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Hydraulic Performance and Vulnerability on Sanitary Sewer Overflow in Southern Pinellas County, FL

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Hydraulic Performance and Vulnerability on Sanitary Sewer Overflow

in Southern Pinellas County, FL

by

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of the requirements for the degree of
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DEDICATION

I will like to dedicate this work to myself, proving that I can accomplish anything if I believe and work hard on it. I will also like to dedicate this work to my family for their patience, encouragement, and support.

ACKNOWLEDGMENTS

I will like to thank Dr. Mahmood Nachabe for his encouragement, support, and valuable guidance throughout the entirety of the study. I will also like to thank the members of my committee, Dr. Mahmood Nachabe, Dr. Mauricio Arias and Dr. Kenneth Trout for their time, support and effort. I believe that I learned a lot from working on this project, and will never forget the experience, struggles, and accomplishments. More so, will like to thank the CHI network for giving me a university grant to explore and use PC SWMM software for my study. It was an excellent exposure to hydraulic modeling, and I liked and enjoyed using the program.

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ABSTRACT

Rain-induced sanitary sewer overflow due to high infiltration is a significant challenge for many utilities, including Pinellas County utilities. The main aim of this study is to develop a hydraulic model to analyze the performance of the existing sanitary sewer system, especially during intense rainfall events.

To calculate the flow inputs for the model, a times series analysis was performed to separate the inflow and infiltration from the actual sewer flow. Using the Stevens-Schutzbach method, daily Base Infiltration (BI) was calculated and was subtracted from the total observed flow to give the Dry Weather Flow (DWF). Adjusting the DWF by the diurnal pattern, residual flows were calculated to test the flow variability in the system and compare to rain events (> 0.5 inches); the residual flow help deduced if there is a significant surface inflow into the system.

Using PC SWMM as the hydraulic model, the average DWF was simulated using the average value and the diurnal daily and weekend pattern during the dry weather periods. The calculated BI was added to the model as a direct contribution from the statistical model. Both the average value of DWF and BI were distributed throughout the system for simulation. The simulated flow shows that few downstream manholes surcharges during extreme rainfall events and remained surcharge for over 48 hours.

Cross-correlation analysis suggests the rainfall of the past seven days still impacts the BI, with the highest impact on days 1, 4 and 5. The correlogram results were used to develop a

regression model, to predict the BI for different rainfall depths, which in turn was used for hydraulic performance analysis.

Increasing the rainfall depths and routing the flow using PC SWMM, showed that the hydraulic grade line, number and hours of the surcharged manholes increases as total rainfall depths increases, but no sanitary sewer overflow. Sanitary sewer overflow occurred at the lift station with a design capacity of 200 GPM for all increased rainfall depths. Furthermore, the analysis results can help locate areas where overflow is more likely to occur, and can also help plan and implement a cost-effective rehabilitation program for the existing sewer network.

CHAPTER 1: INTRODUCTION

One of the challenges facing by municipalities across the United States is the issue of Sanitary Sewer Overflow. Sanitary Sewer Overflow (SSO) is an unauthorized discharge of untreated wastewater from a collection system or wastewater treatment facility, which poses serious public health and environmental problems. According to Petrequin (2011), an estimate of 40,000 overflows occurs per year, and at least one-third of the nation's wastewater treatment municipalities faced fines or disciplinary measures for sewage violations. Due to the risk posed to public health, SSO has been linked to roughly 8.6 million cases of waterborne illness per year (Peterquin, 2011) diseases that range in severity from mild gastroenteritis to life-threatening illness such as cholera, dysentery, infectious hepatitis, and severe gastroenteritis (EPA, 2004).

From a legal perspective, section 301 (a) of the Clean Water Act prohibits unpermitted discharge of pollutants. Furthermore, The National Pollutant Discharge Elimination System (NPDES) allows discharge under certain specific conditions which usually includes an effluent limit, and requires all permittees to properly operate, adhere and maintain all facilities, impose self-monitoring, and reporting requirements (EPA, 1995). SSO is as result of surcharge overflow in the sanitary sewer conveyance system. Sanitary sewer collection and conveyance system surcharges when the hydraulic grade line of the system rises to the ground surface level, because the actual flow exceeds the design capacity of the system. The sewer surcharges can occur at junctions such as manholes, pipe fittings, and outlets, collection wells and treatment facility.

1.1 Scale of Sanitary Sewer Overflow

Sanitary sewer surcharge at a junction such as; manhole, cleanout or pipe fitting, results to SSO when the flow changes from free surface flow to pressurized flow. As the pressure increases, the water level rises until it raises to the surface, diffusing the build-up pressure, thus, SSO. Furthermore, sewer surcharge can occur at the collection wells and at the wastewater treatment facility when the flow exceeds the pumping capacity and volume capacity of the treatment facility respectively. In September 2017, Hurricane Harvey delivered 40-61inches of rain across Texas, which led to approximately 150 million gallons of both SSO and industrial discharge into the environment (TCEQ, 2017). In September 2016, an estimated combined volume of 240 million gallons of partially or untreated sewage was dumped into the Tampa Bay during Hurricane Hermine, which delivered up to 22 inches of rain in some parts of the Tampa Bay area (Neuhaus, 2016).

1.2 Cause of Sanitary Sewer Overflow

As stated above, SSO results from surcharge when the hydraulic grade line rises to the ground surface elevation. SSO occurs during the wet weather due to Rain Derived Inflow and Infiltration (RDII), blockages, cracked pipes and manholes, structural, mechanical and electrical failures and insufficient conveyance capacity. Reduction in pipe capacity caused by blockage often exacerbate surcharging and backups by causing a build-up of debris such as wood logs, plastic bags, household waste and solidified grease.

RDII is rain-induced inflow and infiltration entering the sewer system, usually during wet weather events. Surface runoff (inflow) enters the sewer system via cleanouts, unsealed manholes or illegal connections. Inflow into the system is evident in the flow hydrograph as a fast increase or response in the flow rate during the duration of a rain event and quickly subsides after the rain event. Infiltration is the inflow of groundwater into the sewer pipe and increases with the water table elevation. Groundwater infiltration is associated with soil water or groundwater that seeps into the sanitary sewer through cracks in the pipes, manholes, or wet wells. When the pipe or well is submerged beneath the water table, it creates a positive pressure higher than the atmospheric pressure, thus creating a pressure gradient. This pressure gradient drives the groundwater through cracks and holes into the pipe, leading to infiltration in the sewer pipes. Unlike surface inflow, infiltration in the system shows a slower but persistent response in the flow hydrograph with a rain event.

1.3 Reduction of Sanitary Sewer Overflow

Many programs and designs have been introduced to reduce the SSO at different scales. One of the methods is to maximize the capacity of flow. Maximizing the flow capacity can be accomplished by two methods: utilizing storage facilities and increasing the flow carrying capacity. Due to high volumes and variability caused by RDII, additional wastewater storage facilities can be considered as a control for SSO. The additional storage facility is feasible because it requires relativity low-cost construction and maintenance and can operate regardless of the random high-intensity rain events. The only disadvantage is that the storage facilities are relatively large and requires a large area of land. Increasing the flow carrying capacity includes monthly/daily maintenance and cleaning out the clogged pipes, increasing the pumping capacity, and replacing the existing pipes with high diameter pipes.

Another method for reducing SSO is rehabilitation strategy. Rehabilitation involves lining pipes segments to reduce infiltration induced by an increase in water table via cracks in the pipes, manholes and joint fitting. The advantage of rehabilitation is that it reduces the infiltration rate in the pipes thus reducing the volume of the sewer flow, increasing the efficiency of the treatment facility; hence reduce SSO during extreme events. The disadvantage of rehabilitation is cost. Because of limited resources, one of the challenges of rehabilitation is prioritizing which pipe segment to rehabilitate first to maximize the reduction of SSO.

1.4 Objective of the Study

The objective of the study is to perform system failure analysis on one of the sewershed located in South Pinellas County by developing a hydraulic model. The primary focus of the study is to evaluate hydraulic performance of the sewer system, analyze and predict locations and conditions for SSO, to help plan and retrofit the areas within the sewer shed vulnerable to SSO. The study will focus on the wet weather events from June 1st - September 30th, 2016, and extreme tropical cyclone events.

1.5 Literature Review

1.5.1 Modeling Method

Flow conditions in sanitary sewers vary and are both transient and non-uniform. During dry weather conditions, flow in gravity lines of sanitary sewer systems is designed as free-surface flow. This flow can either be sub-critical or super-critical. However, during wet-weather, flows typically increase, often significantly due to RDII. The free-surface pipe flow may give way to surcharge flow conditions where pipes are full and under pressure causing SSO. Recommended by EPA and often applied in models, RDII is simulated using the R, T, K synthetic unit hydrograph method. The R, T, K synthetic unit hydrograph captures RDII by fitting three triangular unit hydrographs to the observed RDII, and then estimates the fast, medium and slow RDII responses (EPA, 2008). The three-unit hydrographs relate RDII and sewershed characteristics to unit rainfall volume entering the sewershed (R), specified time duration (T) and the ratio of time of recession (K) (9 parameters total). R, T, K parameters are derived from site-specific flow monitoring data and require that a continuous flow monitoring program is implemented at strategic points in the sewer system. As mentioned beforehand, the R, T, K method generates three hydrographs; three R parameters are designated as R_1, R_2, and R_3. If the value of R_1 is high, it signifies that the system is more driven by surface inflow. However, if the total R-value is high for R_2 and R_3, then the system is driven by groundwater infiltration.

EPA Stormwater management model (SWMM) is a versatile tool used to model and study the hydraulic and the dynamic of flow in the system. Furthermore, EPA Sanitary Sewer Overflow Planning and Analysis (SSOAP) toolbox is software that enables the user to estimate the R, T, K values for each rainfall or flow monitoring events and generate corresponding RDII hydrographs. The R, T, K values for the three RDII response hydrographs can be inputted to software packages such as EPA SWMM, PC SWMM (CHI software) to simulate the total sewer flow and be able to pinpoint locations of possible SSO in the sewershed. For example, a study in Melbourne, Australia used both SSOAP toolbox and PC SWMM to perform a hydraulic sewer system assessment. The study analyzed the performance of the existing sanitary sewer system during the wet and dry year, specifically looking at the impacts on short duration intense rainfall (Tasnim et al., 2017). The study used the R, T, K synthetic unit hydrographs to capture the RDII, and PC SWMM to simulate the flow, noting locations and volume of SSO during the two intense rainfall events. Since the R, T, K parameters are different for different rainfall events, extensive data collection and multivariable linear regression are needed to predict the parameter for future rainfall event.

Following the pilot study (Megan, 2017), Steven-Schutzbach method was used in quantifying the groundwater infiltration due to the shallow, and dynamic water table characteristic in Pinellas County region. Thus, negating the use of R, T, K synthetic unit hydrograph for this study sewer modeling. Instead, the groundwater infiltration component of the excess sewer flow will be added as an external source in the model for the hydraulic performance study.

CHAPTER 2: MATERIALS AND METHODS

2.1 Case Study Area and Infrastructure

The study site sewershed, PS-119 (Figure 1) is a small residential neighborhood, located south of Sawgrass Lark Park, spanning approximately 72 acres. The neighborhood is mostly developed, impervious land with a separate sewer system. The ground elevation for this sewershed ranges between 11and 16 feet and the average water table ranges from 2 to 6 feet below the ground surface, which is relatively shallow. The soils type is mostly Myakka fine sands containing silt and organic matter with some Okeechobee muck near Sawgrass Lake (Megan, 2017). The PS-119 sanitary sewer system is a gravity-driven system with approximately 2.3 mile of 8-inch diameter pipes, which eventually discharges into a wet well PS-119 located downstream of the system, and finally routed to South Crosss Bayou Wastewater Facility (SCBWF).

2.2 Instrumentation

2.2.1 Flow Meters

Isco 2150 flow meters were installed in three locations within PS-119 sewer shed: one in the pipe just before the wet well at PS-119, and two in the manholes throughout the neighborhood (Megan, 2017). The flow meters measure and record the flow depths (within ±0.008ft/ft.), the velocity (within ±0.1ft/s), and the total flow in the sewer pipe at 15-minute interval. The 15 minutes time interval, provides a fine resolution for identifying potential surface inflow (Megan, 2017)

2.2.2 Rain Gages

At the study site, a tipping bucket gage was installed on top of the wet well, PS-119 as part of the Pinellas County Utilities system. The rain gage was refined to provide hourly readings starting in February 2016. Since the rain data readings are in hourly instead of 15 minutes interval to match the flow records, available rain data on the area were assessed from the Southwest Florida Water Management District (SWFWMD) and the United States Geological Survey (USGS). The rain gauges are located approximately 0.4 miles north and at St. Joes Creek, 2 miles southeast of the sewershed for the SWFWMD and USGS gages respectively. This additional rainfall data was used to fill any time gaps in the rain data at PS-119.

2.2.3 Groundwater Monitoring Wells

Two monitoring wells were installed to measure and record the groundwater levels in the study site. The first monitoring well is located directly next to PS-119 northwest of the sewer shed. The second monitoring well is located the southeast corner of the sewer shed. The two monitoring wells are both 15-feet deep, 2-inch diameter PVC with Solinst Levelogger® pressure transducer water level sensors that record the water level every hour within 0.05% accuracy, (Megan, 2017).

Figure 1: PS-119 (the outfall) sanitary sewer layout

2.3 Methods

2.3.1 Time Series Analysis

The objective of the study is to evaluate the hydraulic performance of the system and determines which part of the system might fail during high intense events. The sanitary sewer flow comprises of sewage and freshwater intrusion. The sewage is the household wastewater production and follows typically in a diurnal pattern. The freshwater contribution includes surface inflow and infiltration. While surface inflow can be noted quickly, a high spike in the time series graph corresponding to the rain event, groundwater infiltration is a slow, gradual process and varies with rainfall events and fluctuation in the water table.

The first step of the analysis is to perform a time series analysis, differentiating between the dry weather flow and the infiltration (Appendix A). The Stevens-Schutzbach is an empirical equation, using the minimum daily flow (MDF) and the average daily flow (ADF) to calculate the daily Base Infiltration (Equation 1)

$$BI = \frac{0.4\ (MDF)}{\left(1 - 0.6\left(\frac{MDF}{ADF}\right)^{ADF^{0.7}}\right)}$$

Equation 1: Steven-Schutzbach equation for Base Infiltration calculation.

For this analysis, the minimum daily flow was calculated from the hours of 12:00 am to 6:00 am. The inputs and the outputs of the equations is the flow measured in gallons per minute (gpm). The sewer flow data, the typical sewer flow value, were filtered by subtracting the BI from total sewer flow for each day. Adjusted by the diurnal pattern, residual flow was calculated to test the variability of the flow. The residual flow was used to determine if there is additional inflow from the surface runoff or random variability in household wastewater production for different rainfall events (Megan, 2017). For this study, a rainfall event is defined as rainfall depth greater than 0.5-inches. The variability of the residual flow was captured by setting boundaries of two standard deviations, subtracting from series average zero to create the upper and lower bounds of the time series graph. If the rainfall event falls above the limits, it is considered a surface inflow; however if the rainfall event falls within or below the boundaries, it cannot be discerned as significant surface inflow. For PS-119, 49% of total observed sewer flow, during wet weather is base infiltration, and the rainfall events fell within the boundaries. Therefore, it is deduced that there is no significant surface inflow at the site.

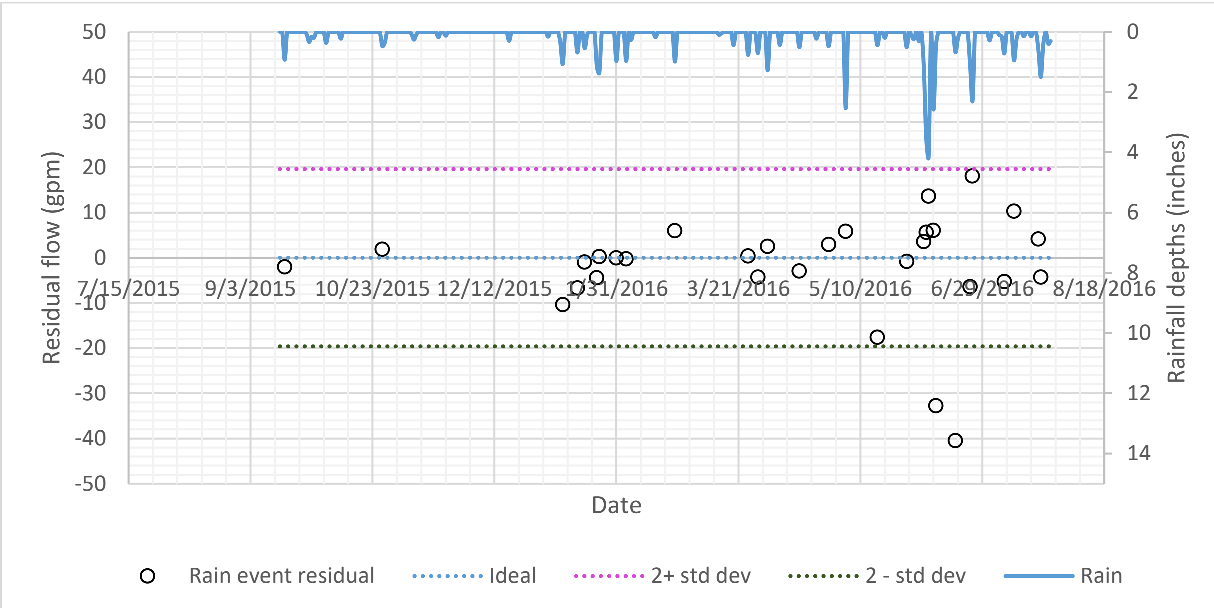


Figure 2: Average residual flow for significant rainfall events.

2.3.2 Cross-Correlation and Regression Analysis

Cross-correlation is a measure of the strength of the relationships between two variables in a time series. Cross-correlation analysis shows the strength of the relationship between the two variables as a lag time for each value in the time series and calculates the variance between two variable time lags (Megan, 2017)

The head above the pipe invert elevation is an important variable to consider for cross-correlation analysis. Understanding the occurrence of SSO reveals that groundwater infiltration into the sewer system is highly dependent on the water table fluctuations. As the water table increases, submerging the pipes, it creates an elevated pressure head that forces the groundwater to infiltrate through the cracks into the sanitary sewer system, thus increasing the BI. Because the study site experience high inflow and infiltration problems after severe storm events (Megan, 2017), and water table fluctuation is highly dependent on the rainfall, rainfall is used for the cross-correlation analysis and used as an input variable in the regression analysis to predict the BI. For this study, the cross-correlation analysis is applied to the time series to help discern the strength of the BI and the rain events which will be useful inputs for a regression model to predict the BI for future events. Cross-correlation analysis was performed with the observed rain and calculated BI data during the wet weather periods in 2016 and 2017

Regression analysis is used in this study as a predictive tool to estimate the BI for future rainfall events. While factors causing infiltration into the system may not be linear due to the system's complexity, a linear regression model based on the cross-correlation analysis, with sufficient accuracy may help estimate the BI response to rain events.

2.3.3 PC SWMM Model Analysis

In this analysis, hydraulic modeling was conducted using PC SWMM to analyze how the flow moves through the system, and determine when and where the system fails. PC SWMM, hydraulic software from Computation Hydraulic International (CHI) was used to simulate and route the sewer flow, assessing the hydraulic performance of the existing system at the study site. The performance indicators for this study are defined as when the flow surcharges and SSO (flooding) occurs in the system. As mentioned in the introduction, the flow surcharge occurs when the flow changes from a gravity driven to pressurized flow, and SSO occurs when the flow depth is above the maximum pipe depth (ground elevation) of the system.

2.3.3.1 Flow Routing Methods

Similar to EPA SWMM 5.1, PC SWMM model flow routing is primarily governed by the conservation of mass and momentum and offers three methods of flow routing. The first method, steady flow routing, is the simplest flow routing method, assuming the flow is uniform and steady within each time step flow. The method translates into flow hydrographs at the upstream and the downstream of the conduit with no delay or variability. Furthermore, the steady flow routing method does not account for channel storage, backwater effects, entrance/exist loss, and in this case study, pressurized (surcharged) flows. The second method is the kinematic wave routing, which is governed by continuity equation and a simplified form of the momentum equation for each conduit. The method assumes that the slope of the water surface is equal to the slope of the conduit, thus, this method mostly applies to steeply sloped conduits, shallow flow with high velocity. Similar to the steady flow routing, kinematic wave routing cannot account for backwater effects, entrance/exit losses, and pressurized (surcharged) flow. However, kinematic wave routing can be accurate and effective for long-term simulation because it maintains numerical stability for large time steps by ignoring both inertia and pressure force. The last method is the dynamic wave routing method. The dynamic wave routing is governed by one-dimensional St. Venant flow equation (Equation 2), which consists of the combination of both continuity and the momentum equations for each conduit, and a volume continuity equations at the manholes. This method can be applied to any network layouts, including diversions, loops, pumps and flow regulators such as weirs, culvert, and orifices. Unlike the steady flow and the kinematic wave routing, the dynamic wave routing does account for channel storage, entrance/exist losses, and pressurized flows.

Furthermore, each routing method uses the Manning equation to relate to flow rate, flow depth, and the slope. For this study, the modeling was conducted using the dynamic wave routing approach.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \ \ (Contiunity)$$

Equation 2a: St. Venant continuity equation

$$\frac{\partial Q}{\partial t} + \frac{\partial (\frac{Q^2}{A})}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f = 0 \ \ (Momentum)$$

Equation 2b: St. Venant momentum equation

$$\frac{\partial V}{\partial t} = \frac{\partial V}{\partial H}\frac{\partial H}{\partial t} = A_s\frac{\partial H}{\partial t} = \sum Q$$

Equation 2c: Volume continuity equation

where A is the cross-sectional flow area (ft^2), Q is the flow rate (ft^3), t is the time, x is the distance (ft.), S_f is friction slope, V is the node assembly volume (ft^3), A_s is the node assembly surface area (ft^2) and ΣQ is the net flow (inflow-outflow) into the node assembly (cfs)

2.3.3.2 Flow Inputs

As mentioned in the time series analysis, the flow inputs are classified into two: dry weather inflow (DWF), and the BI. The dry weather inflow, DWF is a continuous inflow, reflecting the household sewage production or the base flow sanitary sewer in the system. DWF is represented by an average value (gpm) that can be adjusted on monthly, daily and hourly diurnal pattern (Figure 3).

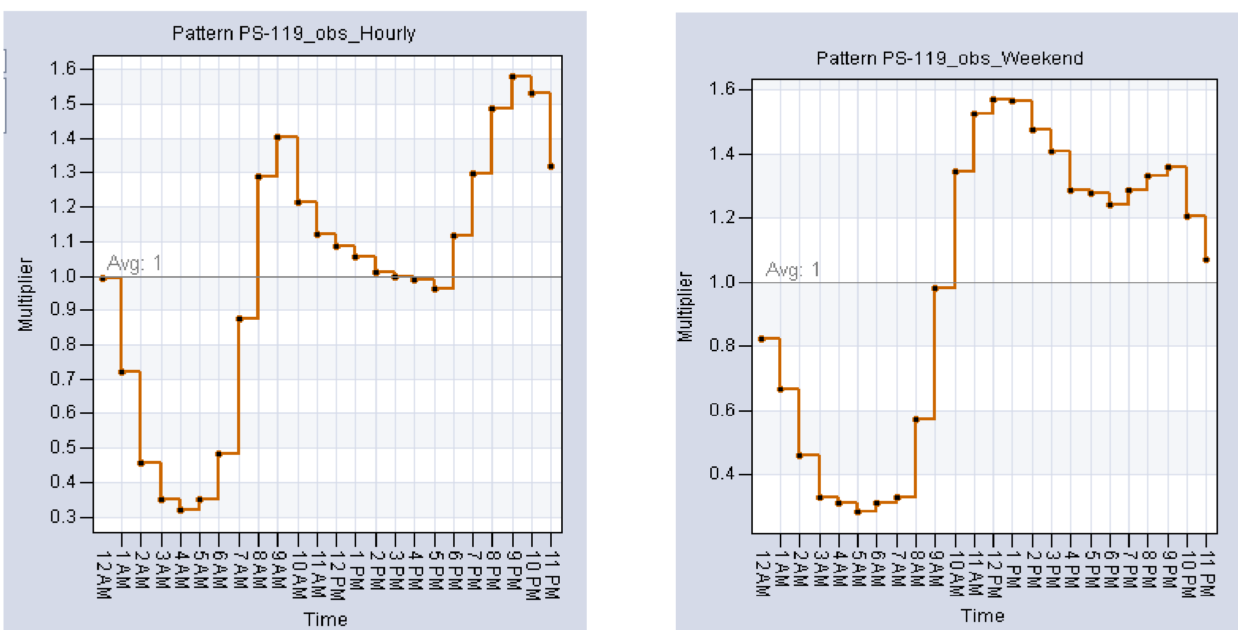


Figure 3: Diurnal pattern simulated using PC SWMM. Average value = 35.89 gpm

The average value is calculated using the flow data during the dry weather periods, January 1st - March 31st, 2016, with no rainfall and applied to the diurnal pattern with equation 3. Thus, the DWF for the entire time series was simulated (Figure 4). The DWF values are different for each type of drainage system node (junction, outfall, storage units and flow divider) and can be edited to fit any specified node, but for the simplicity of the model, the average value is apportioned equally across each node by dividing the average value by the number of manholes in the system.

$$DWF = Average\ Value * dirunal\ pattern\ (Hourly) * dirunal\ pattern\ (Weekend)$$

Equation 3: Hourly/Weekend Dry Weather Flow formula calculation for the flow simulation

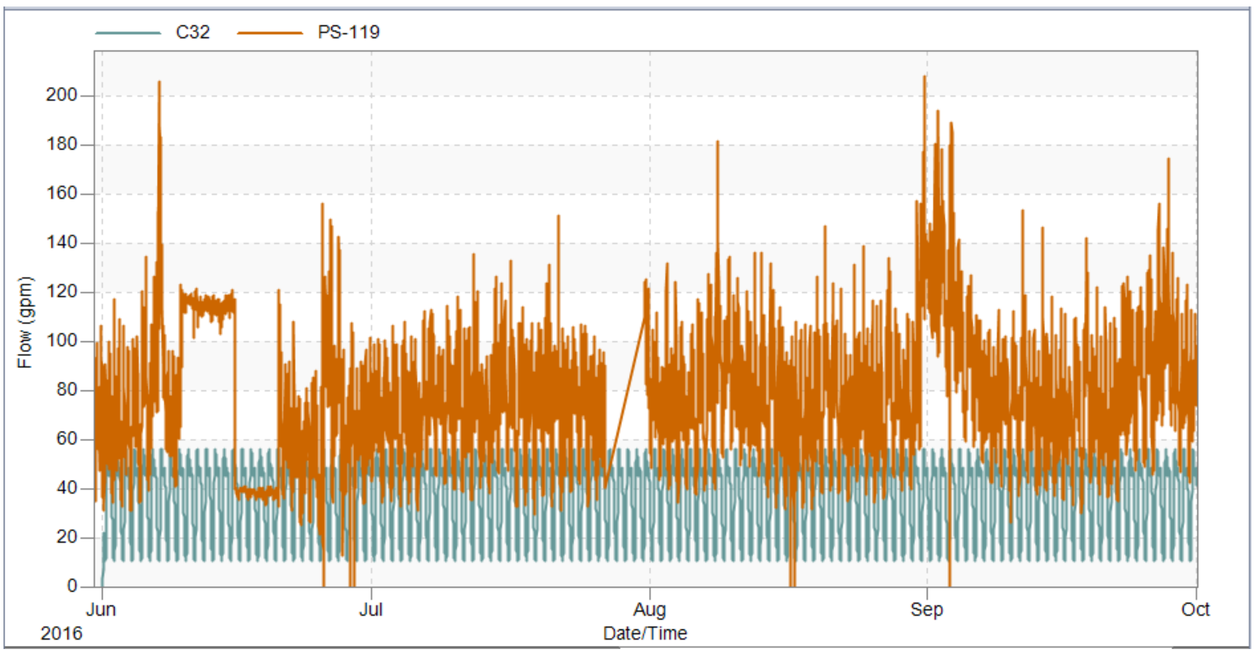


Figure 4: PS-119 simulated average DWF from June 1st–September 30th. C32 = Q_{sim}, PS-119 = observed flow

Because the Stevens-Schutzbach method was adopted instead of the convention RDII method, the BI was added as an external source into the system. External source is a user-defined time series inflows that are directly added to each node (manhole). The BI values, calculated from the time series analysis, was added into system through direct inflow (under external source) using equation 4 below. From equation 4, the baseline pattern is left blank because the BI flow has no pattern unlike the DWF. Thus, no baseline value is generated. The time series is the calculated daily BI, normalized by average daily BI during the dry weather period, January 1st - March 31st, 2016.

$$Direct\ Inflow = (baseline\ value * baseline\ pattern) + (scale\ factor * time\ series\ )$$

Equation 4: External source. BI direct inflow formula calculation for flow simulation. Scale factor = 1

2.3.3.3 Geometric Parameters

The geometric parameters used for the hydraulic modeling include; invert and manhole rim elevations, length, slope and size of the pipes, and Manning's coefficient n for closed conduits. For this study, the depth of the pipes was attained from the Pinellas County Utilities, and since the manhole rim elevation was not given, the ground surface elevations, attained from North American Vertical Datum (NAVD) (Megan, 2017) were used. Since the invert elevation was also not given, PC SWMM used a simple equation (ground elevation – depth) to calculate the pipe invert elevation. The pipe slope is automatically calculated with length and the elevations of inflow/outflow manholes.

CHAPTER 3: ANALYSIS RESULTS

3.1 Cross-Correlation and Regression Analysis

The correlogram (Figure 5) of the total rainfall (in inches) and the BI (in gpm) shows that the strength of the relationship drops significantly after seven days (lag time), indicating that the BI is significantly impacted by the total rainfall in the preceding seven days. The correlogram also shows that the most significant relationship occurs on day 1, 4 and 5, and there is no correlation on day 0. Considering the area has a shallow water table, the results are perceptive, as the rainfall takes about 1-2 days to infiltrate the soil and raise the water table, submerging the pipes and increasing pressure head. Thus, forcing the groundwater to infiltrate into the sewer system.

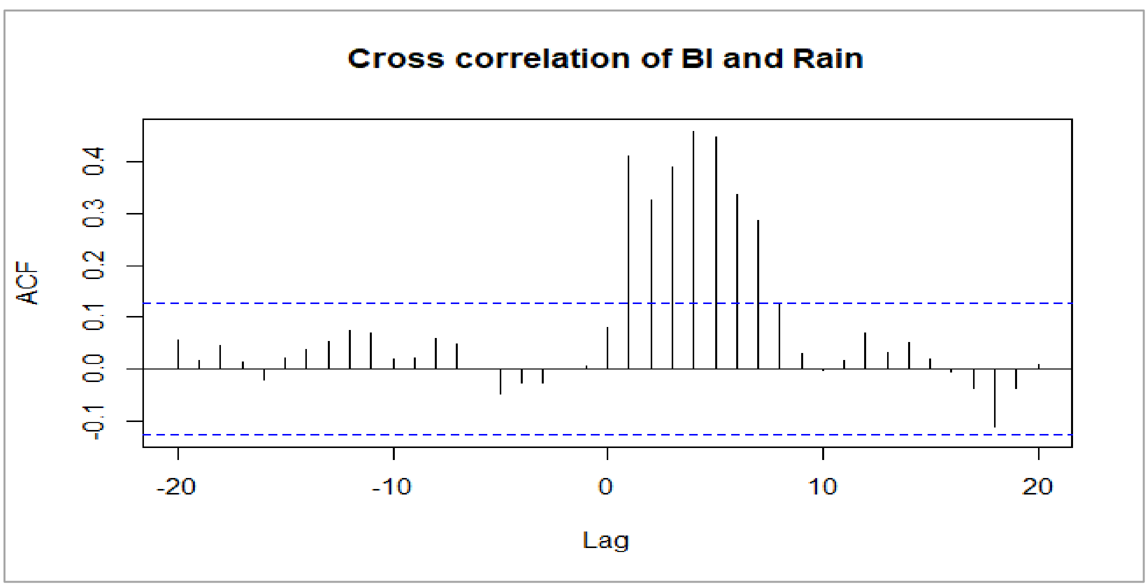
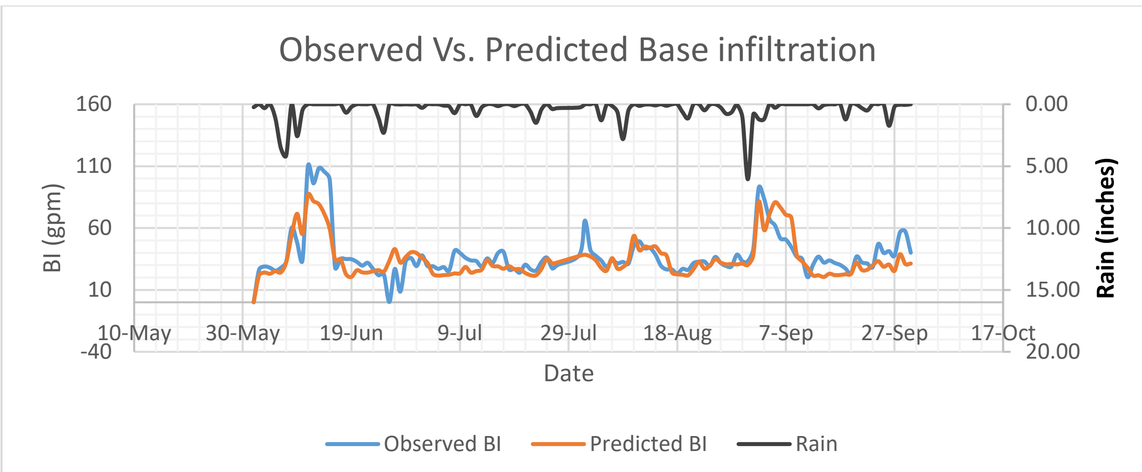


Figure 5: Cross-correlation between BI and rain during wet weather periods. June-September 2016 and June-September 2017. Significance ±0.13

For the regression analysis, using the total rainfall for the previous seven days as the predictor variables and the BI as the response variable, a regression model (Equation 4) was developed for the study.

$$BI_{(gpm)} = 20.45 + 7.92P_1 + 2.74P_2 + 4.28P_3 + 5.56P_4 + 6.28P_5 + 4.26P_6 + 4.86P_7$$

Equation 4: Regression model equation of BI (gpm) for PS-119. P_i is the total rainfall (in inches) for each preceding day.



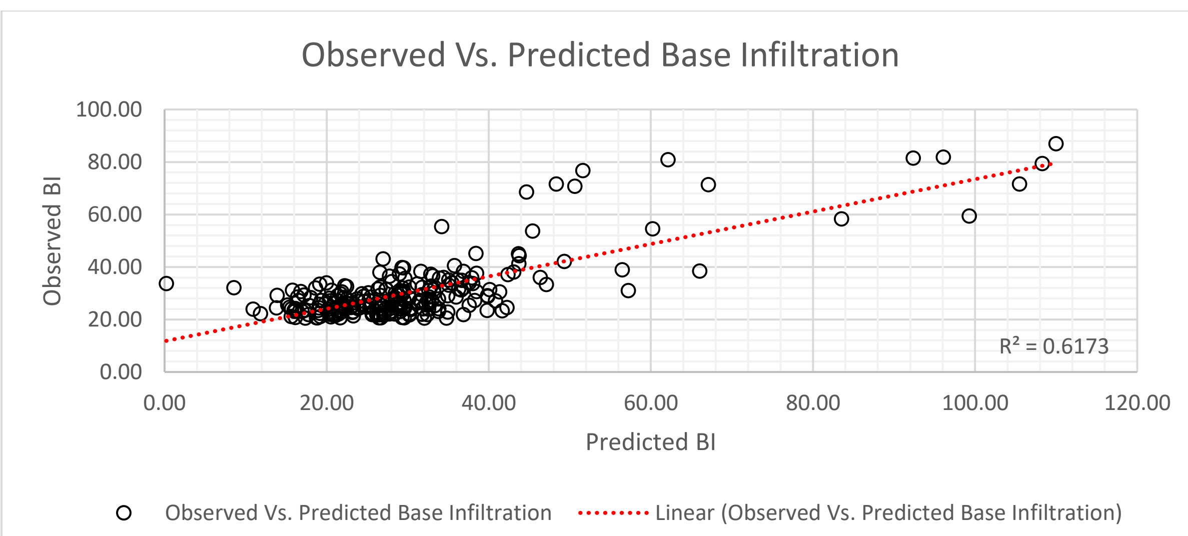


Figure 6: Regression model to predict BI at PS-119.

From the regression model, the coefficients for rainfall on day 1, 4 and 5 are greater than the coefficients of other days, thus showing a strong correlation of the rainfall event on the BI. The R-squared value for this regression model is 0.62, which is considered satisfactory for the model due to the complexity of the system's response to different rainfall patterns, for different events and the complexity of cracks geometry in the sewer network (Figure 6)

As previously mentioned the regression model is used to predict the BI for different rainfall events including hurricane events and routed through the system to analyze the hydraulic performance of the system. For hurricane events, the rainfall was spiked up with the period of the hurricane and sewer flows were routed for the following days to observe how the system reacts to the events. Table 1 and Figure 7 below shows different rainfall depths and BI distribution respectively, corresponding to different hurricane events used for the analysis

Table 1: Different rainfall depths for different hurricane events.

Hurricane events	Date	Total rainfall depths
Hurricane Matthew	August 28th - September 3rd, 2016	14 inches
Hurricane Hermine	September 28th - October 1st ,2016	17 inches
Hurricane Irma	September 10th - September 12th, 2017	22 inches
Hurricane Harvey	August 30th - September 1st, 2017	38 inches

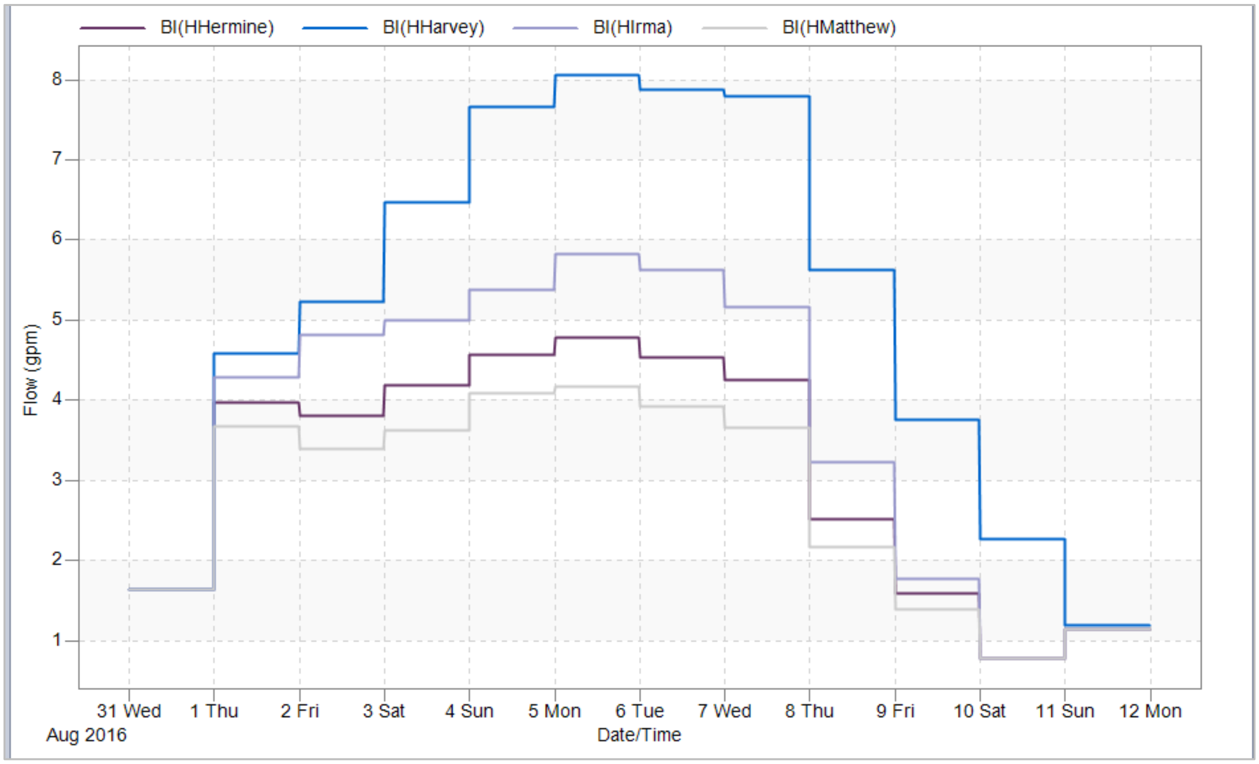


Figure 7: BI distribution for different rainfall depths.

3.2 PC SWMM Model Analysis

As mentioned beforehand, a set of performance indicators; flow surcharge, and flooding (SSO), were defined for assessing the hydraulic performance of the system.

Since, the total observed flow is the addition of the BI and DWF, the flow was simulated by combining both flow inputs and routed for the wet weather periods, June 1st- September 30th, 2016. From Figure 8, the simulation result is greater than the observed flow with the routing continuity error of -0.01 percent. Since all the variables are either given or calculated for the model, there are fewer chances for calibrating the system to match the observation. Thus, the simulation results are considered satisfactory for further analysis. Figure 9 presents a hydraulic profile showing the manholes which had flow surcharges in the system. The flow surcharge occurred during two-time periods, June 10th and September 1st (Tropical storm after Hurricane

Hermine), and lasted for about 96 hours after these events. The total rainfall of the seven previous days for the two events were greater than 10 inches.

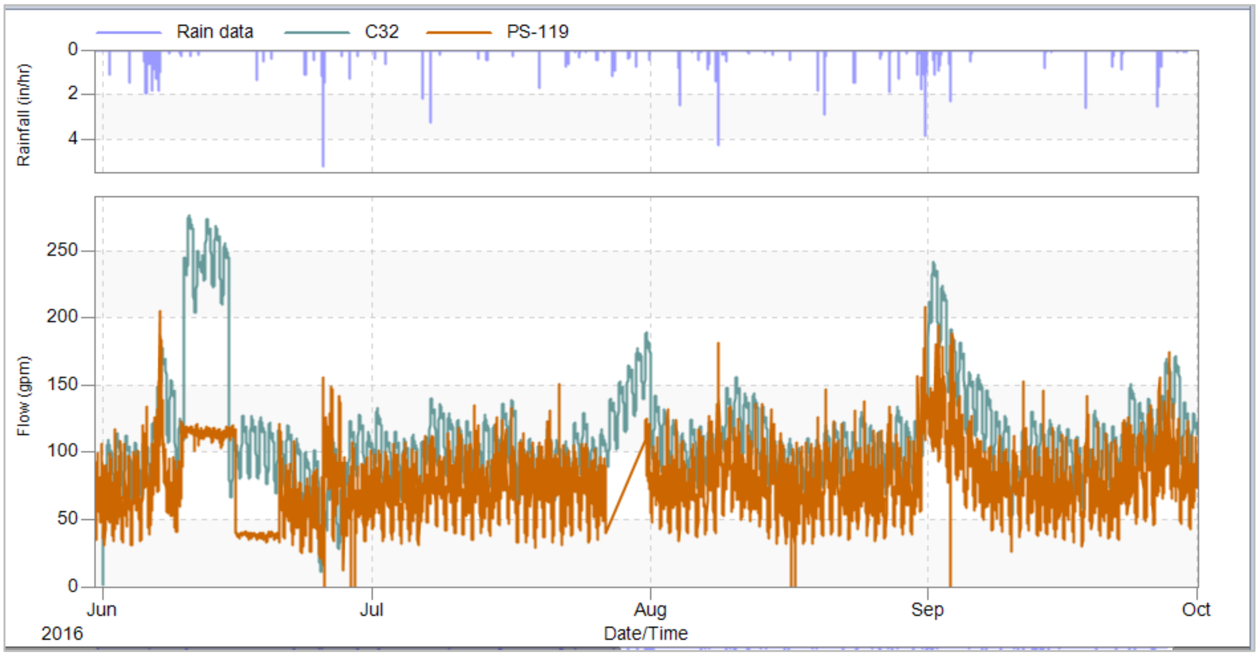


Figure 8: PS-119 simulated time series graph, DWF+BI from June–September 2016. C32 = Q $_{sim}$, PS-119 = observed flow

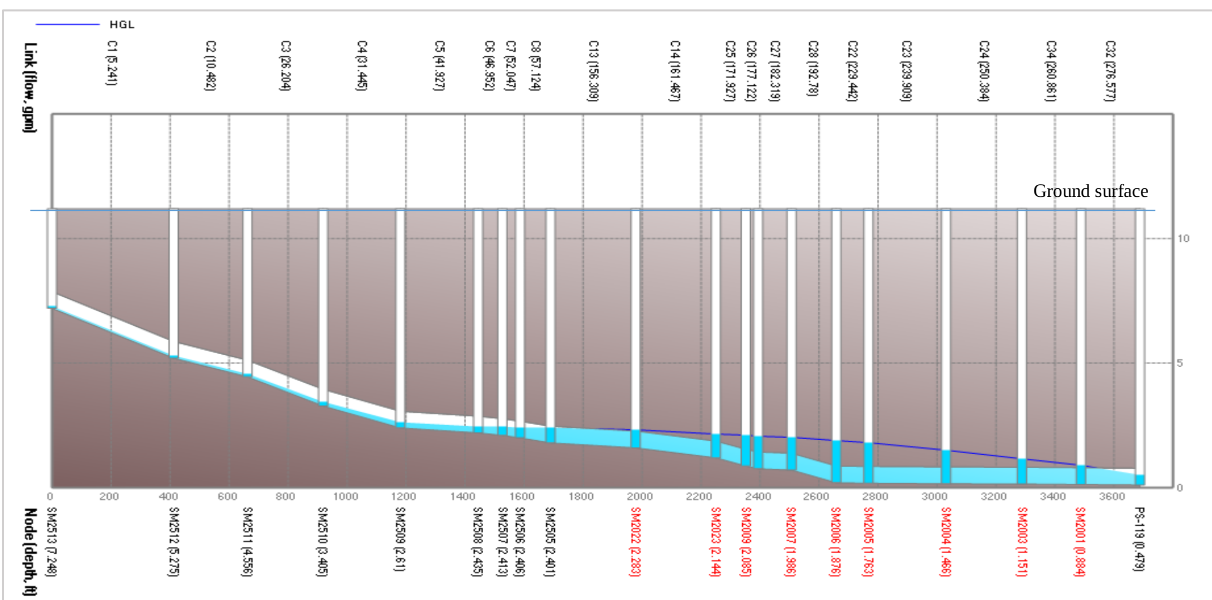


Figure 9a: Hydraulic profile of flow surcharge downstream on June 10th. Total rainfall = 11.49 inches

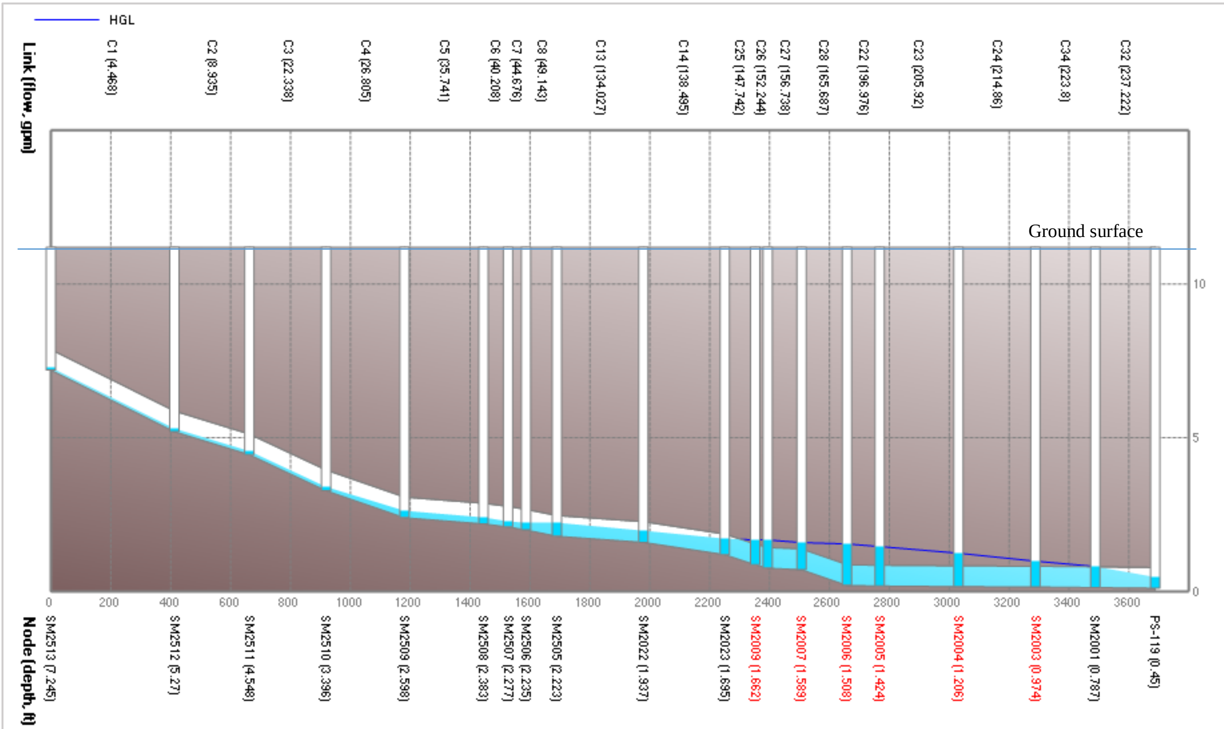


Figure 9b: Hydraulic profile of flow surcharge downstream on September 1st. Total rainfall = 10.46 inches

Using the regression model, and increasing the rainfall exceeding 11 inches, the performance indicators regarding SSO (flooding) and surcharge and their values are presented in Table 1. The performance indicators show that as rainfall depth increases, the hydraulic grade line, the number of manholes and hours the manholes stayed surcharged increases (Figure 9). More so, it is intuitive that the longest surcharge manholes are located downstream of the system, since that is the location where all the flow converges before flowing into the wet well, PS-119. Additionally, looking at the pipe slopes, the slopes of the downstream pipes are mild, almost horizontal, thus increasing the potential for the flow to go from gravity to pressurized flow. Although the number and the length of time of surcharged manholes increased, there was no SSO at the manhole. Thus, the existing sewer system is most reliable and less vulnerable to

SSO. However, as mentioned in the introduction, SSO can occur at the wet well, and in this study case at the lift station, PS-119.

Since the capacity of PS-119 is unknown, PS-119 capacity (in gpm) was calculated using the number of houses, the average household sewer flow, and the peaking factor. As mentioned beforehand, the area of the sewershed is about 72 acres, and assuming each house is about one-quarter acre, the average household sewer flow is 300 GPD, peaking factor is 3 and the roads and curbs are about 11 acres, the lift station capacity is approximately 200 gpm (equation 5)

$$PS - 119\ capacity = \left(\frac{(72 - 11)}{0.25}\right) * (300\ GPD) * \left(\frac{1}{1440}\right) * 3$$

Equation 5: Lift station (PS-119) design capacity

Furthermore, SSO occurred at the wet well, PS-119 (Figure 10), where the total flow received exceeds the calculated capacity at PS-119. Figure 10 shows the flow hydrographs of the different rainfall depths and the observed sewer flow compared to the PS-119 flow capacity. From the hydrographs and from Table 2, it shows that as the rainfall depths increase, the volume (area under the curve) of SSO at the lift station increases. Thus, the existing lift station, PS-119, is less reliable and more vulnerable to SSO.

Table 2: Sewer system hydraulic performance indicators for different rainfall depths.

Performance indicators	**Details**	**Rainfall depths**						
		Matthew	Hermine	Irma	25-inches	30-inches	Harvey	40-inches
Manhole surcharge	Number of surcharged manholes	10 manholes	14 manholes	15 manholes	17 manholes	17 manholes	20 manholes	21 manholes
	Manhole with maximum hours surcharged	SM 2006 (188.87 hrs.)	SM 2006 (198.47 hrs.)	SM 2006 (207.79 hrs.)	SM 2006 (211.69 hrs.)	SM 2006 (220.21 hrs.)	SM 2006 (238.14 hrs.)	SM 2006 (245.75 hrs.)
PS-119 SSO	Total volume of SSO	24,833	43,850	74,344	83,321	116,312	148,512	172,895

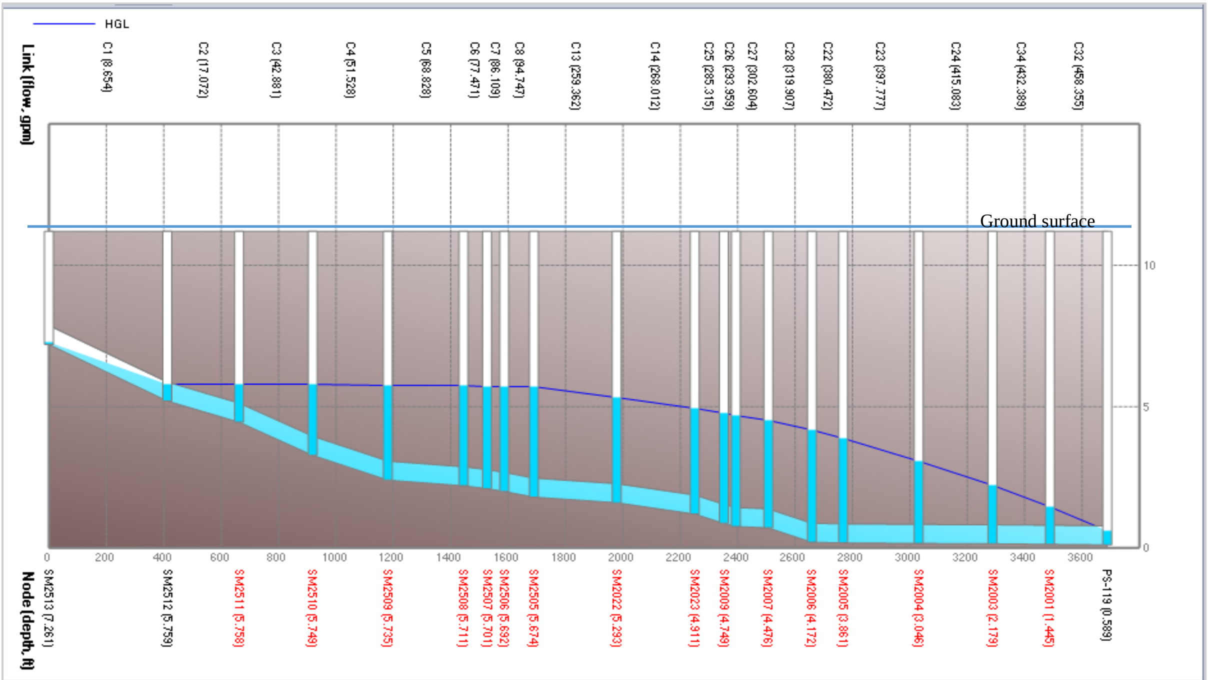


Figure 10a: Hurricane Harvey rainfall depth. Hydraulic profile plot showing surcharged manholes

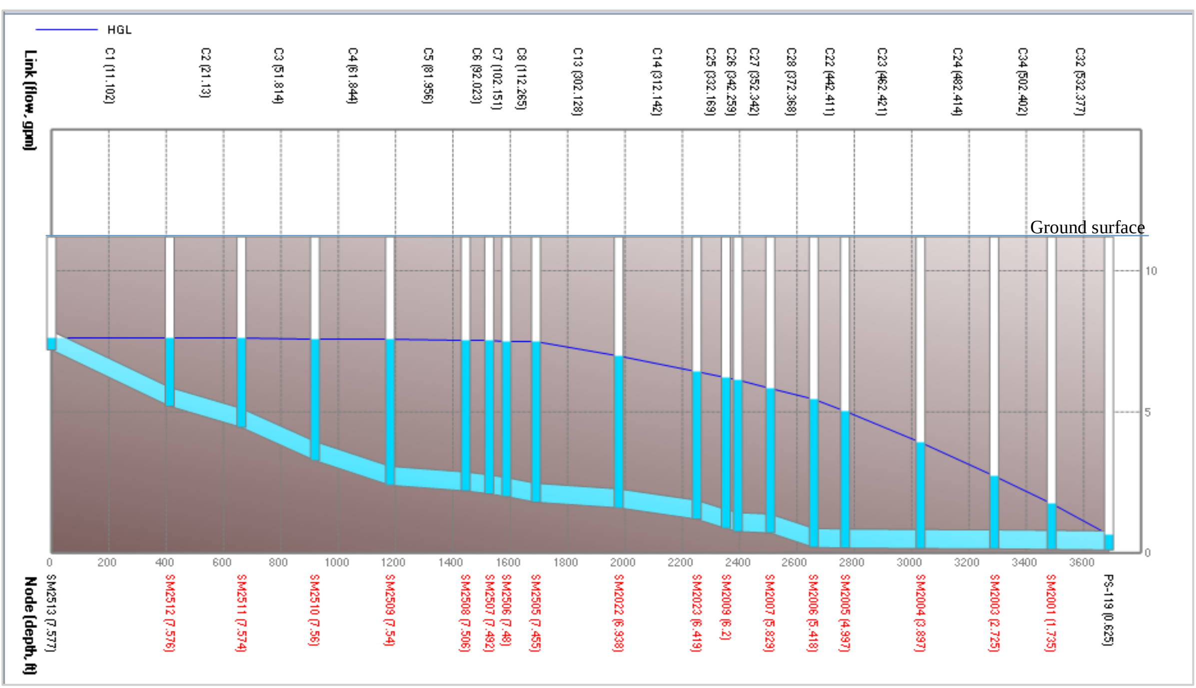


Figure 10b: 40-inches rainfall depth. Hydraulic profile plot showing surcharge manholes

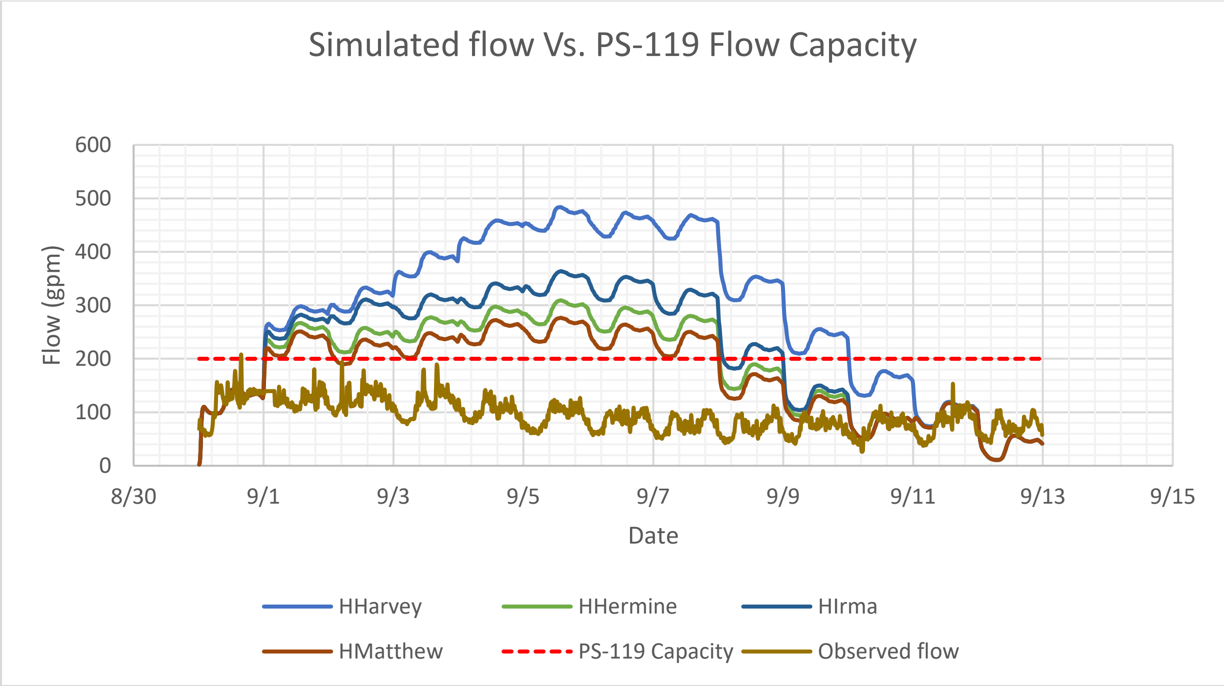


Figure 11: Flow hydrographs of the different rainfalls depths vs. PS-119 design capacity

CHAPTER 4: CONCLUSION

Sanitary sewer overflow releases harmful contaminants, pollutants and nutrients that are detrimental to the environment, ecosystem and public health, and more so poses a financial difficulty to clean out the effects both on the environment and the public. In this study, performance indicators were defined to help evaluate the hydraulic performance of the existing system. Since the PS-119 sewer is located on an area with shallow water table (ranging from 2 to 6 ft. below the ground elevation), groundwater infiltration would be a major problem, in addition to blockages and debris build up, thereby reducing the pipe diameter, will lead to flow surcharge and SSO.

The time series analysis ruled out surface inflow as a significant source of freshwater contribution to excess sewer flow. Using the Steven-Schutzbach method, the base infiltration calculation showed that an annual of 49% of the flow during the wet weather, and 42% during dry weather was essentially groundwater infiltration. Thus, presenting a challenge of high infiltration into the sewer system. Correlation analysis suggests that significant relationship for 7 days between base infiltration and rainfall. The analysis suggests that the rainfall takes about 1-2 days to infiltrate the soil and raise the water table, peaking on day 4 and receding from day 5 to day 7 after the rainfall event. Applied to regression analysis to predict future base infiltration for different rainfall depths, it further showed the increase in the base infiltration flow as the rainfall depths increases.

Comparing the results of the hydraulic performance for different rainfall depths, showed that as the rainfall depths increase, the number and hours the surcharged manholes increases but no SSO occurred at the manholes. SSO occurred at the wet well, PS-119, and as the rainfall depths increased, the volume of SSO increased. However, since the occurrences of such high rainfall depths for SSO are rare, the system is considered reliable and less vulnerable. Furthermore, carefully looking at the surcharge manholes, the locations of the manholes are downstream of the system, where all the flow converges, and the pipe slopes are relatively horizontal. The observation helps pinpoint crucial locations where system failure is more likely to occur and can help propose a more strategic, sustainable, cost-effective plan to mitigate the negative impacts of sanitary sewer overflows.

In conclusion, the hydraulic performance study helps provide information for strategic planning, implementing and improving the existing sanitary system to reduced rainfall-induced overflows. Future studies will detail the impacts of rehabilitation on the reduction of the infiltration in the system. This study will serve as a primary hydraulic model for the future study and will help compare and analyze the results, before and after rehabilitation.

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APPENDIX A: SUPPLEMENTAL FIGURES

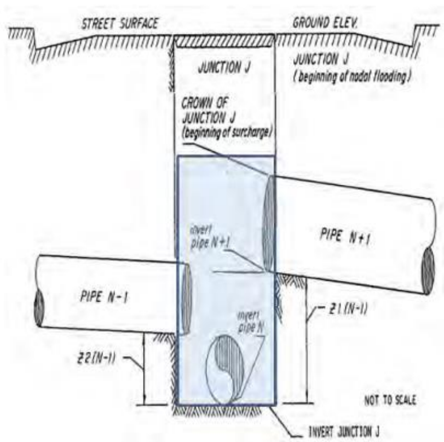

Figure A1: Cross section of surcharged manhole

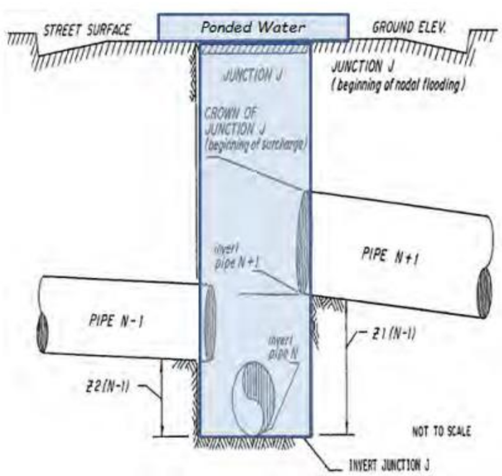

Figure A2: Cross section of ponded/overflowed manhole

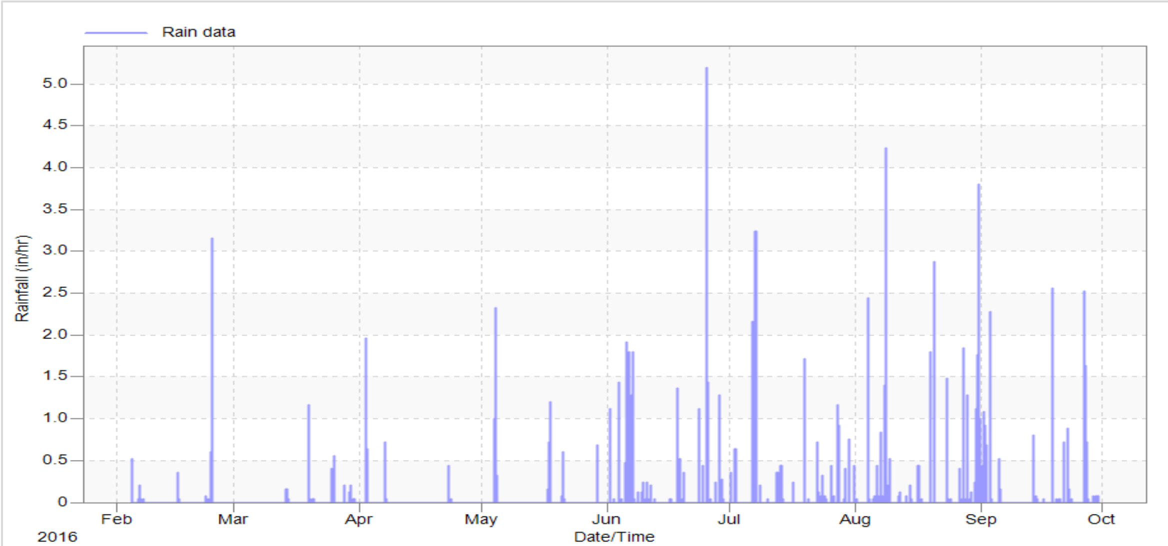

Figure A3: Rainfall intensity from February-September 2016

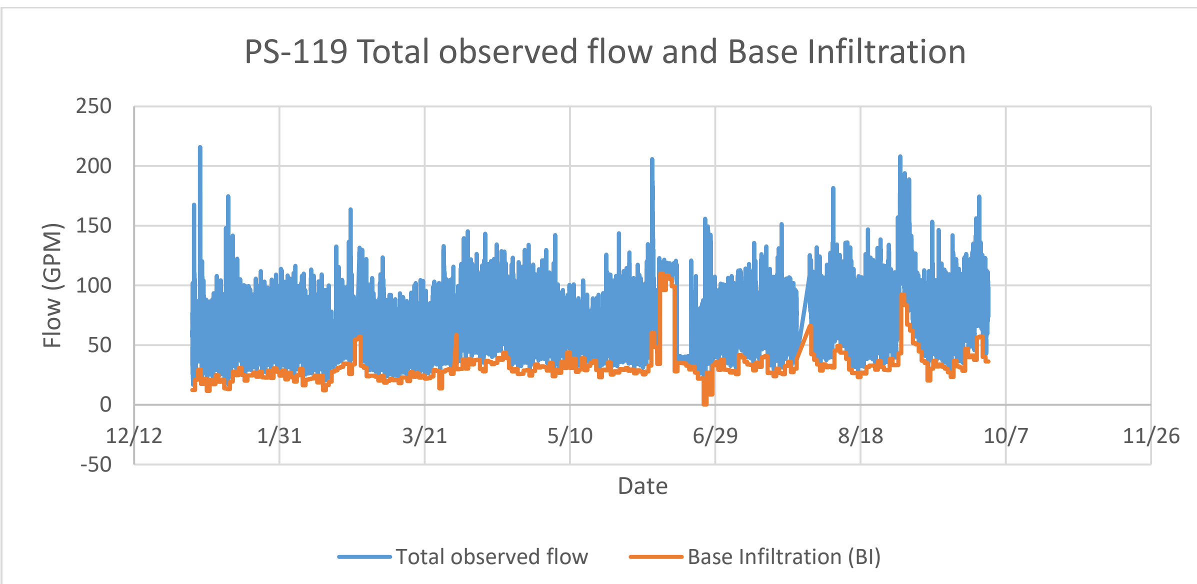

Figure A4: Total observed flow and BI for PS-119.

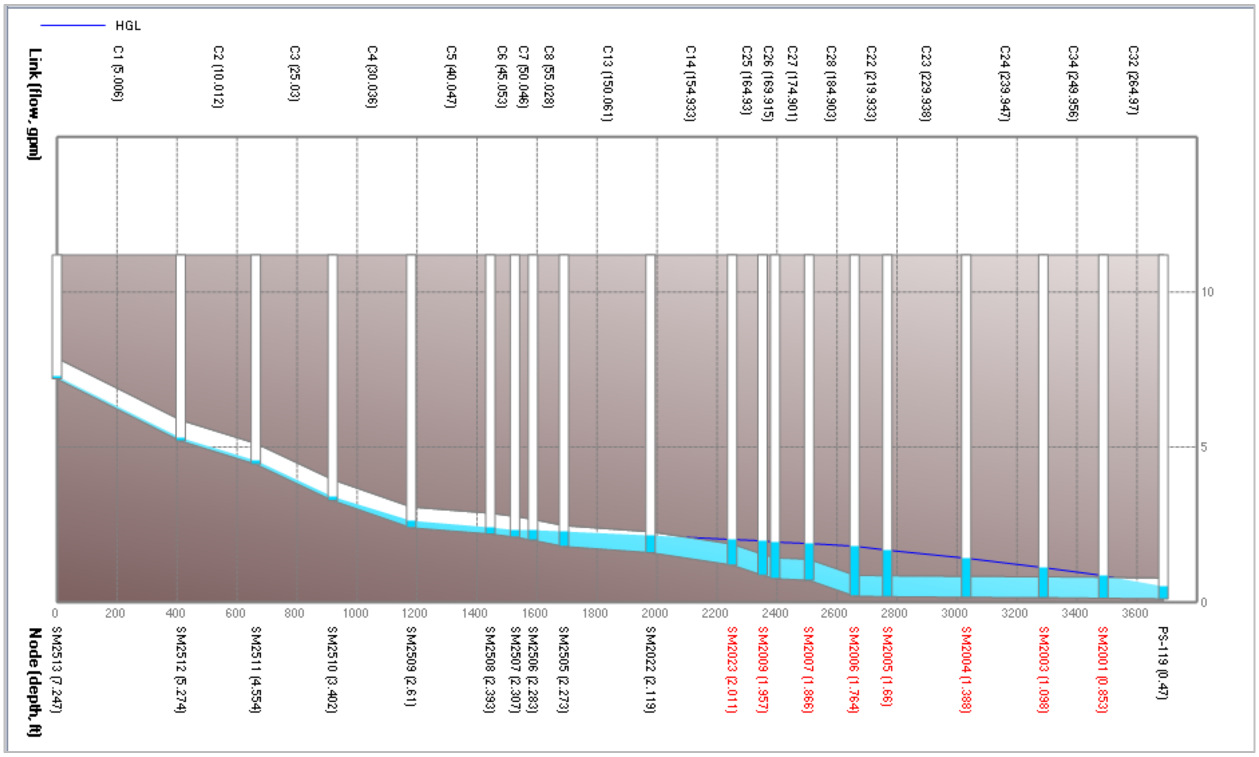

Figure A5: Hurricane Matthew rainfall depth. Hydraulic profile plot showing surcharged manholes

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Node Surcharge Summary
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Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                           Max. Height   Min. Depth
                                  Hours    Above Crown    Below Rim
Node                Type      Surcharged          Feet         Feet
---------------------------------------------------------------------
SM2001              JUNCTION       56.98         0.084       10.316
SM2003              JUNCTION      167.92         0.331       10.049
SM2004              JUNCTION      181.67         0.637        9.733
SM2005              JUNCTION      187.21         0.914        9.436
SM2006              JUNCTION      188.87         1.007        9.323
SM2007              JUNCTION      140.44         0.608        9.212
SM2008              JUNCTION      139.36         0.631        9.139
SM2009              JUNCTION      123.40         0.547        9.113
SM2022              JUNCTION        1.74         0.015        8.915
SM2023              JUNCTION       41.34         0.276        9.054
```

Figure A6: Hurricane Matthew rainfall depth. Summary of surcharged manholes

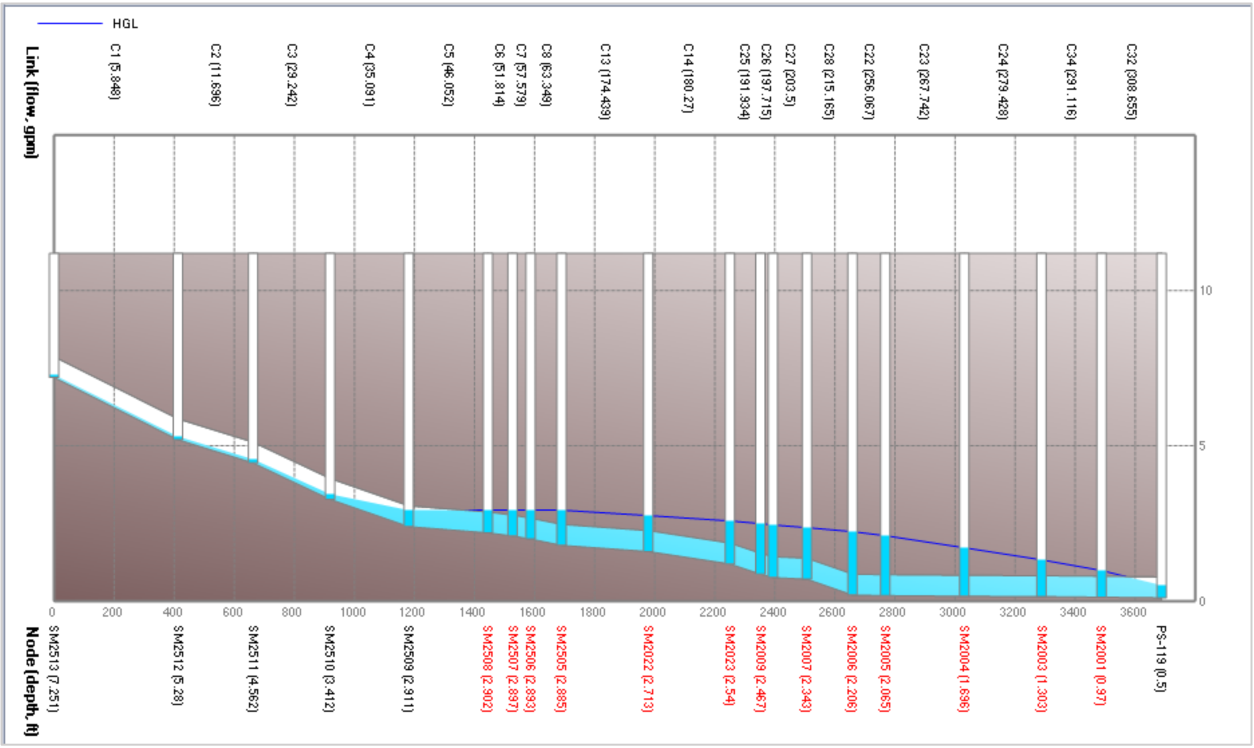

Figure A7: Hurricane Hermine rainfall depth. Hydraulic profile plot showing locations of surcharged

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Node Surcharge Summary
**********************

Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                           Max. Height   Min. Depth
                              Hours        Above Crown    Below Rim
Node             Type      Surcharged          Feet         Feet
---------------------------------------------------------------------
SM2001           JUNCTION      132.72         0.172       10.228
SM2003           JUNCTION      170.30         0.487        9.893
SM2004           JUNCTION      185.05         0.872        9.498
SM2005           JUNCTION      195.17         1.223        9.127
SM2006           JUNCTION      198.47         1.344        8.986
SM2007           JUNCTION      166.73         0.973        8.847
SM2008           JUNCTION      164.72         1.015        8.755
SM2009           JUNCTION      156.23         0.937        8.723
SM2022           JUNCTION       53.16         0.455        8.475
SM2023           JUNCTION      116.61         0.681        8.649
SM2505           JUNCTION       43.35         0.428        8.302
SM2506           JUNCTION       19.76         0.236        8.294
SM2507           JUNCTION        9.15         0.140        8.290
SM2508           JUNCTION        3.07         0.045        8.285
```

Figure A8: Hurricane Hermine rainfall depth. Summary of surcharged manholes

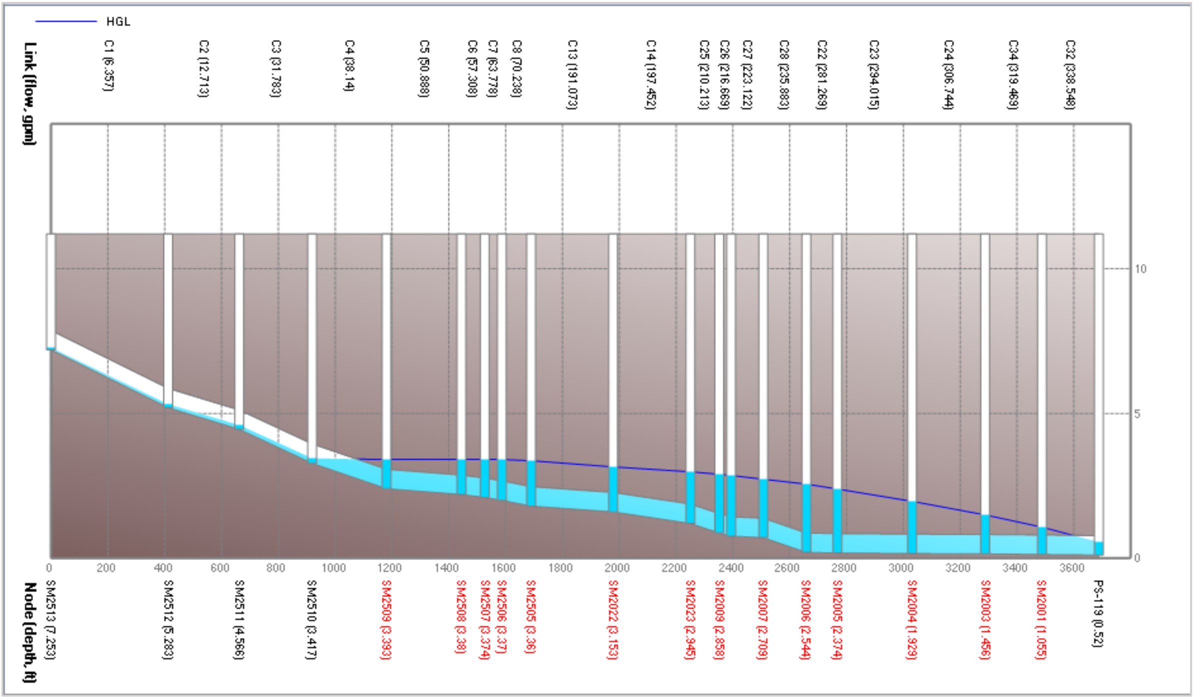

Figure A9: Hurricane Irma rainfall depth. Hydraulic profile plot showing locations of surcharged manholes

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Node Surcharge Summary
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Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                               Max. Height   Min. Depth
                                   Hours       Above Crown    Below Rim
Node                 Type       Surcharged           Feet         Feet
---------------------------------------------------------------------
SM2001               JUNCTION       161.61          0.330       10.070
SM2003               JUNCTION       186.24          0.773        9.607
SM2004               JUNCTION       192.38          1.309        9.061
SM2005               JUNCTION       203.22          1.802        8.548
SM2006               JUNCTION       207.79          1.978        8.352
SM2007               JUNCTION       181.90          1.660        8.160
SM2008               JUNCTION       181.69          1.737        8.033
SM2009               JUNCTION       171.91          1.672        7.988
SM2022               JUNCTION       142.71          1.286        7.644
SM2023               JUNCTION       159.29          1.444        7.886
SM2505               JUNCTION       131.86          1.326        7.404
SM2506               JUNCTION       118.66          1.137        7.393
SM2507               JUNCTION       109.31          1.043        7.387
SM2508               JUNCTION        97.34          0.949        7.381
SM2509               JUNCTION        68.61          0.764        7.366
```

Figure A10: Hurricane Irma rainfall depth. Summary of surcharged manholes

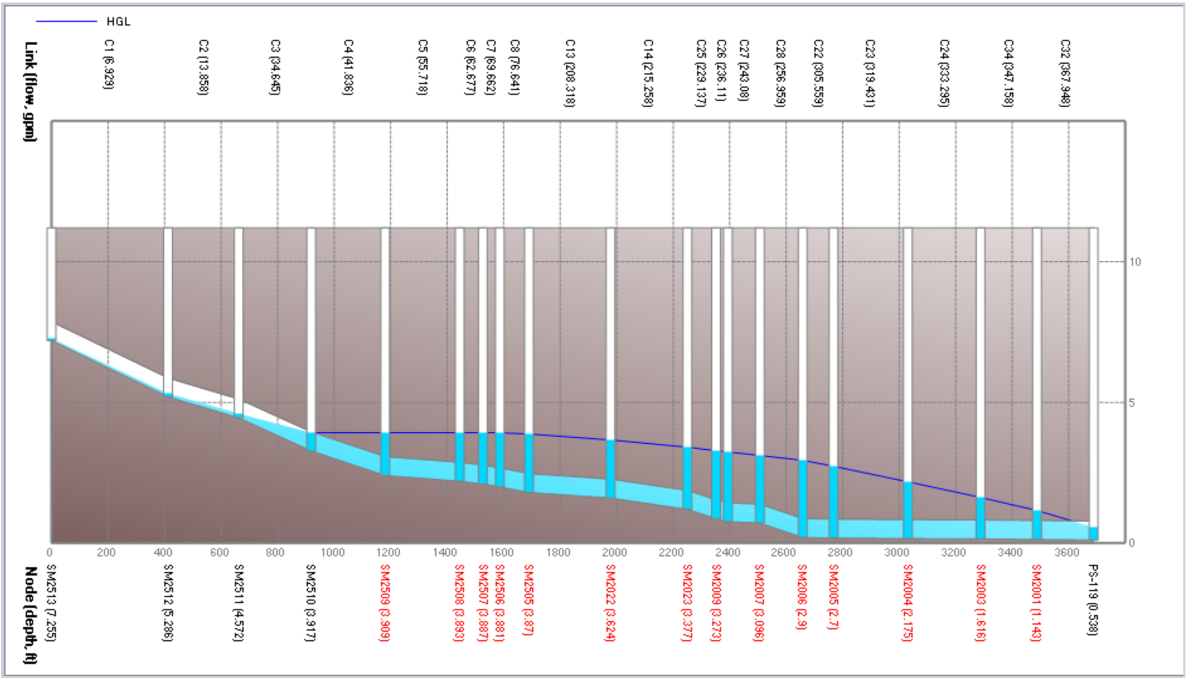

Figure A11: 25-inches rainfall depth. Hydraulic profile plot showing locations of surcharged manholes

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Node Surcharge Summary
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Surcharging occurs when water rises above the top of the highest conduit.

Node	Type	Hours Surcharged	Max. Height Above Crown Feet	Min. Depth Below Rim Feet
SM2001	JUNCTION	166.27	0.366	10.034
SM2003	JUNCTION	192.03	0.839	9.541
SM2004	JUNCTION	200.63	1.411	8.959
SM2005	JUNCTION	210.33	1.938	8.412
SM2006	JUNCTION	211.69	2.126	8.204
SM2007	JUNCTION	185.90	1.820	8.000
SM2008	JUNCTION	185.57	1.906	7.864
SM2009	JUNCTION	183.76	1.844	7.816
SM2014	JUNCTION	16.66	0.130	8.200
SM2022	JUNCTION	142.99	1.479	7.451
SM2023	JUNCTION	159.71	1.622	7.708
SM2505	JUNCTION	132.11	1.535	7.195
SM2506	JUNCTION	125.00	1.347	7.183
SM2507	JUNCTION	121.58	1.253	7.177
SM2508	JUNCTION	109.54	1.160	7.170
SM2509	JUNCTION	90.44	0.976	7.154
SM2510	JUNCTION	4.29	0.106	7.144

Figure A12: 25-inches rainfall depth. Summary of surcharged manholes

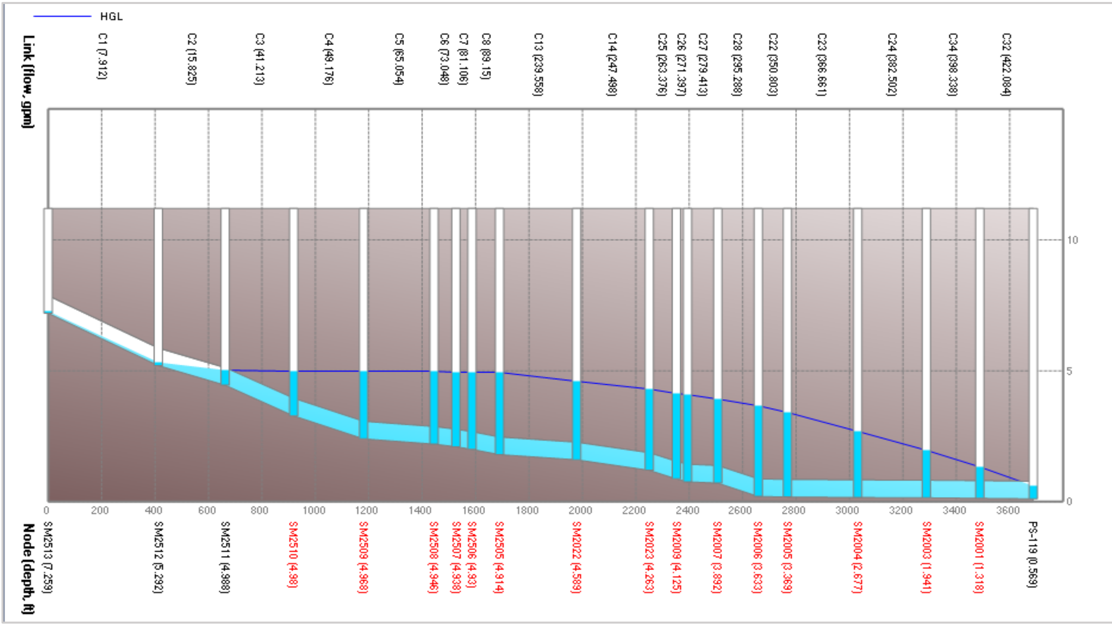

Figure A13: 30-inches rainfall depth. Hydraulic profile plot showing locations of surcharged manholes

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**********************
Node Surcharge Summary
**********************

Surcharging occurs when water rises above the top of the highest conduit.
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Node	Type	Hours Surcharged	Max. Height Above Crown Feet	Min. Depth Below Rim Feet
SM2001	JUNCTION	184.78	0.539	9.861
SM2003	JUNCTION	192.39	1.159	9.221
SM2004	JUNCTION	208.11	1.906	8.464
SM2005	JUNCTION	215.46	2.597	7.753
SM2006	JUNCTION	220.21	2.848	7.482
SM2007	JUNCTION	192.05	2.603	7.217
SM2008	JUNCTION	192.04	2.729	7.041
SM2009	JUNCTION	191.90	2.681	6.979
SM2014	JUNCTION	99.82	0.853	7.477
SM2022	JUNCTION	163.58	2.425	6.505
SM2023	JUNCTION	183.81	2.492	6.838
SM2505	JUNCTION	159.82	2.557	6.173
SM2506	JUNCTION	158.51	2.373	6.157
SM2507	JUNCTION	152.31	2.281	6.149
SM2508	JUNCTION	143.72	2.189	6.141
SM2509	JUNCTION	134.08	2.010	6.120
SM2510	JUNCTION	88.53	1.142	6.108

Figure A14: 30-inches rainfall depth. Summary of surcharged manholes

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Node Surcharge Summary
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Surcharging occurs when water rises above the top of the highest conduit.

Node	Type	Hours Surcharged	Max. Height Above Crown Feet	Min. Depth Below Rim Feet
SM2001	JUNCTION	201.49	0.740	9.660
SM2003	JUNCTION	216.17	1.537	8.843
SM2004	JUNCTION	230.77	2.492	7.878
SM2005	JUNCTION	236.42	3.379	6.971
SM2006	JUNCTION	238.11	3.705	6.625
SM2007	JUNCTION	211.46	3.533	6.287
SM2008	JUNCTION	211.15	3.708	6.062
SM2009	JUNCTION	208.62	3.677	5.983
SM2014	JUNCTION	111.59	1.712	6.618
SM2022	JUNCTION	182.47	3.553	5.377
SM2023	JUNCTION	195.65	3.527	5.803
SM2505	JUNCTION	181.95	3.778	4.952
SM2506	JUNCTION	166.88	3.598	4.932
SM2507	JUNCTION	159.90	3.508	4.922
SM2508	JUNCTION	158.23	3.419	4.911
SM2509	JUNCTION	150.92	3.246	4.884
SM2510	JUNCTION	111.19	2.381	4.869
SM2511	JUNCTION	80.40	1.222	4.858
SM2512	JUNCTION	25.33	0.474	4.856
SM2514	JUNCTION	36.81	0.574	4.856

Figure A15: Hurricane Harvey rainfall depth. Summary of surcharged manholes

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Node Surcharge Summary
*********************

Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                          Max. Height   Min. Depth
                               Hours      Above Crown    Below Rim
Node                 Type      Surcharged        Feet         Feet
---------------------------------------------------------------------
SM2001               JUNCTION     209.34        0.956        9.444
SM2003               JUNCTION     221.13        1.944        8.436
SM2004               JUNCTION     234.15        3.126        7.244
SM2005               JUNCTION     243.22        4.224        6.126
SM2006               JUNCTION     245.75        4.631        5.699
SM2007               JUNCTION     216.12        4.538        5.282
SM2008               JUNCTION     216.11        4.765        5.005
SM2009               JUNCTION     215.96        4.752        4.908
SM2014               JUNCTION     134.69        2.640        5.690
SM2022               JUNCTION     190.36        4.768        4.162
SM2023               JUNCTION     208.34        4.644        4.686
SM2505               JUNCTION     183.85        5.091        3.639
SM2506               JUNCTION     182.52        4.916        3.614
SM2507               JUNCTION     181.77        4.828        3.602
SM2508               JUNCTION     175.22        4.741        3.589
SM2509               JUNCTION     161.17        4.575        3.555
SM2510               JUNCTION     129.98        3.714        3.536
SM2511               JUNCTION      95.86        2.556        3.524
SM2512               JUNCTION      75.99        1.808        3.522
SM2514               JUNCTION      85.14        1.909        3.521
SM2516               JUNCTION       9.54        0.195        3.555
```

Figure A16: 40-inches rainfall depth. Summary of surcharged manholes