Characterization of the rainfall-runoff response of an urban combined sewer catchment using observed and analytical methods

Scott Martin Jeffers

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Department of Civil, Architectural, and Environmental Engineering

Drexel University

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ABSTRACT

Characterization of the rainfall-runoff response of an urban combined sewer catchment using observed and analytical methods

Scott Jeffers

Franco Montalto, PhD

In this study, hydrologic and hydraulic observations were made in two catch-basins and a manhole at the end of a two hectare urban combined sewer catchments in Bronx, New York City over the course of nine months. These measurements included 28 rain-events that were used to characterize the rainfall-runoff response and combined sewer flow in the collection system. The observations were used to assess the ability with which standard hydraulic and hydrologic methods can predict the actual rainfall-runoff response of this particular urban catchment. The analytical method assessed in this study are listed in the Technical Release 55 (TR-55), a manual for developed by the Soil Conservation Service (SCS) for urban stormwater analysis and design. These methods currently have popular usage by municipality stormwater code and practicing engineers and included the following: the SCS Curve Number Runoff Method, Rational Method for peak flow, and analysis of lag-to-peak time between peak rainfall intensity and peak sewer flow. The results of this study show a strong regression correlation ($R^2 = 0.95$) for the Curve Number method, and a weaker correlation for the Rational Method ($R^2 = 0.60$) and the lag-to-peak

analysis ($R^2 = 0.69$). Observed deviations from each model may be the result of rainfall variability and antecedent moisture conditions.

INTRODUCTION

Study Goals

The goal of this study is to experimentally characterize the rainfall-runoff response for a urban combined sewer catchment. With much interested paid to emerging green infrastructure (GI) stormwater management, it is important to establish a baseline of current hydrologic and hydraulic conditions from which to compare future GI projects. Similar experimental studies have been conducted to observe the result of urbanization on the hydrologic response (the effect of rainfall on surface runoff), but none have focused particularly on small urban residential catchments nor their hydraulic component (the resulting sewer flow). Results from a study by James A. Smith et al 2005. characterized an urban watershed by measuring creek discharge in response to urban runoff. While this study offers a detailed field hydrologic analysis of an urban watershed, it does not offer analysis into the hydraulics of stormwater infrastructure, an important component of modern urban water resource engineering. A second study conducted by Mark J. Hood et at. 2007 observed this hydraulic response while demonstrating the potential that GI can have at reducing stormwater runoff and delaying the hydraulic rainfall runoff response of traditional stormwater infrastructure. Because this study was conducted in a more suburban landscape (32% impervious cover), however, the results are not fully compatible with most urban environments.

An additional motivating factor for this study is to compare common analytical methods for predicting the rainfall-runoff response of an urban combined sewer catchment. There is a variety of analytical methods that are commonly used by water resource engineers to determine the hydrological response of urban watersheds and, in addition, designing stormwater management structures and strategies (including those associated with GI). The methods included in this study are found in the TR-55 from the SCS and include the SCS Runoff Curve Number, Rational Peak Flow, and lag-to-peak time between peak rainfall and peak runoff discharge. These methods were selected based upon their wide level of usage among practicing engineering in addition to their prevalence in municipal code for proper stormwater management (NYCDEP 2000; PWD 2011). While these methods have been empirically tested for many years now, their are few studies that test their effectiveness at predicting the rainfall-runoff response for an urban combined sewer system in particular.

Background

In many older United States cities, stormwater management has become a major priority for reducing combined sewer overflows (CSOs). The underlying issue is that much of the urban landscape has been covered with impervious materials. As a result, during wet weather precipitation water that normally would have been largely infiltrated into the ground in most natural environments is instead convolved into runoff. This runoff then enters the engineered collection system. These sewer systems in many older cities are combined sewers, which means that sanitary sewage and stormwater runoff are collected together in a collection system. During particular depths, durations, and intensities of precipitation, the conveyance capacity of these sewers is exceeded from the stormwater runoff entering the system. The result is a combined sewer overflow (CSO) in which the untreated sewage and stormwater are discharged directly into the local waterways including rivers and streams. A detailed schematic of the process is shown if Figure 1 below.

This CSO pollution contaminates the waterways posing risks to both ecosystem and public health. The nonpoint pollution resulting from the CSO has been linked to increases in the pathogens such as the oocysts of *Cryptosporidium*, a parasitic protozoa that can cause severe gastrointestinal illness in humans. These pathogens make their way to drinking water treatment plants that draw water from local water sources. Common water treatment practices often do not eliminate all the pathogens increasing the chances of infection for the general public. In addition, the public can come into contact with the pathogens through recreational use of the polluted waters. The EPA estimates that this recreational exposure results in 3,500 to 5,500 gastrointestinal illnesses per year. (Tibbetts 2005)

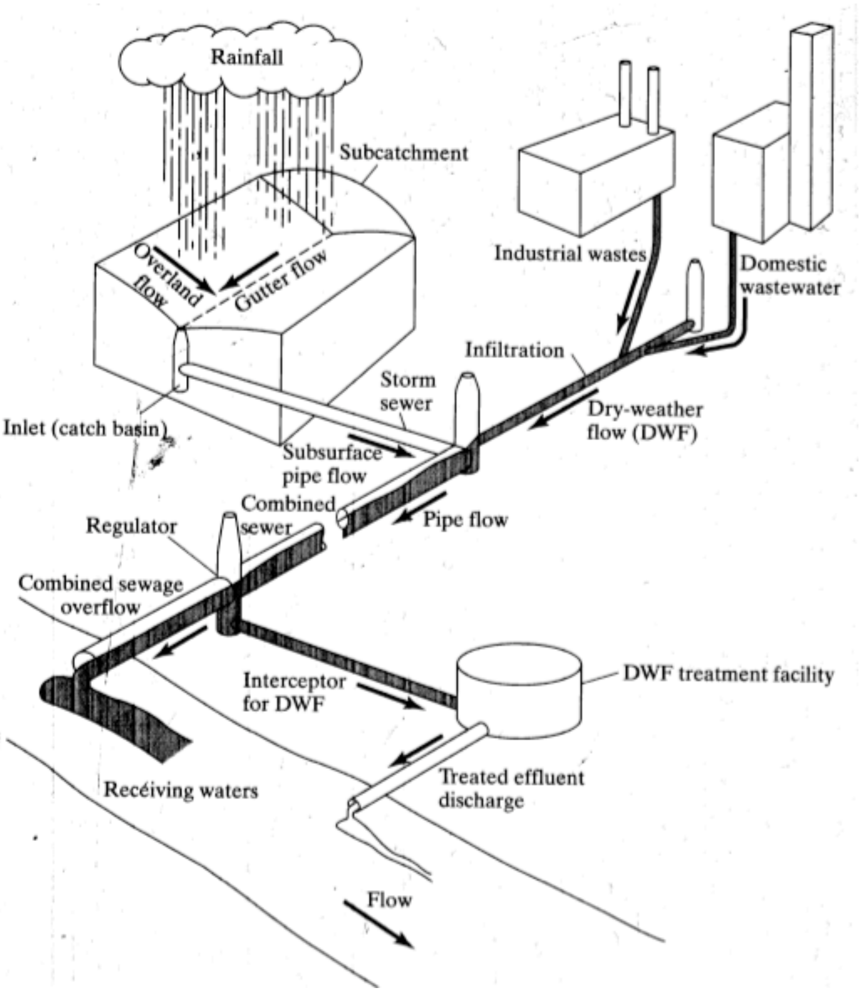

Figure 1: *Diagram of combined sewer urban drainage and potential of combined sewer overflow (Metcalf&Eddy 1991)*

During a CSO, nutrient rich material enters the receiving waters increasing biological oxygen demand (BOD). The potentially resulting eutrophication allows for a brief increase in photosynthetic microorganism populations which increase dissolved oxygen. Once this initial population begins to die, hypoxia can occurs as a result of increases in aerobic microorganism which deplete the dissolved oxygen content in the water. This negatively impacts the environment by causing the larger fauna such as fish to perish. It is only farther down the waterway that this effect stabilizes back to the waterway's natural as the microorganism populations return to equilibrium. This effect is classically characterized by an oxygen sag curve and is shown graphically in Figure 2 (Masten 2008).

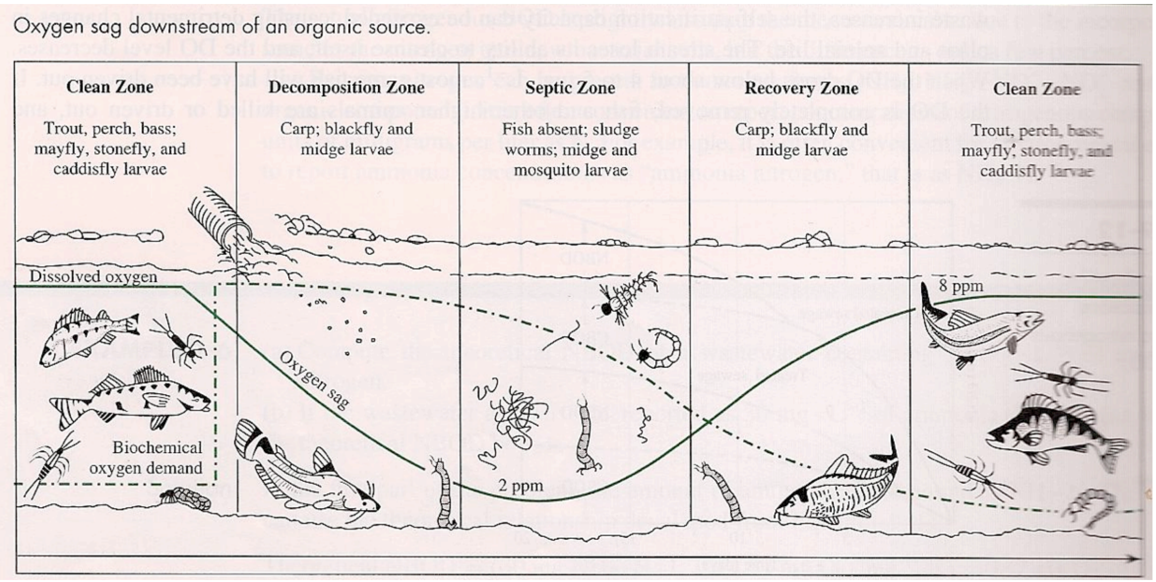

Figure 2*: Illustration of an Oxygen Sag Curve. High nitrogen content produces nutrient loading and eutrophication. This is turn induces aerobic metabolism that leading to hypoxia which decrease dissolved oxygen levels (Masten 2008).*

In a 2001 Report to Congress, the EPA has determined that 1,260 billion gallons of untreated water is released resulting from CSOs in the United States every year (EPA December 2001). It is estimated that 40 million Americans in 32 states live in cities with CSOs and are at risk of exposure. To address this issue, the EPA in 1994 issued the Combined Sewer Overflow Control Policy mandating that communities establish long-term plans to reduce CSO pollution to the Clean Water Act standards (Tibbetts 2005). Due to logistic and economic restraints, meeting these requirements has proven difficult for most members of the CSO communities.

Green Infrastructure Solutions to CSOs

Widespread development of stormwater management is being considered by many cities in the United States that currently suffer from the CSO problem. The EPA has estimated a national cost of $50.6 billion using traditional "grey infrastructure" approaches for controlling CSOs (EPA, 2001). Due to a lack of funding for such an extensive redevelopment plan, alternative methods have been considered. One increasingly popular solution to the CSO problem is to reduce the amount of stormwater runoff that enters the collection system. This can be accomplished through the implementation of green infrastructure (GI) including bioretention basins, rain barrels, and porous pavement among other apporaches. A major block in this green development is the lack of understanding of the level of impact each system has on reducing runoff (EPA August 2004). While it is understood that GI will reduce runoff, it is not fully understood quantitatively how well they will improve the current system. In a 2008 action strategy, the EPA has included that research into this hydrology as necessary to understanding solutions for CSOs (EPA 2008). To address this issue, ongoing research is being done to understand the effectiveness of this form of green infrastructure.

In order to understand the effectiveness of GI at reducing stormwater runoff, however, first a baseline of current combined sewer hydrology must be established providing a metric with which to compare GI performance. Key hydrologic performance metrics important to reduce the effect of CSOs include the following: the total runoff volume, peak sewer flow rate, and the lag-to-peak duration between peak rainfall intensity and peak sewer flow (Richard Field 1997). Runoff volume is a crucial metric as it represents the amount of runoff entering into the collection system. Reducing this ultimately results in less water entering the sewer and less of a chance of a CSO. Peak sewer flow is also important because it is the instantaneous rate of flow that determines whether the conveyance capacity and whether a CSO or surcharge condition occurs. Increasing lag time is important as greater volumes of runoff will be able to pass through the collection system without triggering a CSO. The more circuitous the route that excess precipitation takes to leave the catchment, the longer it will take the catchment to reach peak flow rate. Additionally, this elongates the hydrograph diminishing the peak runoff rate. This effect is demonstrated in Figure 3 where GI tried to mimic the pre-urbanized conditions.

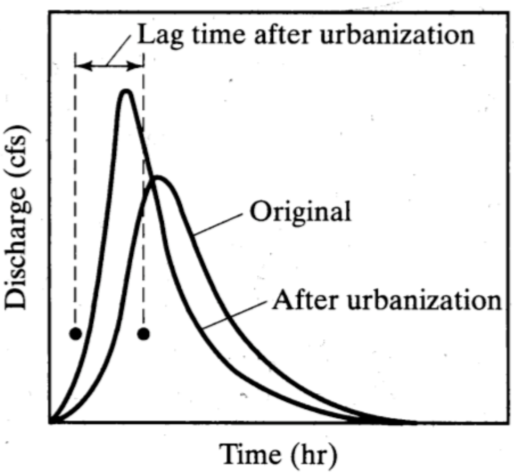

Figure 3: *Peak discharge and lag time between rainfall and increases in sewer discharge is decreases in urban catchments increase peak (Warren Viessman 2003)*

Analytical Methods for understanding Urban Hydrology

This section serves to outline the predictive analytical methods that are used in this study. Each method will be presents and its use explained. In addition, current understood shortcomings of each model will be outlined following each introduction.

Curve Number

The Curve Number method is a widely used method used to calculate the total depth of runoff resulting from a discrete rain-event. Developed by the the Soil Conservation Service in the 1950s for agricultural purposes, it is an empirically derived method that can be used for analysis of many small watersheds. This method factors in land use including infiltration of land type (Warren Viessman 2003). The basic equation used in the curve number method is as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{for} \quad P > 0.2S \qquad (1)$$

$$\text{where} \quad S = \frac{1000}{CN} - 10$$

Q = runoff (in)
P = precipitation (in)
CN = Curve Number
S = landscape conditions

Curve Numbers can be found using values determined by the TR-55 listed in the Appendix (NRCS 1986). The CN corresponds to the amount of impervious area of the catchment where more impervious environments have higher CN values than rural environments. Runoff using this method is given as a depth, so in order to convert this into volume, the result is multiplied by the area of the catchment. This method only can be used for relatively large storms where the amount of rainfall is greater than one-fifth the landscape condition value (S). As soil conditions change based upon antecedent moisture levels, adjustments can be made to urban landscapes using the antecedent moisture content (AMC) guidelines described in TR-55 (NRCS 1986). These AMC criteria are listed below in Table 1. Based upon the AMC criteria, changes to the curve number are made using equations 2 below:

Table 1*: Antecedent Moisture Conditions for Blue Grass Lawns (Terstriep and Stall)*

AMC Number	***Description***	***Total rainfall during 5 days preceding storm (in)***
1	Bone Dry	0
2	Rather Dry	0-0.5
3	Rather Wet	0.5-1
4	Saturated	Over 1

$$\begin{aligned} \text{CN I} &= \frac{\text{CN II}}{2.2 - 0.013\ \text{CN II}} \\ \text{CN II} &= \text{CN} \qquad\qquad (2) \\ \text{CN III} &= \frac{\text{CN II}}{0.43 + 0.0057\ \text{CN II}} \end{aligned}$$

The CN method has since been improved for application in urban catchments with the release of the TR-55 in 1976 (NRCS 1986). While this has improved the spectrum of CN usage, limitations of the CN method can be found in its assumptions regarding rainfall intensity. For one, the CN method can not response to different storm intensities treating a 2 inch storm in 3 hours as the same scenario to the same storm over 12 hours. Moreover, the method cannot determine the initial abstraction for smaller more intense storms as it treats the initial abstraction as constant. (Richard Hawkins 2009)

Rational Method

The rational method is a standard predictive model used for determining the peak runoff flow rate during rain-events. Developed in 1889 by Emil Kuichlin (Thompson 2007) for understand hydraulics of small catchments, its use has since become widely popular and is taught in contemporary hydrology textbooks for stormwater management design in addition to hydrologic analysis (Warren Viessman 2003; Philip B. Bedient 2008). The basic model is shown below in equation 3:

$$Q_p = k_c CiA \qquad (3)$$

Q_p = peak flow (m^3/s)
C = runoff coefficient
i = rainfall intensity (mm/hr)
k_c = conversion factor (0.00278)
A = area (ha)

Peak flow is determine through a multiplication of rainfall intensity, catchment area, and runoff coefficient defined below define in equation 4. This method assumes that rainfall intensity is uniform throughout the duration of the storm (e.g. block rainfall), such that there is no peak in rainfall intensity.

$$\mathrm{C} = \frac{\text{Total Depth of Runoff}}{\text{Total Depth of Precipitation}} \qquad (4)$$

The runoff coefficient is determined using similar methods to the curve number described above. Various types of catchment types are described in the Appendix with more impervious areas having higher C values. In order to determine the C value for a catchment, a weighted average of C values by area is performed.

The rational method is popular mainly due to its simplicity; however, this simplicity limits the scope to which it can be applied. For example, because the method does not factor details in topography and complexities of the catchment, applications are generally limited to catchments less than 200 acres. Additionally, results from the rational method can be skewed when using composite catchments where downstream areas are more developed than upstream areas. (A. Osman 2003)

Lag-to-Peak

The lag to peak time describes the lag time between peak rainfall intensity and peak runoff flow. This method developed by the SCS was empirically derived based on analysis of hydrographs ranging from large to small watersheds from various geographic locations (Warren Viessman 2003). This analysis can be performed using the time to peak equation below.

$$t_{peak} = \frac{D}{2} + t_{lag} \qquad (5)$$

$$t_{lag} = \frac{2.587L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900H^{0.5}} \qquad (6)$$

D = duration of excess rainfall (hr)
t_{peak} = time to peak (hr)
t_{lag} = lag time of catchment (hr)
L = hydraulic watershed length (m) = 110 catchment area $^{0.6}$
CN = curve number
H = average watershed slope (%)

The duration of excess rainfall (D) is determined to be the duration of rainfall after the initial abstraction as determined by the curve number method (0.2 S shown above) has been filled. The hydraulic watershed length (L) represents the distance from the farthest point of the catchment to the inlet of the sewer catchment.

METHODS

Site Description

The data collected in this study came from the combined sewer inlet at the intersection of Stratford Ave and 174th Street in the Bronx, New York City. The site is an urban residential block serviced by a combined sewer through Stratford Ave and two catchment basins located on adjacent corners of the 174th Street intersection. The Stratford Ave combined sewer collects residential water in addition to street runoff collected during rain events. These inlets are shown below in Figure 4. This site was chosen for this study a number of reasons. First, the site is representative of a typical urban residential block as determined by Khader and Montalto 2008 (Khader 2008). Second, the site located at the top of the sewershed meaning that sewer flow from other blocks does not enters the Stratford pipes. Third, a local community organization Youth Ministries for Peace and Justice (YMPJ) is on site and could provide support for the study including housing for rain gauges and remote monitoring. Finally, this site is serviced by the New York City Department of Environment Protection (NYDEP) who provided continuous monitoring assistance over the duration of the study.

Figure 4: *The 2 hectare Stratford Ave Catchment Area (Google 2011)*

Data Collection

Sewer flow and rain gage data were collected from the Stratford Ave and 174th combined sewer site from June 2011 to March 2012. Hach Flow-Tote 3 area-velocity flow sensors (details shown in the Appendix) were placed into both catchment basins leading into the combined sewer as well as an additional sensor in the main combined pipe servicing Stratford Ave and secured using sewer spring ring. The basic configuration of one sensor is shown in Figure 5. This method allowed monitoring of both catchments and the combined sewer of Stratford Ave. Sewer flow data was continuously collected at 15 minute intervals to the Hach FL900 data logger (Appendix) and communicated wirelessly using cellular modem to the FSDATA Hach Flow server (Appendix).

Figure 5: *Basic configuration of the flow sensor. Logger is mounted to the manhole ladder. Flow sensor is mounted using a spring ring. This study uses three sensors in three pipes. (HACH 2011)*

The two Global Water tipping bucket rain gauges (Appendix) continuously monitored precipitation at 5 minute intervals and stored to a Global Water GL500 data logger (Appendix). This logger was connect to an onsite computer linked to the internet. Using remote computing, the data was relayed to the Sustainable Water Resource Engineering Lab (SWRE) server located at Drexel University using FTP. A summary of the devices used in this study are shown in Table 2 below. Figure 37 in the Appendix shows a schematic of the devices implemented for the study.

Table 2: *Instrumentation Used in the Collecting Data*

Device	Description	Sensitivity	Logging Interval
Hach FL900	Sewer Flow Data Logger	-	15 minute
March-McBirney Flo-Tote 3	Flow Sensor	+/- 5%	-
Global Water RG200	Rain Gauge	+/- 3%	5 minute
Global Water GL500 Data Logger	Rain Gauge Logger	-	5 minute

Uncertainty in this study is present in the accuracy limitations of each sensor. The reading from the area-velocity flow sensor is only accurate to 5% of its reading. In addition, due to the size of the sensor, only sewer flow reading with a depth of more than 1 inch are accurate. The rain gauge results are also only accurate to 3% of the reading. Also, storms less than 0.254 mm are disregarded as this is the minimum resolution of the rain gauges.

Data Analysis

From the data collected, each rain event and hydrologic sewer response were analyzed. These metrics that characterized each storm included the following:

1. *Storm duration (min)*

The storm duration was taken to be the amount of time between the start of the rain to the end as read from the rain gauge. A storm was considered to be over if no rain occurred for 4 consecutive hours.

2. *Storm Depth (mm)*

The storm depth was determined by summing the rain gauge depths readings over the duration of the storm.

3. *Peak rain intensity (mm/hr)*

Peak rain intensity occurred during the greatest period of rainfall. This was taken the peak depth per hour.

4. *Dry weather flow (DWF) (cms)*

Dry weather flow or baseline sewer flow was taken as the average non-storm sewer flow through the combined sewer system over the period of observation. All dry days during the study period are included in this metric.

5. *Runoff (m^3)*

Runoff was determined by adding the sewer flows of the two catch-basins and adding that to the difference between the total sewer flow in the combined pipe and the dry weather flow. This relationship is shown below in equation 7:

$$\text{Runoff}(\text{m}^3) = \sum\left(\left[Q_{\text{cp}}(\text{cms}) - \text{DWF}(\text{cms})\right] + Q_{\text{cb1}} + Q_{\text{cb2}}\right) \times \text{duration(s)} \tag{7}$$

6. *Peak sewer flow (cms)*

Peak sewer flow occurred at the maximum combined flow between all three sensors. It is taken as the centroid of the sums of all three flow rates minus the DWF.

7. *Lag to Peak*

The lag-time between peak rainfall and peak sewer flow(lag to peak) is defined as the amount of time between the time of peak rainfall and time of peak sewer flow.

Analytical Methods

This section serves to outline how each analytical method was applied to to the catchment area. Described here is how each parameter was obtained and how the results were generated.

Curve Number

The curve number for the Stratford Catchment was determined using high resolution spatial analysis of the site using Google Earth imaging and area calculations. Most of the area is impervious asphalt and rooftop, however, there is some tree canopy and grass behind some of the residential buildings. Figure 6 shows all of the pervious land in the catchment. The overall CN number of the catchment was

Figure 6: *Areas of non-impervious land in the catchment area.*

determined using a weighted average of CN value to total area. CN values were determined using the SCS Curve Numbers while assuming soil type B (NRCS 1986). This calculation is shown in Table 3.

Table 3: *Estimation of the CN for the entire catchment*

Type of Area	*CN Value*	*Area (ha)*	
Open Space (good condition) Soil Type B	61	0.67	20.435
Impervious	98	1.33	65.17
Total		***Weighted CN***	**85.605**

The amount of runoff accumulated during each storm-event was determined using the CN listed above. The depth of rain of each storm was plugged into equation 1 in order to determine a depth of runoff. This depth was multiplied by the total catchment area to determine runoff volume for each depth of storm.

Rational Method

The rational method runoff coefficient (C) was determined using similar spatial methods to the curve number. Using the values from the SCS shown in the Appendix a weighted C value could be determined as shown in Table 4.

Table 4: *Calculation of Weighted C Value*

Type of Area	*C Value*	*Area (ha)*	
Open Space (good condition)	0.17	0.67	0.05695
Impervious	0.9	1.33	0.5985
Total		***Weighted C***	**0.65545**

The rain intensity used in the rational method assumes a constant rainfall throughout the storm. The rain gauge depths from each storm were average over the duration of the storm to fit the assumptions of the rational method. These values were then used in conjunction with equation 3 to determine peak flow.

Lag-to-Peak

Using equations 5 and 6, the lag-to-peak was calculated. The duration of excess rainfall (D) was determined as the duration of the storm after 0.2S was reach as determined by the rain gauges. The hydraulic watershed length (L) was determine as the farthest distance in the catchment to the catchment inlet. This was measured using Google Earth distance measuring tool (Google 2011) and was determined to be about 251 m. The slope of the catchment was determined based upon previous surveys to be less 3% throughout the catchment (Goldstein 2011).

RESULTS

This data collected for this analysis spanned 10 months from June 2011 to March 2012 and included 28 storms ranging from 1.3 to 54.4 mm. Table 5 summarizes the basic storm characterizations included in this analysis. Hydrographs shown in Figure 7 illustrate the basic trends observed in the sewer response to rainfall during small (8.1 mm), medium (22.6 mm), and large (54 mm) storm events which are representative of the general hydrologic response observed over this study. In each event, sewer flow in each catchment increased with storm intensity with little lag time between the peaks. The combined sewer pipe saw quicker increases in flow than the other two pipes due to the minimum accurate depth requirement of the sensors of 2 inches. As the combined pipe has a dry flow above the minimum depth, any additional runoff is immediately detected. Flow through the catchments must first reach the 2 inch minimum before being detected causing a slight delay in detection. Overall, the hydrologic response of the catchment area to rain is comes quickly with increased rain and rapidly returns to dry flow conditions. In larger storms, this return to dry flow conditions is less rapid possibly due to infiltration of groundwater into the system.

Table 5: *List of storms included in the data analysis*

Date	Precipitation (mm)	Duration (min)	Peak Rain Intensity (mm/hr)	Peak Flow (cms)	Runoff (m^3)
Jun 22, 2011	3.56	510	0.041	0.0058	23.1
Jun 23, 2012	6.6	170	0.173	0.0055	23.5
Jun 24, 2011	0.76	920	0.003	0.0047	49.2
Jul 26, 2011	4.83	75	0.091	0.0082	5.91
Jun 29, 2011	2.54	25	0.137	0.0035	4.15
Jul 29, 2011	8.13	120	0.117	0.0232	25.0
Jul 29, 2011	10.1	70	0.142	0.0172	15.3
Aug 3, 2011	22.6	410	0.147	0.0254	55.3
Aug 6, 2011	18.7	740	0.056	0.0048	-
Aug 9, 2011	43.9	185	0.508	0.1102	177
Aug 14, 2011	125	1325	0.351	0.1615	-
Aug 21, 2011	23.88	-	-	0.0090	-
Sep 15, 2012	1.78	205	0.030	0.0043	32.2
Sep 23, 2011	54.36	715	0.467	0.0680	309
Sep 29, 2011	13.92	365	0.269	0.0226	36.8
Oct 29, 2011	50.8	3080	0.056	0.0160	413
Nov 16, 2011	15.6	775	0.063	0.0075	59.7
Nov 17, 2011	1.95	135	0.035	0.0045	9.05
Nov 21, 2011	2.34	175	0.023	0.0049	7.07
Nov 22, 2011	43.18	1280	0.102	0.0276	208
Feb 11, 2012	2.29	425	0.010	0.0094	91.6
Feb 16, 2012	5.59	1060	0.030	0.0159	231
Feb 24, 2012	16.76	1005	0.102	0.0098	91.4
Feb 29, 2012	14.99	1425	0.051	0.0132	-
Mar 2, 2012	6.10	245	0.046	0.0119	64.3
Mar 3, 2012	1.52	195	0.020	0.0090	35.4
Mar 9, 2012	1.25	130	0.020	0.0040	4.23
Mar 13, 2012	1.27	45	0.025	0.0049	5.04

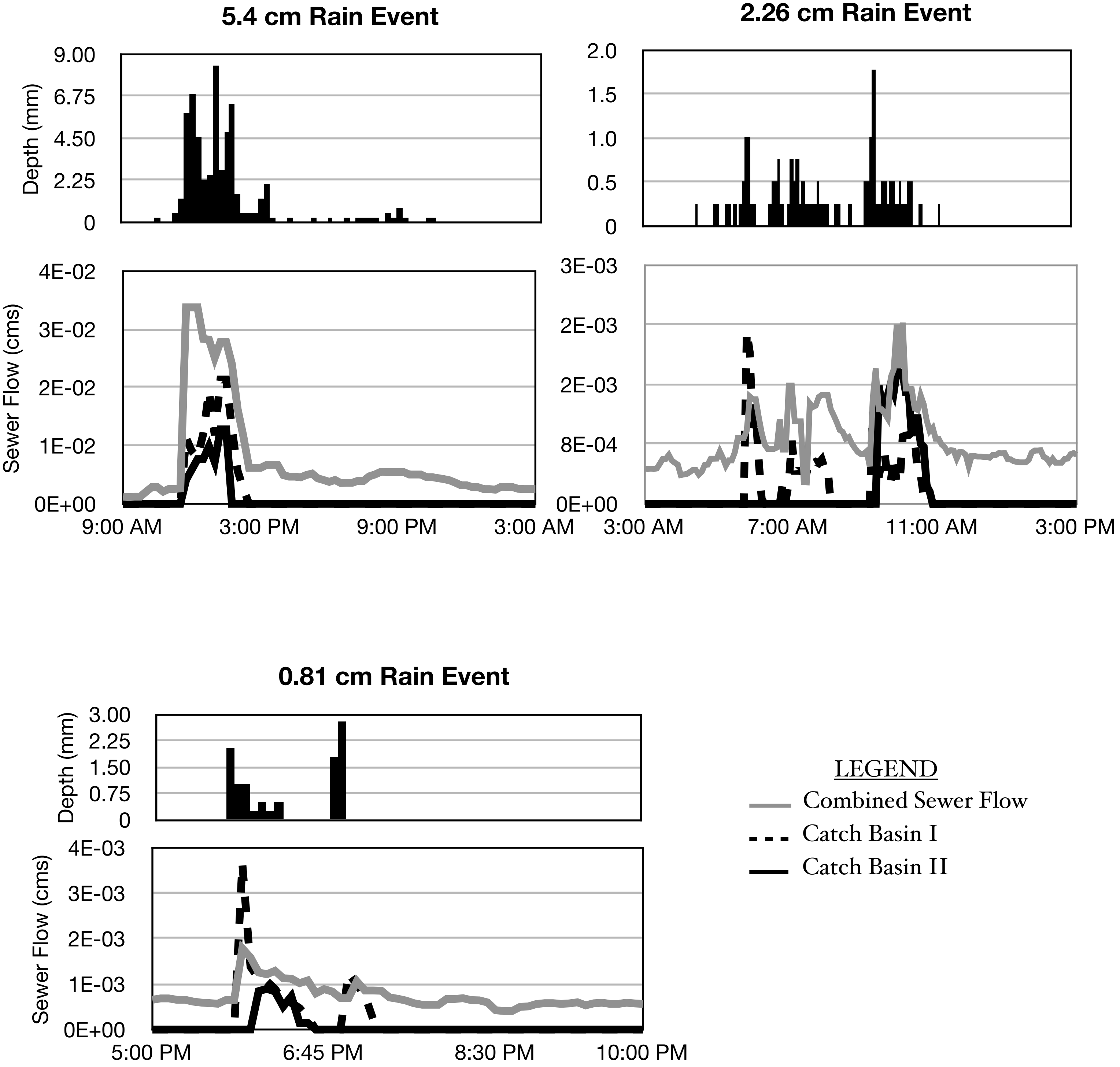

Figure 7: *Hydrographs and hyetographs illustrating a 54, 22.6, and 8.1 mm rain-event*

Dry Weather Flow

The dry weather flow (DWF) through the combined sewer pipe was taken as the average measured flow through the sewer during dry days. Each time interval was averaged to create a baseline flow. This baseline flow was than averaged itself to establish the DWF. The DWF is illustrated in Figure 8 below:

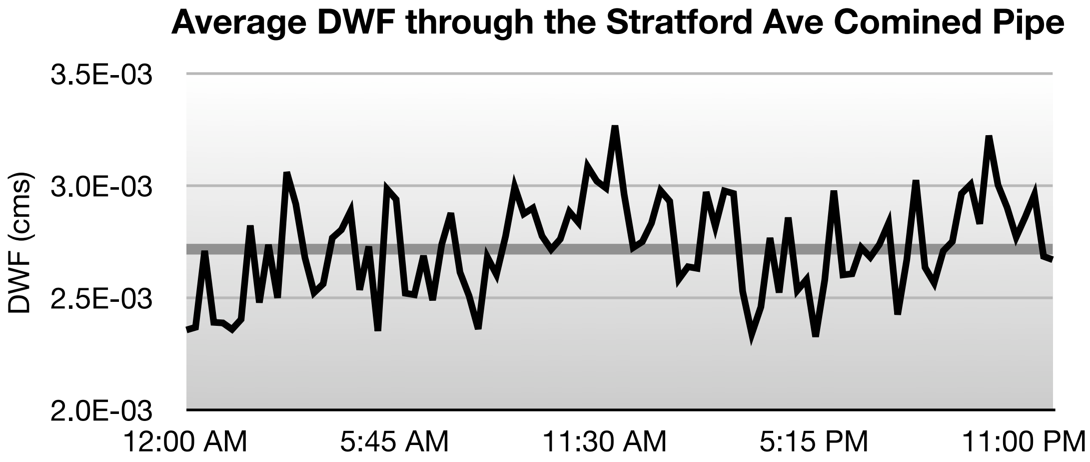

Figure 8: *Average dry weather flow through the Stratford Ave combined pipe. The grey middle line illustrates the mean flow.*

General Observations

Based on this research, general observations were noticed regarding the combined sewer response to rainfall and are listed below:

1. *Total flow in the combined sewer was greater during larger precipitation storms.*

During rain-events water flowed into the combined sewer. Larger rain events contributed more runoff to the collection system than smaller ones. There was be a linear relationship with $R^2 = 0.78$ between increases in storm precipitation and increase in sewer flow.

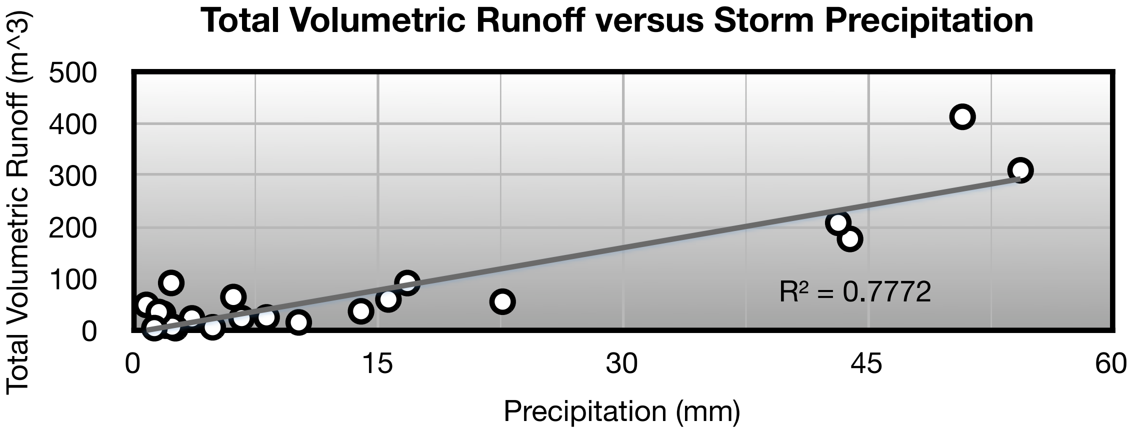

Figure 9: *Increases in rainfall precipitation resulted in increases in detected runoff in the sewer*

2. *Peak flow rate was greater with greater precipitation amounts, regardless of rainfall duration.*

In general, greater rainfall amounts caused greater increases in combined sewer flow rate. This may be because once the soil reaches saturation, all further inputs become outputs and abstractions are insignificant.

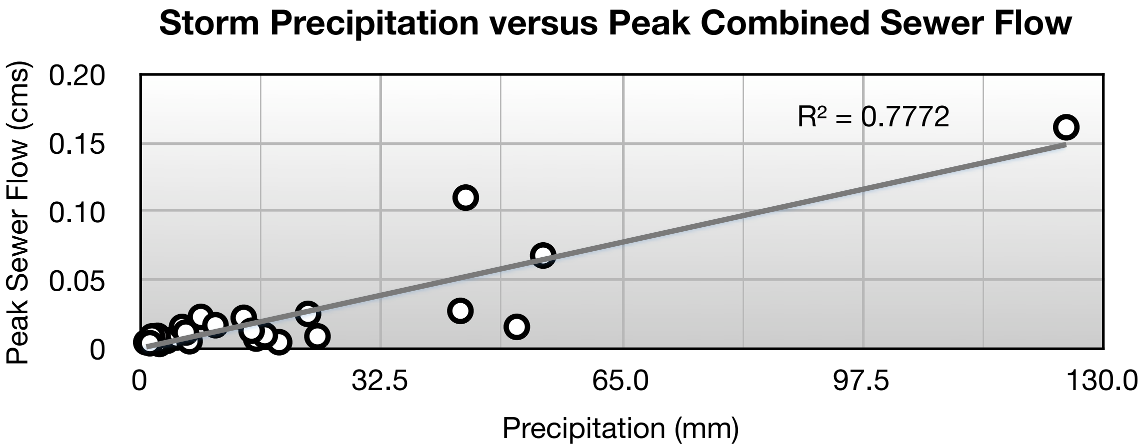

Figure 10: *Increases in total storm rainfall depth generally produced increases in peak combined sewer flow*

3. *Peak total flow in the sewer increased with peak event rainfall intensity.*

Peak flow rates in the combined sewer during a rain-event were greater in storms with higher peak rainfall intensities. Greater rainfall intensity increased the peak rate runoff thus causing a spike in sewer flow runoff proportional to the rainfall intensity.

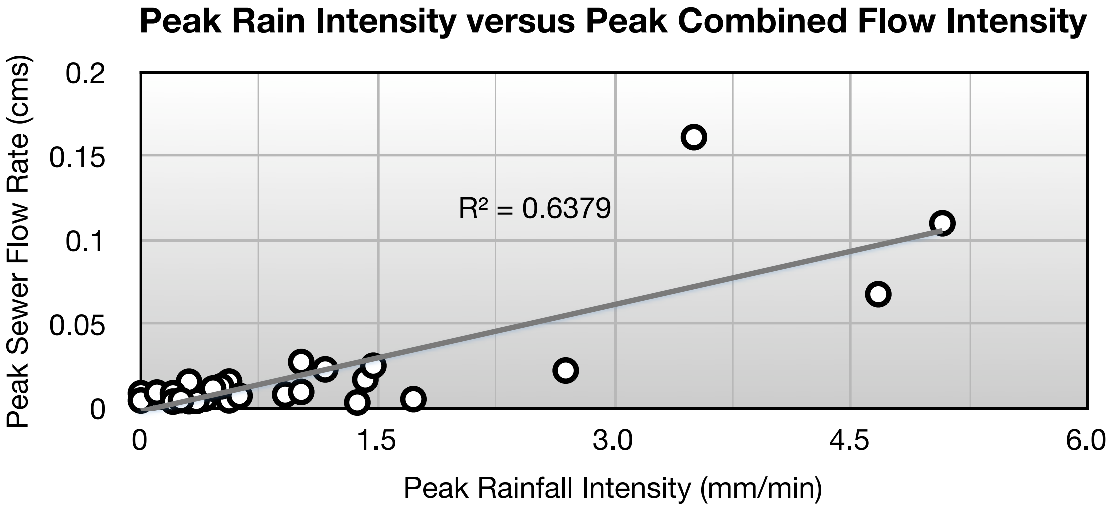

Figure 11: *Storms with great peak rainfall intensity tended to result in high peak combined sewer flow.*

4. *Peak flow occurred with peak rain intensity and lag time was minimal.*

Due to the short time of concentration for this urban catchment, the time to peak rain corresponds closely to the time to peak flow in the collection system. This means that during the heaviest rain intensities of the storm, the greatest flow rate was detected. This trend had a strong correlation with an $R^2 = 0.90$.

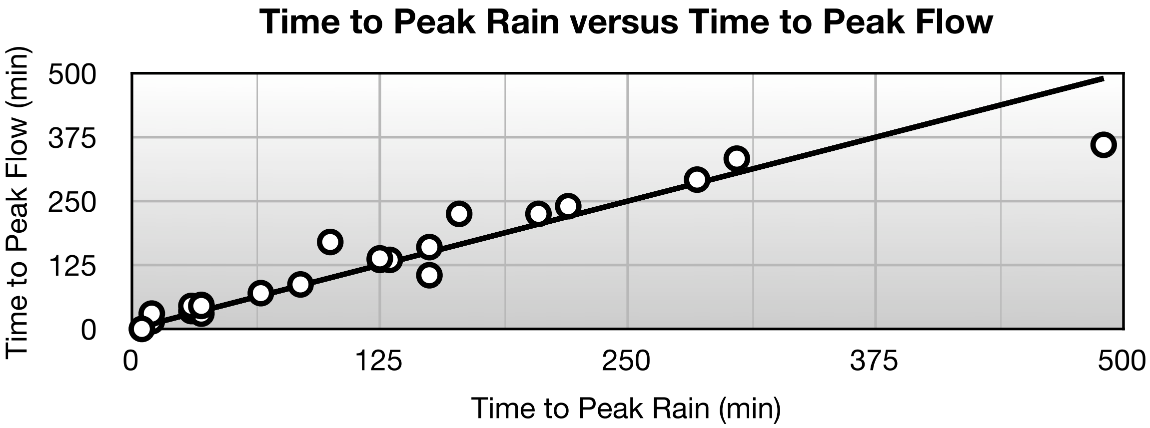

Figure 12: *Peak rainfall occurred generally minutes before peak combined sewer flow. The 1:1 line plotted alongside the data represents peaks occurred simultaneously, illustrating that time to peak flow tended to occur after peak rainfall.*

5. *Shorter storms reached peak rainfall intensity quicker than larger storms.*

Long storms tended to reach rainfall peaks after longer time periods compared to short storm. This illustrates the nature of many of the storms included in this study.

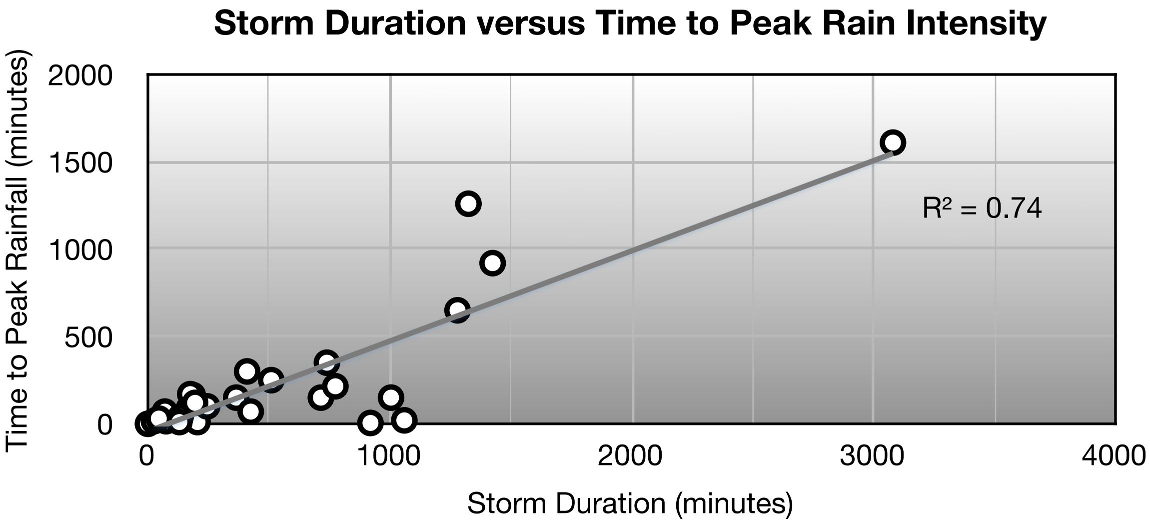

Figure 13: *Shorter storms tended to reach peak rainfall intensity quicker than longer storms.*

DISCUSSION

The follow section compares the predictive analytical methods described in the preceding sections to experimentally observed field data. The purpose of this section is determine to what extent these methods can be applied to a residential urban catchment.

Curve Number

From the storms listed in Table 5 above, only storms that exceeded the initial abstraction were considered in the analysis as required by the curve number method. The total measured runoff of these storms were then plotted in Figure 14 with the curve number predictions as a function of the depth of precipitation over the catchment.

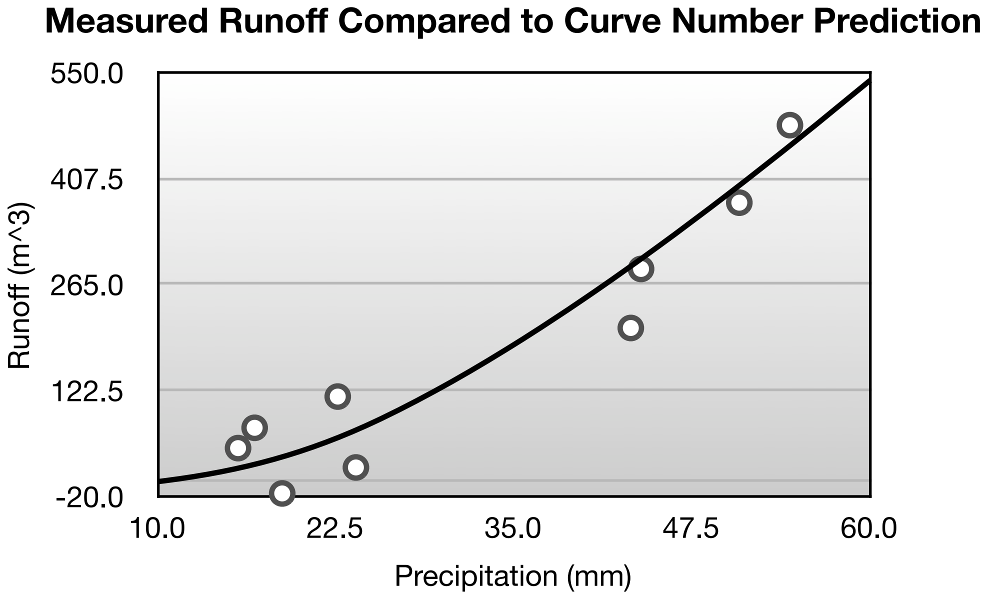

Figure 14: *The curve number predictions are shown as the continuous line. Each point represents the measured runoff from each storm. Nonlinear* $R^2 = 0.95$

Using nonlinear regression analysis, the $R^2 = 0.95$ showing that the curve number method for calculating total storm runoff is a good predictor of measured results for this urban catchment for the storms between 10 to 60 mm in total storm depth. Deviations from the curve may be a result of rainfall variability in addition to variability in antecedent conditions of the catchment.

Rational Method

The results for the rational method plotted 24 storms ranging from 1.3 to 54.4 mm in storm depth. The measured peak flow for each storm was plotted against against the predicted peak as per the rational method as shown in Figure 15.

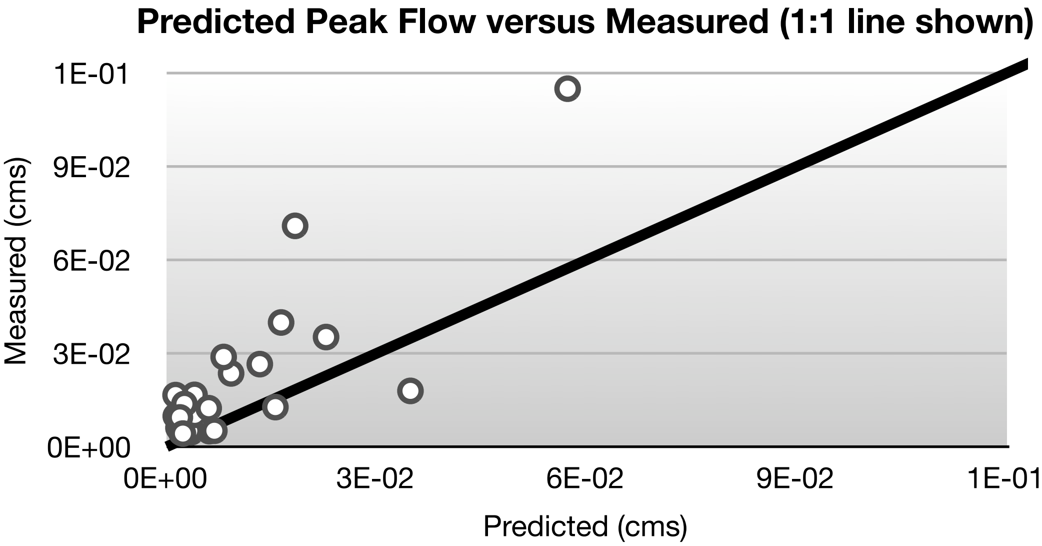

Figure 15: *The measured peak combined sewer flow compared to the rational method predicted peak flow. The line shows a 1:1 relationship indicating perfect correlation between measured and predicted results with an $R^2 = 0.60$.*

The results from this relationship indicate that the rational method predictions followed the general trend of the measured results but generally underestimated the the peak flow of the combined catchment. Deviations in the rational method are the result of variability rainfall throughout the duration of a storm. Whereas the rational method assumes a constant average rainfall intensity, observed storms do not adhere to this uniformity. As a result, large peaks of rainfall intensity are not account for.

Lag-to-Peak

The predicted lag to peak time was plotted against the measure lag to peak as is shown below in Figure 16. The lag to peak results included storms greater than 8.4 mm in order to meet the initial abstraction required for the predictive equations. This analysis included storms between 10 and 60 mm in total storm depth.

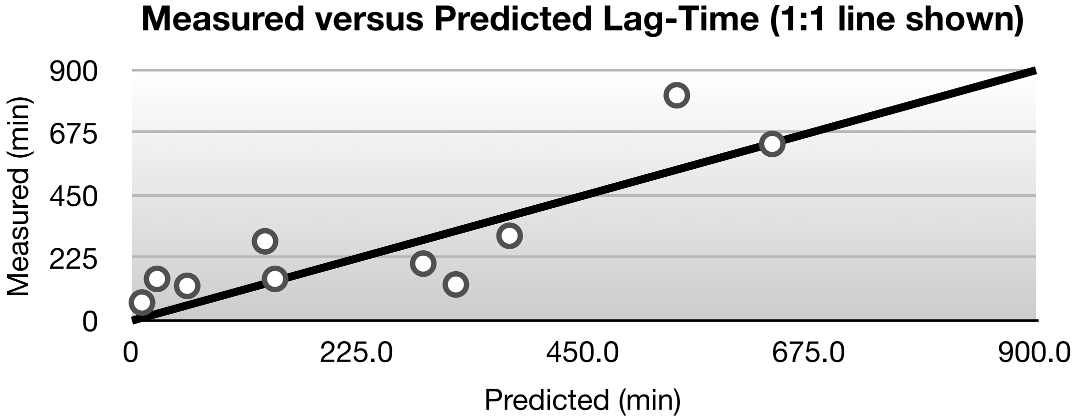

Figure 16: *The measured lag to peak compared to the predicted lag. The line indicates the 1:1 ratio assuming a perfect correlation between the two with an* R^2 = *0.69.*

With a linear regression $R^2 = 0.69$, the lag to peak prediction were able to generalize the trend of the measured results, but remained inconsistent as to whether or not predictions were over of under estimation of measured results. This may be a result of deviations in the preceding hydrologic rainfall intensities. Low preceding rainfall before the peak intensity will create a longer lag than heavy preceding rainfall.

CONCLUSIONS

With contemporary focus by urban municipalities to manage CSOs, it is important to understand the rainfall-runoff response of the urban catchments and its impact on the combined collection system. Traditional analytical methods exist to analyze and design for these catchments which are written into municipal code and include the SCS Curve Number runoff method and the Rational Method. These methods, due their contemporary application, must be strictly scrutinized in order to determine appropriateness for modeling urban catchments.

The results from this study suggest that the current analytical methods for hydrologic and hydraulic understanding of combined sewer flow for an urban residential catchment are relatively applicable as slight deviations from the model are to be expected. In a nine month field survey, the rainfall-runoff response of a 2 hectare catchment in Bronx, New York was determined. This measured response was then compared to a predicted analytically derived rainfall-runoff response. Relative to measured results, the SCS Curve Number had a non-linear $R^2 = 0.95$ showing a strong applicability for this catchment. The Rational Method had a linear $R^2 = 0.60$ suggesting a weak, but relevant correlation for determining peak flow. The lag-to-peak method had a linear $R^2 = 0.69$ suggesting usefulness for this catchment. While these predictive methods were pertinent to this catchment, the same might not be true for all residential catchments with more heterogeneous land cover. Environments with more unique topography might deviate even more from the assumed models. To better understand the extent to which these analytical methods can be applied, further studies are recommended on different types of urban topography. For this type of catchment, however, the Curve Number method could accurately be used for sizing of stormwater management infrastructure based on total runoff volume. The Rational Method, while not fully accurate for predicting the study storms, is normally implemented alongside larger design storms for proper hydraulic sizing in collection systems. This study cannot comment on its usability in that scenario as no storm reached the large design storm depths typically employed with the Rational Method.

With the rise of modern GI stormwater management techniques, a similar study should be conducted on this same catchment after urban greening efforts to reduce stormwater runoff have been made. This comparison would illustrate the actual hydrologic and hydraulic difference GI can have regarding stormwater runoff in addition to the usefulness of predictive methods at modeling such efforts. Such a study would improve future models and help calibrate existing models to field observations.

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APPENDIX

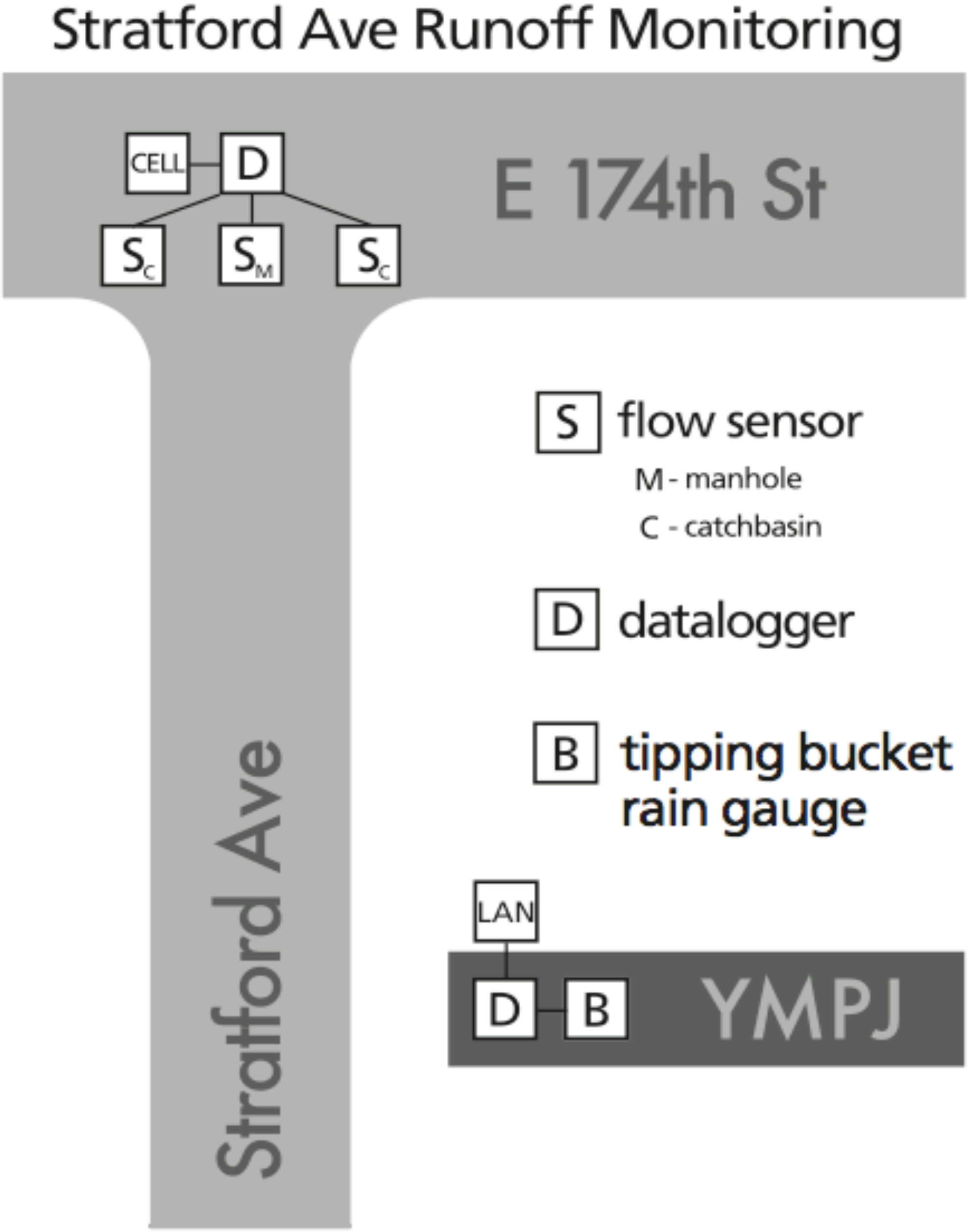


Figure 17: *Schematic for the sensors in the Stratford Ave study*

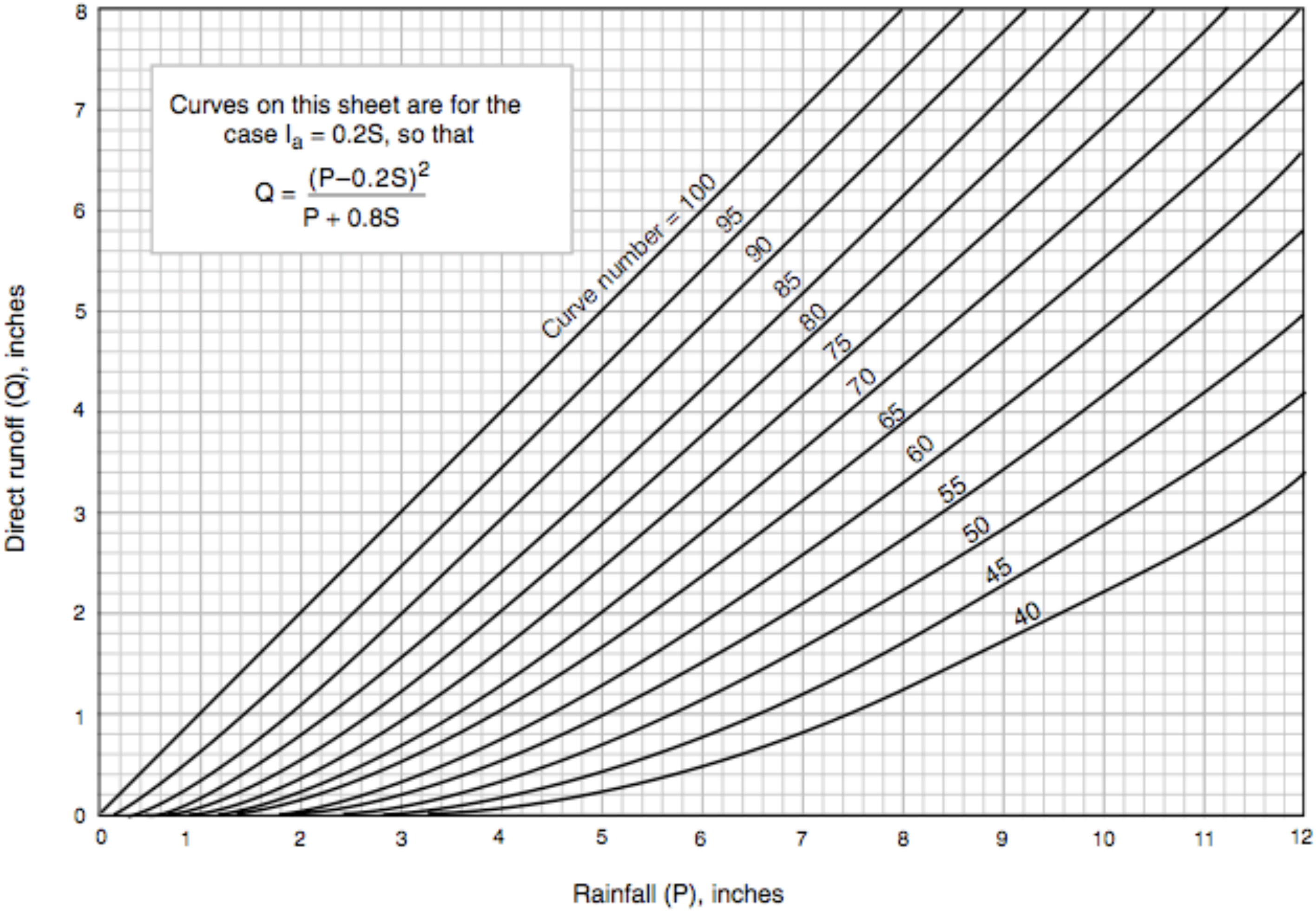


Figure 18: *Curve Number method for determining runoff*

Table 6: Runoff Curve Numbers for urban areas

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

---

[1] Average runoff condition, and $I_a = 0.2S$.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table 7: Recommended Runoff Coefficient Values

Recommended Runoff Coefficient Values

Description of Area	Runoff Coefficients (C)
Lawns:	
Sandy soil, flat, 2%	0.10
Sandy soil, average, 2 – 7%	0.15
Sandy soil, steep, > 7%	0.20
Clay soil, flat, 2%	0.17
Clay soil, average, 2 – 7%	0.22
Clay soil, steep, > 7%	0.35
Unimproved areas (forest)	0.15
Business:	
Downtown areas	0.95
Neighborhood areas	0.70
Residential:	
Single-family areas	0.50
Multi-units, detached	0.60
Multi-units, attached	0.70
Suburban	0.40
Apartment dwelling areas	0.70
Industrial:	
Light areas	0.70
Heavy areas	0.80
Parks, cemeteries	0.25
Playgrounds	0.35
Railroad yard areas	0.40
Streets:	
Asphaltic and Concrete	0.95
Brick	0.85
Drives, walks, and roofs	0.95
Gravel areas	0.50
Graded or no plant cover	
Sandy soil, flat, 0 – 5%	0.30
Sandy soil, flat, 5 – 10%	0.40
Clayey soil, flat, 0 – 5%	0.50
Clayey soil, average, 5 – 10%	0.60

Marsh-McBirney FLO-TOTE® 3 Electromagnetic Area/Velocity Flow Meter Sensor

The Marsh-McBirney Flo-Tote 3 Flow Meter Sensor, when combined with a Hach FL900 Series Flow Logger, provides an ideal solution for cost-effective portable flow monitoring. (For permanent flow monitoring applications, use with Flo-Station.) Electromagnetic sensor technology provides highly accurate flow measurements.

Features and Benefits

The Marsh-McBirney Flo-Tote 3 Electromagnetic Flow Meter Sensor measures both velocity and depth in the same cross-section providing accurate measurements based on the Continuity Equation. Combined with the portable FL900 Flow Logger or permanent Flo-Station, users have an ideal solution for their flow measurement needs.

Accurate Flow Measurement

Flo-Tote 3 provides the user with highly accurate flow measurements under a wide range of flows and site conditions. The flow accuracy of the Flo-Tote is based upon the accurate measures of both velocity and depth in hydraulic flow labs, as well as under actual sewer conditions. Verification of our specifications by an independent flow laboratory assures you of our commitment to accuracy.

Disconnectable, Interchangeable and Field Replaceable Sensor

Provides easy maintenance and eliminates meter down time.

Grease Tolerant Sensor

Grease shedding electrodes allow for reliable data collection even in these difficult environments.

Q-Stick Band/Sensor Install Tool

Sensor and band can be safely and easily installed from street level with the Q-Stick tool eliminating confined space entry.

Ideal for a Variety of Open Channel Sizes & Shapes

- *Wastewater Sewers-
  Round, Rectangular, and Odd Shaped*
- *Storm Sewers*
- *Creeks, Rivers, and Streams*

Applications

- *Inflow/Infiltration Studies*
- *Modeling/Sewer System Evaluation*
- *EPA Permitting Requirements*
- *Combined Sewer Overflow (CSO Monitoring)*
- *Sewer System Evaluation*
- *Wastewater Treatment Plant Balancing*

Specifications*

FLO-TOTE 3 FLOW METER SENSOR

Material
Polyurethane

Dimensions
13.6 L x 4.4 W x 2.8 H cm (5.37 L x 1.73 W x 1.10 H in.)

Weight
1.1 kg (2.4 lb) with 30 ft cable

Operating Temperature
0 to 45°C (32 to 113°F)

Storage Temperature
–20 to 52°C (–4 to 125°F)

Power Requirements
Supplied by FL900 Logger, Flo-Logger/Logger XT, or Flo-Station

VELOCITY MEASUREMENT

Method
Electromagnetic (Faraday's law)

Range
-1.5 to 6.1 m/s (-5 to +20 ft/s)

Accuracy
±2% of reading

Zero Stability
±0.015 m/s (±0.05 ft/s) at 0 to 3 m/s (0 to 10 ft/s)

Resolution
±0.0003 m/s (0.01 ft/s)

DEPTH MEASUREMENT

Method
Submerged pressure transducer

Standard Operating Range
10 mm to 3.5 cm (0.4 to 138 in.)
Contact the factory for extended ranges.

Accuracy
±1% of reading

Zero Stability
±0.009 m (±0.03 ft.), for 0 to 3 m (0 to 10 ft.)
Includes non-linearity, hysteresis and velocity effects.

Resolution
2.5 mm (0.1 in.)

Over Range Protection
2X range

FLOW MEASUREMENT

Method
Conversion of water depth and pipe size to fluid area.
Conversion of local velocity reading to mean velocity.
Multiplication of fluid area by mean velocity to equal flow rate.

Conversion Accuracy
±5.0% of reading. Assumes appropriate site calibration coefficient, pipe flowing 10% to 90% full with a level greater than 5.08 cm (2 in.).

TEMPERATURE MEASUREMENT

Method
1 wire digital thermometer

Range
–10 to 85°C (14 to 185°F)

Accuracy
±2°C (±3.5°F)

SENSOR CABLE

Material
Polyurethane jacketed

Length
Available in specified lengths from 30 to 1000 ft.

Connectors
To use with portable FL900 Series Logger or Flo-Logger:
Sensor with connector end (30 to 1000 ft. lengths)

Sensor with junction box, desiccant hub, sealant/potting kit and connector; allows for usage with conduit (30 to 1000 ft. lengths)

Important Note: The sensor cable assembly with desiccant hub is compatible with either the Marsh McBirney Flo-Logger/Logger XT or the Hach FL900 Series Flow Loggers. When using this cable assembly with the Marsh McBirney Flo-Logger, do not disconnect the desiccant cartridge that is attached to the Flo-Logger itself.

If using Tote 3 cable with Flo-Station, sensor will have bare leads on cable end (30 to 1000 ft. lengths), and there will be no desiccant hub, as the air tube terminates inside of the Flo-Station housing.

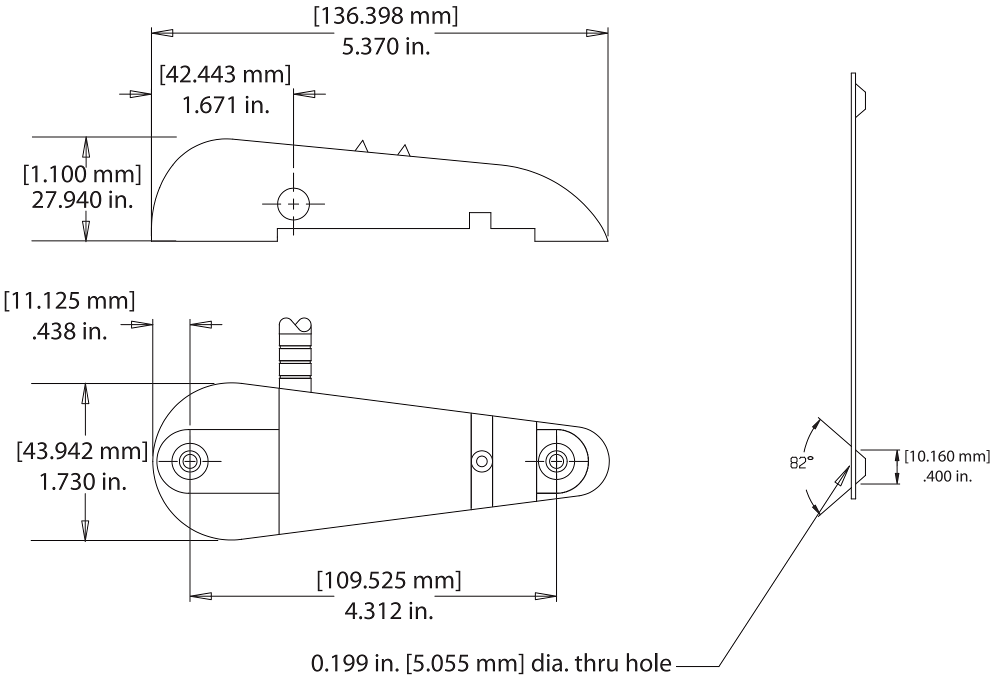
CE Flo-Tote 3 Electromagnetic Flow Meter Sensor meets CE requirements.

**Specifications subject to change without notice.*

Engineering Specifications

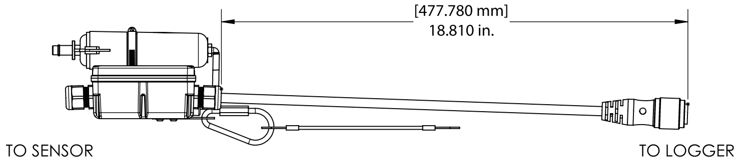
1. The flow meter shall be capable of directly measuring both velocity and depth in the same cross section.
2. The method of measurement shall be electromagnetic.
3. The range of velocity measurement shall be -1.5 to +6.1 m/s (-5 to +20 ft/s)
4. The accuracy of the velocity measurement shall be ±2% of reading.
5. Zero stability of the velocity measurement shall be ±0.015 m/s (±0.05 ft/s) at 0 to 3 m/s (0 to 10 ft/s).
6. The range for depth measurement shall be 10 mm to 3.5 m (0.4 to 138 in.). (Contact the factory for extended ranges.)
7. The accuracy of the depth measurement shall be ±1% of reading.
8. Zero stability of the depth measurement shall be ±0.009 m (±0.03 ft), for 0 to 3 m (0 to 10 ft). Includes non-linearity, hysteresis and velocity effects.
9. The flow sensor shall be the Marsh-McBirney Flo-Tote 3 Open Channel Flow Meter Sensor.

Dimensions



Flo-Tote 3 Electromagnetic Flow Meter Sensor

The desiccant hub assembly includes a junction box to connect sensor cable to the desiccant and subsequently to the FL900 Logger. The desiccant can easily be replaced without need to purchase a separate desiccant module.




Side View

Top View

Desiccant Hub Assemblies for use with portable FL900 Series loggers and Flo-Logger.
(Sensor cable for use with Flo-Station will not contain a desiccant hub and will have bare wires on cable end.)

Ordering Information

Flo-Tote 3 Sensor with Cable

EM9000-XXX*	FL900 Logger, Flo-Logger/Logger XT Includes sensor with cable, sealed desiccant hub and connector to logger.
EMJCTBOXCBL-XXX*	FL900 Logger, Flo-Logger/Logger XT (For use with conduit) Includes sensor with cable, unsealed desiccant hub, potting kit and connector to logger.
Model 3000-9	Flo-Station (Specify cable length of Hach Prod. No. 360001901 using table below) Includes sensor and cable with bare leads.

**XXX—specify length from table below.*

Available Cable Lengths (in feet)

30	125	225	400	700
60	150	250	450	800
75	175	300	500	900
100	200	350	600	1000

See Lit. No. 2709 (standard models) and Lit. No. 2711 (wireless models) for FL900 Series Flow Logger ordering information.
See Lit. No. 2616 for Flo-Station ordering information.

Mounting Hardware

Mounting Bands - Several configurations available. Consult factory.

Accessories & Spares

55031-SS	Profiling Adapter - allows sensor to be mounted on pole for profiling flow channel
750000201	Q-Stick Insertion Tool
245000501	Q-Stick Replacement Pole Only
8755500	Bulk desiccant beads (1.5 pounds)

Lit. No. 2712
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At Hach, it's about learning from our customers and providing the right answers. It's more than ensuring the quality of water—it's about ensuring the quality of life. When it comes to the things that touch our lives...

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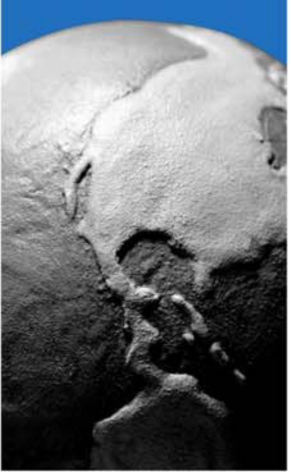


GL500 Multichannel Datalogger

Description

The GL500, Global multichannel datalogger features 7 analog channels and 2 digital channels for data recording. The GL500 can record over 40,000 readings and has four unique recording options, fast (10 samples per second), programmable interval (1 second to multiple years), logarithmic, and exception. The datalogger also has a sample on demand input that triggers a recording of special events, such as when a water sampler was triggered, when a door was opened, etc. Daily start and stop alarm times can be programmed to limit recording intervals during a day. The GL500 includes Windows and PDA software, allowing easy upload of data to a laptop, desktop, or PDA for transfer to a spreadsheet program.

The Global data logger is setup to accept any 4-20 mA sensor. The GL500 provides switched power to the sensors based on the sample interval and sensor warm up time settings. 2-wire and 3-wire sensors can be quickly connected to the datalogger's terminal strip and calibrated via the Global datalogger software. Your sensors can be accessed through dial-out to a remote modem attached to the GL500's serial communication port. The datalogger software has online help files that are easily accessed using drop down menus and links to quickly find the answers to your questions.

The data recorder has an optional rugged, lockable and weather-resistant enclosure that can easily be hidden, bolted to a post, or secured inside an additional container for added protection from the elements, animals or vandals. A 12VDC rechargeable battery and battery charger comes with this option.

NOTE: 64 bit operating systems are not currently supported.

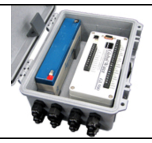
- Four sample modes: 10 times per second, interval, logarithmic, and exception
- Both USB and Serial communication ports
- Monitor up to 9 sensors at a time in addition to battery voltage
- Battery powered for remote locations
- Windows and PDA software included
- Accepts any 4-20mA or 0-5V (upon request) input
- Optional rugged, lockable, weather resistant enclosure

Specifications

Memory: Non-volatile flash memory
Power: *Voltage:* 7.2 VDC Min. to 24.0 VDC Absolute Max
  Standby Current: 70uA Typical
  Logging Current: 5mA Typical + sensor current
Analog Sensor Inputs: 4-20mA (0-5VDC as factory option)
  Resolution: 12-Bit, 4096 Steps
  Channels: 7 Input channels + battery voltage monitor
  Sensor Warm-up Time: Programmable, 0-15 Sec
Digital Inputs: 2 Independent pulse counters
  Maximum Input Voltage: 24VDC
  Maximum Frequency: 100Hz
  Minimum Pulse Width: 2mS
  Maximum Count: 65,535 (16-Bit)
Sample Now Input: Sample-on-Demand input, software enabled
  Maximum Input Voltage: 24VDC
  Minimum Pulse Width: 2mS
Sample Modes: Fixed Interval Programmable from 1 Sec. to >1 Year
  High Speed 10 Samples per second
  Logarithmic Sample Rate (Approximation)
  Exception (Log only on deviation from previous reading)
Storage Capacity: 40,879 Recordings for all inputs plus time stamp
Data Overwrite: Select memory wrap or unwrap (unwrap will stop logging data once memory is full)
Communication Ports: RS-232 DB9 or USB Type B
Selectable Baud Rates: 9600, 19200, 28800, 38400, 57600, and 115200
Clock: Synchronizes to the time and date of user's computer
Operating Temperature: Industrial, -40ºC to +85ºC (Battery may not apply)
Enclosure: Polycarbonate (6.3" x 3.2" x 2.2"), Nema 4X
Weight: 11 oz or *3.5 lbs (with weather-proof enclosure)*

Options and Accessories

GL500 9 channel datalogger

GL450-7-1 Weather Proof Environmental Enclosure	

SP102 Solar Panel (5 watts, 300mA min)

In the U.S. call toll free
at 1-800-876-1172
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Fax: 1-979-690-0440
Email: globalw@globalw.com

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Our Address:
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RG200 6" Rain Gauge
RG600 8" Rain Gauge

- Simple to operate and install
- Rugged design for harsh weather
- Mounting hardware included
- UV-protected plastic or aluminum

Description

The 6” Rain Gauge is a durable weather instrument for monitoring rain rate and total rainfall. With minimal care it will provide many years of service. The rain gauge is constructed of high impact UV-protected plastic to provide reliable, low-cost tipping bucket rainfall monitoring. The simplicity of the rain gauge design assures trouble-free operation, yet provides accurate rainfall measurements. The unit has a 6" orifice and is shipped complete with mounting brackets and 40 ft of two-conductor cable. The tipping bucket sensor mechanism activates a sealed reed switch that produces a contact closure for each 0.01" or 0.2 mm of rainfall.

The Global Water 8” Rain Gauge is a rugged weather instrument for monitoring rain rate and total rainfall. With minimal care it will provide many years of services. The rain gauge was designed by the National Weather Service to provide a low-cost, reliable, industrial, tipping bucket rain gauge. Its simple design assures trouble-free operation, yet provides accurate rainfall measurements. The rainfall gauge has an 8" orifice and is shipped complete with mounting brackets and 25 ft of two-conductor cable. The tipping bucket sensor mechanism activates a sealed reed switch that produces a contact closure for each 0.01", 0.2 mm or 1 mm of rainfall. The rain gauge sensor can be pole mounted or bolted to a level plate.

Specifications

6” Rain Gauge
Capacity: Unlimited
Resolution: 0.01 inches
Accuracy: 3% up to 4"/hr
Average Switch Closure Time: 135 ms
Maximum Bounce Settling Time: 0.75 ms
Maximum Switch rating: 30 VDC @ 0.2A
Operating Temperature: 32° to 123.8°F (0° to 51°C)
Cable: 40ft (12.2m), 2 conductors
Dimensions: 6x15 inch (15x38 cm)
Shipping Weight: 3 lbs. (1.4 kg)

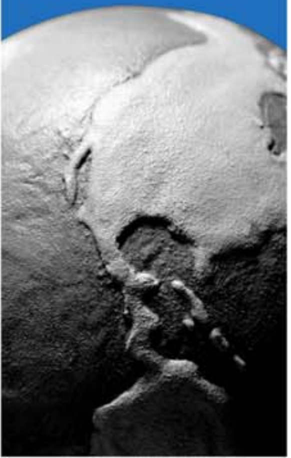
8” Rain Gauge
Capacity: Unlimited
Resolution: 0.01 inches or 0.2mm
Accuracy: ±1% at 1 inch per hour
Average Switch Closure Time: 135 ms
Maximum Bounce Settling Time: 0.75 ms
Maximum Switch rating: 30 VDC @ 0.2A
Operating Temperature: 32° to +123.8°F (0° to +51°C)
Cable: 25ft (7.6m), 2 conductor
Dimensions: 10-1/8x8 inch (26x20 cm)
Shipping Weight: 8 lbs. (3.6 kg)

Options and Accessories

RG200 6” Rain Gauge

RG600 8" Rain Gauge
Specify 1 mm, 0.2 mm, or 0.01" per tip at time of order

RG700 4-20mA Converter Module
Pulse to current converter. 32 pulses per minute equals 20mA.



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