE 1
 IF NODE **JUNCTION Z** DEPTH \leq 0.33
 THEN OUTLET **RESTRICTED FLOW OUTLET** Setting = 0

RULE 2
 IF NODE **JUNCTION Z** DEPTH $>$ 0.33
 THEN OUTLET **RESTRICTED FLOW OUTLET** SETTING = 1
 AND CONDUIT **LOW FLOW CONDUIT** STATUS = CLOSED

6.3.2.1 Applying a Rating Curve

A “Rating Curve” will be utilized to set the flow rate from the Restricted Flow Outlet, as a function of the height to which water has been backed-up into the system behind the retrofit (defined in SWMM as the depth of water in Junction Z). This tabular relationship will be created using the appropriate “sheet” of the spreadsheet tool discussed in Section 5, and then pasted into SWMM’s “Rating Curve Editor” dialog window. When creating this tabular relationship with spreadsheet tool, the lowest water height value should be just above the height of the low flow orifice. The highest water height value in the tabular relationship will differ between the two retrofit types:

- in the case of a *flap gate retrofit*, the highest water height value in the tabular relationship will correspond to the that which would push the gate open completely (90-degrees from vertical).
- in the case of a *riser retrofit*, the highest water height value in the tabular relationship will correspond to the highest water height one would expect in the sewer system – the elevation of the lowest upstream junction (e.g. manhole or catch basin) from which flooding would be expected to occur.

While the spreadsheet tool described in section 5 reports the “height of water” in inches, these heights must be converted into decimal feet before being pasted into SWMM’s “Rating Curve Editor” dialog window. Flow is reported by the spreadsheet tool feet³/second (CFS); so, flow units in SWMM must be set to CFS or else conversions must be made before the tabular relationship is pasted into SWMM’s “Rating Curve Editor” dialog window.

Note that SWMM objects often have properties (and outputs) associated with water “depth”, while the spreadsheet tool requires inputs of water (and orifice) “height”. These terms are considered interchangeable for the purposes of this document.

7.0 Flood Risk Analysis with SWMM

7.1 Coordinating with Your Local Storm Sewer Utility

Early and continual coordination with the local agency responsible for maintaining and regulating the storm sewer system in question (hereafter the Local Storm Sewer Utility) will be a critical aspect of any storm sewer retrofitting project. It will be the Local Storm Sewer Utility that is ultimately responsible for approving a storm sewer retrofit project and for maintaining the retrofit structure after installation (unless other contractual arrangements are made). If the Local Storm Sewer Utility agrees to work with you to explore the potential for implementing a storm sewer retrofit project they will provide you with criteria for demonstrating that the project will not diminish the flood conductance capacity of the storm sewer to an unacceptable level (e.g. the project cannot increase the magnitude or duration of flooding during the 100-year standardized storm event). Different Local Storm Sewer Utilities may have different criteria and modeling requirements for conducting this demonstration and will require that a final design be certified by an engineer licensed in the state in question.

While the flood risk analysis procedure described here may or may not conform with the methods required for final approval by the Local Storm Sewer Utility, once the SWMMs are created (as is necessary to conduct the critical discharge frequency analysis, the final step in this site screening process described in Section 8), utilizing the SWMMs to conduct flood risk analyses require little additional effort; so, even

The National Oceanic and Atmospheric Administration (NOAA) publishes standard precipitation frequency estimates (rainfall magnitude [inches] for given standardized storm durations [e.g. 24-hours] and statistical return intervals [e.g. 100-years]) throughout the United States. The most current estimates for your region can be obtained from their Precipitation Frequency Data Server²⁴. By applying the total depth of rainfall (inches) for a standard recurrence interval storm event (e.g. 24-hour, 100-year) to the distribution (e.g. SCS Type II) from the spreadsheet obtained from the NRCS's website, you can build a 6-minute interval time series precipitation dataset for the desired standardized storm in your project area. The resulting standardized rainfall distribution can then be formatted appropriately to be copied and pasted in to SWMM's "Time Series Editor".

Once a "Time Series" has been created in SWMM for the desired standardized storm event, it must be linked to the "Rain Gauge(s)" that are linked to the "Subcatchment(s)" in your SWMM (see the appropriate version of SWMM's User's Manual for guidance²⁵. Don't forget to select the appropriate "rain format" for your rain gauge. The NRCS spreadsheets are formatted as cumulative distributions, so unless you transform this, you would select "CUMULATIVE" here. Similarly, the NRCS spreadsheets are formatted in 6-minute intervals, so unless you transform this, you would enter "0:06" in the "time interval" field.

7.3 Analyzing the Results of Your Simulations

Once you have run a simulation using the appropriate standardized storm event, for both the pre-treatment and the post-treatment models, the final step is to compare the "Summary Results" for "Node Flooding" between the two simulations. The relevant results can be found by opening the "Summary Results" window and selecting "Node Flooding" from the *Topics* drop-down. The two fields (columns) of data that will be compared for the pre-treatment and post-treatment results will be "Hours Flooded" (duration) and "Total Flood Volume" (magnitude). If the value of either one of these fields increases for any of the "Nodes" in the post-treatment model, you may need to consider reducing the elevation to which the retrofit is designed to back-up water into the system.

The number of rows in these datasets will depend on the number of "Nodes" in your SWMMs. If there are only a few "Nodes", it will be relatively easy to compare the pre-treatment results to the post-treatment results (perhaps without event pasting the data into a spreadsheet). If there are many nodes it will likely be helpful to combine the two tables in a spreadsheet so that you can look at the pre-treatment and post-treatment results side-by-side. To do this, first open the "Summary Results" window. Then select "Node Flooding" from the *Topics* drop-down. Next go to the *Edit* drop-down of the main SWMM window and select "Copy To...". In the resulting pop-up window leave Copy to "Clipboard" selected and click "OK". You can now paste all the data from the "Node Flooding" table into a spreadsheet program. Repeat this process for both the pre-treatment and the post-treatment results.

With these two datasets combined into one table, you could also create two new columns to quantify increases in flood duration and flood magnitude. Within these new columns, simply subtract the value for the post-treatment dataset from the value from the pre-treatment dataset. You will be hoping for "0"s all the way down - any positive number will represent an increase in either flood duration or magnitude. Any negative numbers should be scrutinized as part of the model de-bugging process.

²⁴ https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html

²⁵ <https://www.epa.gov/water-research/storm-water-management-model-swmm>

8.0 Critical Discharge Frequency Analysis with SWMM

8.1 Summary of the Analysis

To assess the degree to which a proposed storm sewer retrofit project will achieve the hydrologic objective of reducing the frequency of a target *critical discharge*, continuous simulations of the pre- and post-treatment SWMMs will be run using several years of local, historic precipitation data.

Measurement of the frequency of a target *critical discharge* is a statistical measurement that can be expressed as *average annual frequency*, hence the requirement for multiple years of local, historic precipitation data.

Once pre- and post-treatment simulations have been run, analysis of the results involves the relatively simple procedure of counting up the number of flows occurring in each year in exceedance of a target *critical discharge*, and averaging those numbers to obtain the *average annual frequency of critical discharges*. The objective is to reduce this average annual frequency, from the pre-treatment model, to a more natural level in the post-treatment model (see Sections 3.3).

Additionally, attention should also be paid to any increases in magnitude of discharges resulting from “overflows” from the retrofit device. While the frequency of critical discharges is thought to be more important to stream stability than increased magnitude of flows that would exceed the critical discharge anyway, large magnitude surges occurring just as a flap gate retrofit structure is pushed open, or as a riser retrofit begins discharging through its overflow, could cause significant localized erosion problems near the retrofit structure and may also pose a safety risk. These risks must be assessed on a site-by-site basis.

8.2 Obtaining Historical Rainfall Data for a Nearby Weather Station

The purpose of our SWMMs is to estimate the *peak* flow rates resulting from various storm events and generated from a simulated storm event so that we can calculate the frequency of *peak* flow rates that exceed a target *critical discharge*. With this in mind, the time interval associated with the precipitation data (how often precipitation amount is recorded) that we use in our simulation is important – the shorter the interval the better. You may be able to five-minute interval precipitation data from a local government agency or university near your project site. It is worth spending time contacting agencies from multiple surrounding jurisdictions and researchers from multiple University programs to acquire relatively low-interval data. In general, the more years of representative precipitation data, the better, because a larger sample size will facilitate greater confidence in the statistical estimate. Consideration might also be given to whether significant climatic changes may have occurred within your region when judging the representative nature of precipitation data from many years ago.

If no relatively low-interval precipitation data are available from local sources in your region, you can download historic 15-minute interval precipitation data for locations throughout the United States from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information²⁶ (NCEI). This data is currently available up through the end of 2013 and as far back as 1970,

²⁶ <https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00505>

depending on location. Precipitation data from NCEI, can be downloaded in either CSV or TXT format which can be imported into a spreadsheet program and format to a form that can be utilized by SWMM.

8.3 Running Continuous Simulations for Multiple Years

Once multiple years of precipitation data have been imported into your pre- and post-treatment SWMMs, a continuous simulation (or continuous simulations) can be run. Note that running continuous SWMM simulations for long periods of time is computationally intensive and could require long run times and may overwhelm computer systems with relatively low system resources. To get around this issue, one can simply break-up the simulation into multiple smaller durations, such as running simulations for one-year at a time (or even shorter durations if necessary) rather than running a 20-year simulation all at once.

8.4 Analyzing the Results of Your Simulations

Once you have run a continuous simulation (or continuous simulations) for your pre- and post-treatment SWMMs, the final step is to compare the tabular flow data between the pre- and post-treatment models. This tabular data will be copied from SWMM and pasted into a spreadsheet for further analysis. To view the data in SWMM, select “Table” and “By Variable...” from the *Report* drop-down of the main SWMM window. This will open the “Table by Variable Selection” window. Ensure that the entire simulation period is selected in this window; the *Time Format* will be set to “Date/Time”; the *Object Category* will be set to “Nodes”; “Total Inflow” will be selected for *Variables*; and the Outfalls associated with the retrofit will be selected for *Nodes*. For the pre-treatment model the “Node” will be the one Outfall located where the retrofit structure is proposed. For the post-treatment model, you really only need to select the Overflow Outfall since the Low Flow Outfall and the Restricted Flow Outfall should never exceed the target *critical discharge* by design (see Section 6.3.1); however, you may want to select all three of the “Outfalls” associated with the retrofit structure to verify that that is the case as a quality assurance measure. Next go to the *Edit* drop-down of the main SWMM window and select “Copy To...”. In the resulting pop-up window leave Copy to “Clipboard” selected and click “OK”. You can now paste all the data from the “Table – Node Total Inflow” table into a spreadsheet program. Repeat this process for both the pre-treatment and post-treatment results.

The following data processing procedures assume that the simulations were run in SWMM one year at a time, and so the spreadsheet data processing steps are performed on one year of data at a time. If shorter or longer SWMM simulations were run simply combine or split the datasets to yield one year of results per spreadsheet or per “Sheet” within a spreadsheet. Similarly, the pre-treatment and post-treatment datasets should be pasted into separate spreadsheets or separate “Sheets” within a single spreadsheet. Each annual dataset, rather pre-treatment or post-treatment, will be processed in the same manner as follows.

First, daily peak discharges will be extracted from this dataset by creating a “Pivot Table”. To create a “Pivot Table” in Microsoft Excel (2019) click on “Pivot Table” in the “Tables” section of the *Insert* ribbon. This will prompt the opening of the “Create PivotTable” window in which you can select the table range of the dataset and the location where you would like the “Pivot Table” to be located. This will prompt the creation of a new “Pivot Table” and the opening of the “PivotTable Fields” pane. Within this pane, the only two data fields selected should be the *Date* and the *Flow* fields. The Date field should be located in the “Rows” area. In the “Σ Values” area, click on the drop-down menu and select “Value Field Settings”. In the resulting “Value Field Settings” window, select “Max”.

Now that the “Pivot Table” is populated with daily peak flow values, you can now copy and past the contents of the pivot table to another location in your spreadsheet and sort the date by the *Flow* field from Largest to smallest value. You will then be able to easily count the number of days in which peak flows exceeded a give target critical Discharge for the year. Repeat this process for each simulated year and for both the pre-treatment and post-treatment models. Finally, you can calculate the average number of days per year in which peak flows exceeded a give target critical Discharge (*average annual frequency of the critical discharge*) for both the pre-treatment and post-treatment models.

8.5 Interpreting the Results of Your Simulations

At minimum, for a candidate retrofit location/design to be assessed as potentially worth doing, the *average annual frequency of the critical discharge* should decrease from the pre-treatment model to the post-treatment model. The significance of such a decrease in the *average annual frequency of the critical discharge* will require professional judgement based on the context of the amount of the decrease relative to the degree to which the frequency of the target *critical discharge* is believed to be elevated above natural levels.

As discussed in Section 3.3, if a storm sewer retrofit project could be designed to limit “non-overflow” flow to magnitudes < the target *critical discharge* (in the case of excess storage capacity), such a project could make-up for unmitigated flow in other locations of the watershed. Conversely, if storage above a storm sewer retrofit is not sufficient to fully achieve at target discharge, it may still be worthwhile to implement the project if it helps to move you closer to your in-stream hydrologic objectives.

Any earnest effort to mitigate the impacts of urban hydrologic alteration on a receiving stream will likely involve implementation of several different types of mitigation projects - storm sewer retrofits being only one of several tools in the box. Accordingly, the assessment of whether a candidate retrofit project is worth doing will likely be made in the context of a larger watershed-based program in which multiple alternative/complementary projects are being considered.