Appendix G V&A FLOW MONITORING REPORTS

(Included on CD)

DRAFT

City of Lincoln

Nicolaus Pump Station Flow Monitoring and Inflow/Infiltration Study

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Date: June 2016

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V&A Project No. 15-0319

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Table of Contents

TABLES

FIGURES

APPENDICES

Abbreviations, Terms and Definitions used in this Report

Table i. Abbreviations

Abbreviation	Term
ADWF	average dry weather flow
CCTV	closed-circuit television
CDEC	California Data Exchange Center
CIP	capital improvement plan
CO	carbon monoxide
CWOP	Citizen Weather Observing Program
d/D	depth/diameter ratio
FM	flow monitor
gpd	gallons per day
gpm	gallons per minute
GWI	groundwater infiltration
H_2S	hydrogen sulfide
I/I	inflow and infiltration
IDW	inverse distance weighting
LEL	lower explosive limit
mgd	million gallons per day
NOAA	National Oceanic and Atmospheric Administration
Q	flow rate
RDI/I	rainfall-dependent infiltration and inflow
RG	rain gauge
SSO	sanitary sewer overflow
WEF	Water Environment Federation
WRCC	Western Regional Climate Center

Table ii. Terms and Definitions

Term	Definition
Average dry weather flow (ADWF)	Average flow rate or pattern from days without noticeable inflow or infiltration response. ADWF usage patterns for weekdays and weekends differ and must be computed separately. ADWF is expressed as a numeric average and includes the influence of normal groundwater infiltration (not related to a rain event).
Basin	Sanitary sewer collection system upstream of a given location (often a flow meter), including all pipelines, inlets, and appurtenances. Also refers to the ground surface area near and enclosed by pipelines. A basin may refer to the entire collection system upstream from a flow meter or exclude separately monitored basins upstream.
Depth/diameter (*d/D*) ratio	Depth of water in a pipe as a fraction of the pipe's diameter. A measure of fullness of the pipe used in capacity analysis.
Design storm	A theoretical storm event of a given duration and intensity that aligns with historical frequency records of rainfall events. For example, a 10-year, 24-hour design storm is a storm event wherein the volume of rain that falls in a 24-hour period would historically occur once every 10 years. Design storm events are used to predict I/I response and are useful for modeling how a collection system will react to a given set of storm event scenarios.
Infiltration and inflow	Infiltration and inflow (I/I) rates are calculated by subtracting the ADWF flow curve from the instantaneous flow measurements taken during and after a storm event. Flow in excess of the baseline consists of inflow, rainfall-responsive infiltration, and rainfall-dependent infiltration. **Total I/I** is the total sum in gallons of additional flow attributable to a storm event.
Infiltration, *groundwater*	Groundwater infiltration (**GWI**) is groundwater that enters the collection system through pipe defects. GWI depends on the depth of the groundwater table above the pipelines as well as the percentage of the system that is submerged. The variation of groundwater levels and subsequent groundwater infiltration rates is seasonal by nature. On a day-to-day basis, groundwater infiltration rates are relatively steady and will not fluctuate greatly.
Infiltration, *rainfall-dependent*	Rainfall-dependent infiltration (**RDI**) is similar to groundwater infiltration but occurs as a result of storm water. The storm water percolates into the soil, submerges more of the pipe system, and enters through pipe defects. RDI is the slowest component of storm-related infiltration and inflow, beginning gradually and often lasting 24 hours or longer. The response time depends on the soil permeability and saturation levels.
Inflow	**Inflow** is defined as water discharged into the sewer system, including private sewer laterals, from **direct** connections such as downspouts, yard and area drains, holes in manhole covers, cross-connections from storm drains, or catch basins. Inflow creates a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows. Overflows are often attributable to high inflow rates.
Peaking factor	Ratio of peak measured flow to average dry weather flow. This ratio expresses the degree of fluctuation in flow rate over the monitoring period and is used in capacity analysis.
Surcharge	When the flow level is higher than the crown of the pipe, then the pipeline is said to be in a **surcharged** condition. The pipeline is surcharged when the *d/D* ratio is greater than 1.0.
Synthetic hydrograph	A set of algorithms has been developed to approximate the actual I/I hydrograph. The synthetic hydrograph is developed strictly using rainfall data and response parameters representing response time, recession coefficient and soil saturation.

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ES EXECUTIVE SUMMARY

Scope and Purpose

V&A Consulting Engineers (V&A) has completed sanitary sewer flow monitoring and rainfall monitoring with I/I analysis for tributary areas contributing to the Nicolaus Pump Station. Flow and rainfall monitoring was performed over a period of over 10 weeks from January 23, 2016 to April 3, 2016. Open-channel flow monitoring was performed at five sites.

Mid-way through the study, V&A was asked to perform flow monitoring at three additional locations in the Lincoln Crossing region of the City. Flow and rainfall monitoring was performed for these three locations over a period of over 5 weeks from February 26, 2016 to April 3, 2016. There were three general purposes of this study.

1. Establish the baseline sanitary sewer flows at the flow monitoring sites.
2. Estimate available sewer capacity.
3. Isolate I/I response and perform I/I analysis.

Monitoring Sites

The flow monitoring site locations were selected and approved by Stantec and are listed in Table ES-1 and shown in Figure ES-1.

Table ES-1. List of Monitoring Sites

Monitoring Site	City Manhole ID	Pipe Diameter (in)
Site 1	NW319SS07	18
Site 2	NW319SS04	10
Site 3	NW318SS03	12
Site 4	NW318SS01	10
Site 5	NW318SS01	12
Site 6	Not Available	12
Site 7	Not Available	10
Site 8	Not Available	10

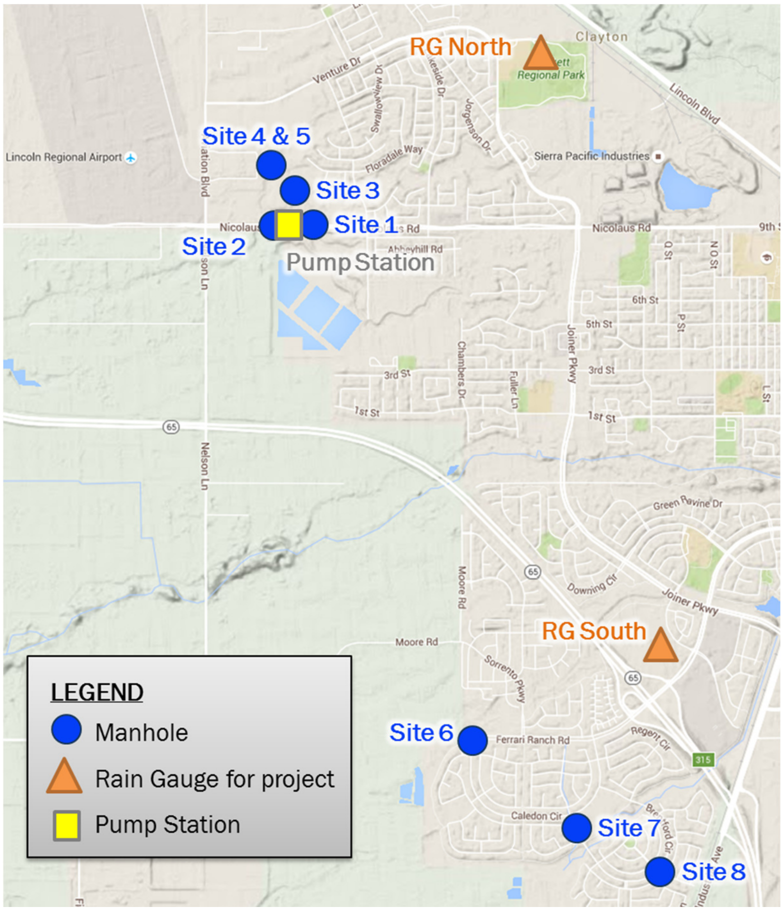

Figure ES-1. Map of Flow Monitoring Sites and Rain Gauges

Rainfall Monitoring

The major rainfall occurred from March 4 to March 14, 2016. Within this storm system, two major rainfall events occurred: Event 1 from March 4 to 7 and Event 2 from March 10 to 14. The classifications for both short-term and long-term durations regionally are summarized in Table ES-2 and were different for the north and south regions of the City.

Table ES-2. Classification of Rainfall Events

Rainfall Event	RG North	RG South
March 4 – March 7, 2016	100-Year, 1-Hour 7-Year, 8-Hour 1-Year, 24-Hour 2-Year, 3-Day	<1-Year Event
March 10 – March 14, 2016	<1-Year, 24-Hour 1-Year, 4-Day	<1-Year Event
Total Storm Duration: March 4 - March 14, 2016	5-Year, 10-Day	2-Year, 10-Day

The following storm event classification items are noted:

- The March 4 - 7 rainfall was the largest classified rainfall event over the monitoring period.
- There was a very strong hour of rainfall in the northern region of Lincoln that registered as a 100-Year event, dropping 1.07 inches on March 4 from 1:45pm to 2:45pm.
- The 10 days of rainfall from March 3 – 14 was classified as a 5-Year, 10-Day storm event at RG North and as a 2-Year, 10-Day storm event at RG South.

Site Flow Monitoring and Capacity Results: Peak d/D Ratio and Peaking Factors

Peak measured flows and the consequent hydraulic grade line data (flow depths) are important to understand the capacity limitations of a collection system. The following capacity analysis terms are defined as follows:

- **Peaking Factor:** Peaking factor is defined as the peak measured flow divided by the average dry weather flow (ADWF). A peaking factor threshold value of 3.0 is commonly used for sanitary sewer design of new pipe; however, it is noted that this value is variable and subject to attenuation and the size of the upstream collector area. The City should follow its own standards and criteria when examining peaking factors.
- **d/D Ratio:** The d/D ratio is the peak measured depth of flow (d) divided by the pipe diameter (D). Standards for d/D ratio vary from agency to agency, but typically range between d/D ≤ 0.5 and d/D ≤ 0.75.

Table ES-3 summarizes the peak recorded flows, levels, *d/D* ratios, and peaking factors per site during the flow monitoring period. Results of note have been shaded in RED. Capacity analysis data is presented on a site-by-site basis and represents the hydraulic conditions only at the site locations; hydraulic conditions in other areas of the collection system will differ.

Table ES-3. Capacity Analysis Summary

Metering Site	ADWF (mgd)	Peak Measured Flow (mgd)	Peaking Factor	Pipe Diameter, *D* (in)	Max Depth, *d* (in)	*Max d/D* Ratio	Surcharge above Pipe Crown (ft)
Site 1	0.044	0.26	5.8	18	3.0	0.17	-
Site 2	0.008	0.18	23	10	2.3	0.23	-
Site 3	0.086	0.47	5.4	12	3.9	0.32	-
Site 4	0.016	0.15	9.7	10	4.8	0.48	-
Site 5	0.067	0.53	7.9	12	6.1	0.51	-
Site 6	0.169	0.55	3.1	12	6.4	0.53	-
Site 7	0.084	0.32	3.7	10	4.0	0.40	-
Site 8	0.017	0.054	3.1	10	3.6	0.36	-

The following capacity analysis results are noted:

- **Peaking Factor**
  - **Site 2:** The peak flow occurred on March 14 1:00, immediately after the last rainfall of the March 4 to 14 storm and appeared to be directly related to rainfall.
    - The ADWF of Site 2 was very low, potentially exaggerating the significance of the peaking factor. The peak measured flow was below average amongst these similar sized pipes.
    - It is noted that Site 2 has fluctuating and sporadic flows and flow spikes during the flow monitoring period, both before and after rainfall. The flows behave as though there is a holding basin with pump station upstream from the monitoring location. If so, the high peaking factors would also be explained by high flows resulting from a pump station discharge.
    - For a high peaking factor of 23, Site 2 had a relatively low max d/D ratio of 0.23.
  - **Sites 4 and 5** had high peaking factors.
- **d/D Ratio:** None of the sites had a maximum *d/D* ratio that exceeded a d/D value of 0.75. None of the sites reached a surcharged condition during this study.

Figure ES-2 shows a schematic diagram of the peak measured flows with peak flow levels

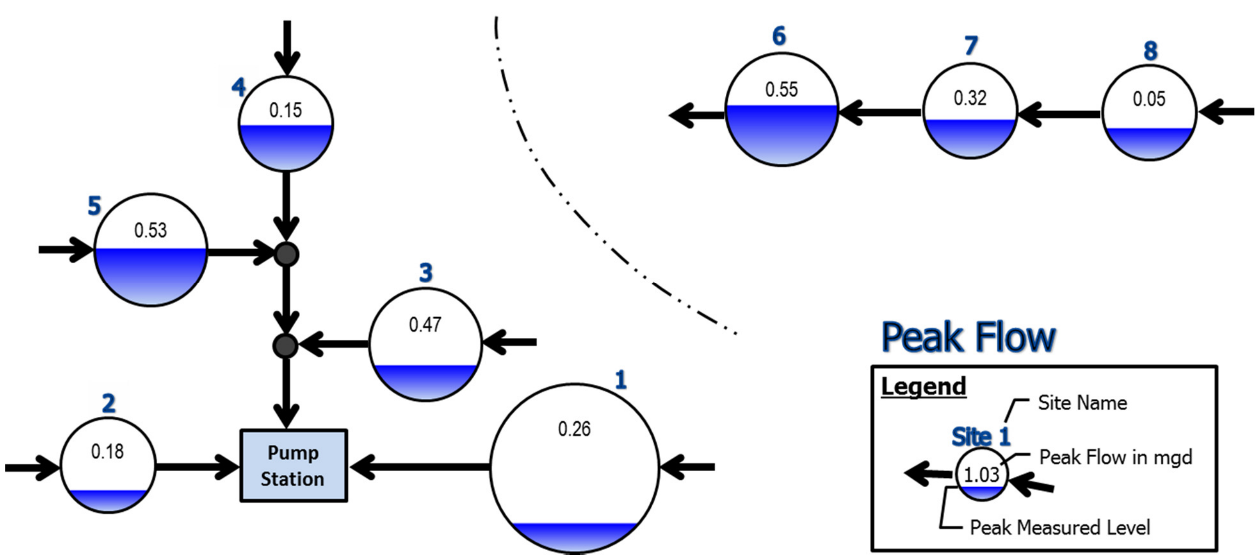

Figure ES-2. Wet Weather Flow Schematic

Infiltration and Inflow Analysis

Table ES-4 summarizes the flow monitoring and I/I results for the flow monitoring sites that were monitored during this study. I/I analyses were for conducted for the March 4 – 14 rainfall event. A basin was ranked "high" if it had high I/I factors when normalized by both "per-ADWF" and "per-IDM" methods. A basin was ranked "medium" if it had high I/I factors for one of the methods. Please refer to the *I/I Methods* section for more information on inflow and infiltration analysis methods and ranking methods.

Table ES-4. I/I Analysis Summary

Metering Basin	ADWF (mgd)	Peak I/I Rate (mgd)	Combined I/I (gallons)	Peak I/I Ranking	RDI Ranking	High GWI?	Combined I/I Rank
Basin 1	0.044	0.18	987,000	Medium	Medium	Low	Medium
Basin 2	0.008	0.18	536,000	High	Medium	N/A [A]	Medium
Basin 3	0.086	0.35	1,524,000	Medium	Low	High	Medium
Basin 4	0.016	0.12	963,000	Medium	High	None	High
Basin 5	0.067	0.44	2,990,000	High	High	Low	High
Basin 6	0.169	0.10	316,000	Low	Low	None	Low
Basin 7	0.084	0.12	722,000	Low	Low	None	Low
Basin 8	0.017	0.031	12,000	Low	Low	Low	Low

[A] Evidence that basin is a commercial/ industrial area and does not follow typical residential trends.

The following inflow/infiltration analysis results are noted:

- **Basin 5** was ranked "High" for all inflow/infiltration components except for groundwater infiltration.
- **Basins 3 and 4** also had strong inflow and infiltration rankings in all more most I/I categories. Basin 3 had the largest groundwater infiltration component.

Peak Design Storm Event Flows

Synthetic I/I hydrographs were developed and applied to the 10-year, 24-hour design storm event to approximate the peak flow response for this design scenario. These results assume full ground saturation, and the peak I/I flows from the design storm coincide with peak sanitary flows to get a "worst-case" scenario of peak wet weather flows.

Table ES-5 summarizes the final results for the design storm on a site-by-site basis. The peak flows presented in Table ES-5 show the projected peak flows without accounting for system capacity limitations. A comprehensive dynamic model is required to determine the locations of the capacity issues and methods for relieving capacity.

Table ES-5. Design Storm I/I Analysis Summary

Monitoring Site	Peak Dry Weather Flow (mgd)	Peak I/I Rate (mgd)	Peak Flow (mgd)
Site 1	0.127	0.224	0.351
Site 2	0.016	0.328	0.344
Site 3	0.158	0.550	0.708
Site 4	0.039	0.097	0.136
Site 5	0.127	0.599	0.726
Site 6	0.394	0.385	0.779
Site 7	0.161	0.278	0.439
Site 8	0.038	0.070	0.108

Recommendations

V&A advises that future I/I reduction plans consider the following recommendations:

1. **Determine I/I Reduction Program:** The City should examine its I/I reduction needs to determine a future I/I reduction program.
   a. If peak flows, sanitary sewer overflows, and pipeline capacity issues are of greater concern, then priority can be given to investigate and reduce sources of inflow within the basins with the greatest inflow problems.
   b. If total infiltration and general pipeline deterioration are of greater concern, then the program can be weighted to investigate and reduce sources of infiltration within the basins with the greatest infiltration problems.
2. **Basins 3, 4 and 5:** On an I/I contribution basis, the City should focus future I/I reduction efforts within Basins 3, 4 and 5, though it is noted that Basins 1 and 2 also had significant I/I contribution:
   a. Basins 3, 4 and 5 all ranked in the upper ranges of the system for normalized inflow, RDI and combined I/I contributions. Basin 3 also had higher than typical GWI rates.
3. **I/I Investigation Methods:** Potential I/I investigation methods include the following:
   a. Smoke testing: This method is typically used to locate inflow sources.
   b. CCTV inspection: This method is typically used to locate condition assessment defects linked to infiltration sources. This would need to take place immediately after a strong rainfall event when groundwater levels are high so as to try and capture the infiltration "in the act".
   c. Mini-basin flow monitoring: This method can be used to isolate smaller catchment areas in which to locate infiltration and inflow sources. This may be the most prudent course of action to try and better isolate the areas within Basins 3, 4 and 5 where the I/I is originating.

   d. Nighttime reconnaissance work to (1) investigate and determine direct point sources of inflow and (2) determine the areas and pipe reaches responsible for high levels of infiltration contribution.

4. **I/I Reduction Cost-Effectiveness Analysis:** The City may wish to conduct a study to determine which is more cost-effective: (1) locating the sources of inflow and infiltration and systematically rehabilitating or replacing the faulty pipelines or (2) continued treatment of the additional rainfall-dependent I/I flow.

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1.0 INTRODUCTION

1.1 Scope and Purpose

V&A Consulting Engineers (V&A) has completed sanitary sewer flow monitoring and rainfall monitoring with I/I analysis for tributary areas contributing to the Nicolaus Pump Station. Flow and rainfall monitoring was performed over a period of over 10 weeks from January 23, 2016 to April 3, 2016. Open-channel flow monitoring was performed at five sites.

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There were three general purposes of this study.

4. Establish the baseline sanitary sewer flows at the flow monitoring sites.
5. Estimate available sewer capacity.
6. Isolate I/I response and perform I/I analysis.

1.2 Flow Monitoring Sites, Sewerage Basins and Rain Gauges

Flow monitoring sites are identified the manholes where the flow monitors were secured and the pipelines wherein the flow sensors were placed. Flow monitoring site data may include the flows of one or many drainage basins. To isolate a flow monitoring basin, an addition or subtraction of flows may be required[1]. Capacity and flow rate information is presented on a site-by-site basis.

Flow monitoring basins are localized areas of a sanitary sewer collection system upstream of a given location (often a flow meter), including all pipelines, inlets, and appurtenances. The basin refers to the ground surface area near and enclosed by the pipelines[2]. A basin may refer to the entire collection system upstream from a flow meter or may exclude separately monitored basins upstream. I/I analysis in this report will be conducted on a basin-by-basin basis. For this study subtraction of flows was required to isolate the drainage areas of some flow monitoring basins.

[1] There is error inherent in flow monitoring. Adding and subtracting flows increases error on an additive basis. For example, if Site A has an error of ±10% and Site B has an error of ±10%, then the resulting flow when subtracting Site A from Site B would have an error of up to ±20%.

[2] Basin boundaries and IDM were determined using base sanitary sewer maps provided by Stantec. It is noted the IDMs were scaled and measured off of the provided maps; if not indicated, pipe diameters were estimated. Calculated IDMs for this project are considered estimates.

Rain data was obtained from two installed rain gauges intending to capture rainfall in the northern and southern regions of the collection system.

The flow monitoring sites were selected and approved by Stantec and the City. Information regarding the flow monitoring and rain gauge locations and associated sewerage basins are listed in Table 1-1 and shown in Figure 1-1 and Figure 1-2. Detailed descriptions of the individual flow monitoring sites, including photographs, are included in *Appendix A*.

Table 1-1. List of Flow Monitoring and Rain Gauge Locations

Site / Basin	Pipe Monitored	Dia. (in)	Location	Basin Size (IDM)	Basin Isolation Equation
1	East Inlet	18	on Nicolaus Road, 1100 ft west of Tea Hollow Dr S, right lane, nearest address 2821-3099 Nicolaus Road	22.9	$= Q_1$
2	West Inlet	10	on Nicolaus Road, 1600 ft east of Aviation Blvd, middle lane, nearest address 2858-3004 Nicolaus Road	26.8	$= Q_2$
3	NE Inlet	12	off road, approx. 850 ft NW of 2856 Nicolaus Road parking lot, nearest address 1297 Canvasback Cir.	42.6	$= Q_3$
4	NW Inlet	10	off road, approx. 450 ft east of 305-525 Business Park Dr.	22.3	$= Q_4$
5	NE Inlet	12	off road, approx. 450 ft east of 305-525 Business Park Dr.	59.7	$= Q_5$
6	South Inlet	12	Intersection of Ferrari Ranch Rd and Caledon Cir.	52.4	$= Q_6 - Q_7$
7	South Inlet	10	Brentford Cir. 300 ft south of Caledon Cir.	39.6	$= Q_7 - Q_8$
8	South Inlet	10	Intersection of Brentford Cir and Caradale Ln	7.4	$= Q_8$

Rain Gauge	Location
North	Latitude: 38.9069° Longitude: -121.3157° Elevation: 141 feet. Field adjacent to Foskett Ranch Elementary School
South	Latitude: 38.8738° Longitude: -121.3060° Elevation: 143 feet. Field adjacent to intersection of Groveland Land and Ferrari Ranch Road

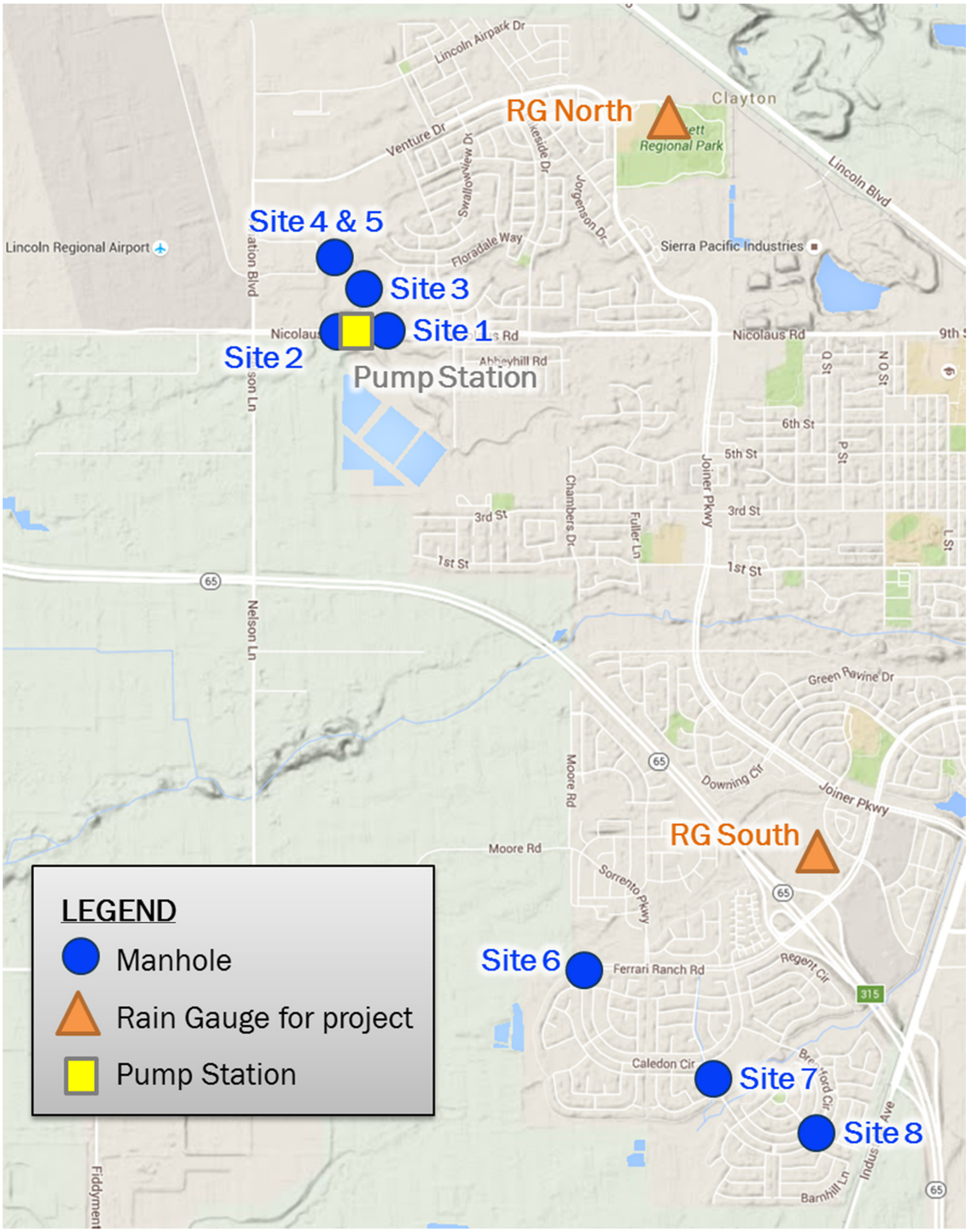
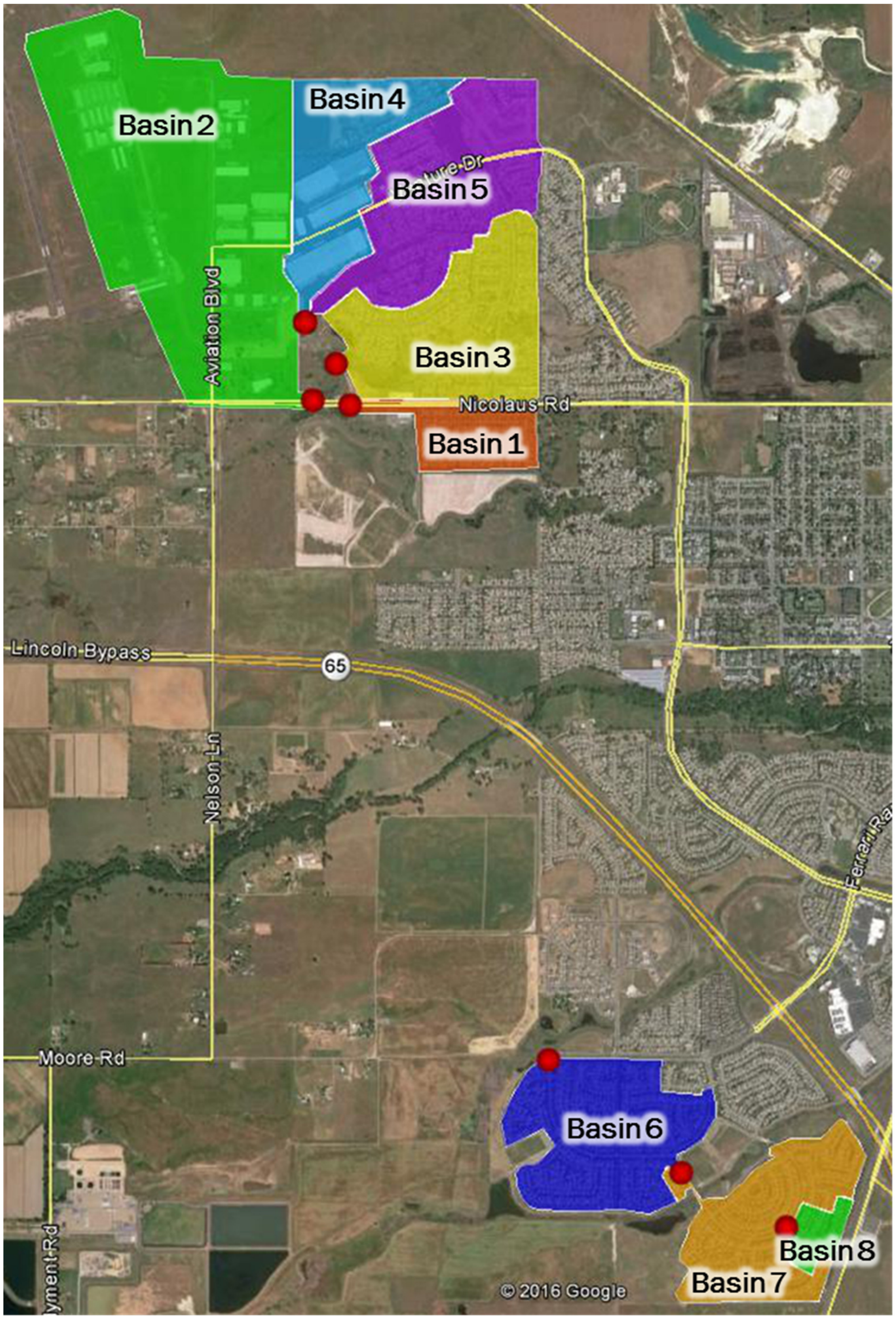


Figure 1-1. Map of Flow Monitoring Sites and Rain Gauges



Note: colors shown in this figure are intended to differentiate sewerage basins only. The colors do not represent any additional basin information.

Figure 1-2. Map of Flow Monitoring Basins

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2.0 METHODS AND PROCEDURES

2.1 Confined Space Entry

A confined space (Photo 2-1) is defined as any space that is large enough and so configured that a person can bodily enter and perform assigned work, has limited or restricted means for entry or exit and is not designed for continuous employee occupancy. In general, the atmosphere must be constantly monitored for sufficient levels of oxygen (19.5% to 23.5%), and the presence of hydrogen sulfide (H_2S) gas, carbon monoxide (CO) gas, and lower explosive limit (LEL) levels. A typical confined space entry crew has members with OSHA-defined responsibilities of Entrant, Attendant and Supervisor. The Entrant is the individual performing the work. He or she is equipped with the necessary personal protective equipment needed to perform the job safely, including a personal four-gas monitor (Photo 2-2). If it is not possible to maintain line-of-sight with the Entrant, then more Entrants are required until line-of-sight can be maintained. The Attendant is responsible for maintaining contact with the Entrants to monitor the atmosphere using another four-gas monitor and maintaining records of all Entrants, if there are more than one. The Supervisor is responsible for developing the safe work plan for the job at hand prior to entering.

Photo 2-1. Confined Space Entry

Photo 2-2. Typical Personal Four-Gas Monitor

2.2 Flow Meter Installation

V&A installed eight Isco 2150 area-velocity flow meters for temporary metering within the collection system. Isco 2150 meters use submerged sensors with a pressure transducer to collect depth readings and an ultrasonic Doppler sensor to determine the average fluid velocity. The ultrasonic sensor emits high-frequency (500 kHz) sound waves, which are reflected by air bubbles and suspended particles in the flow. The sensor receives the reflected signal and determines the Doppler frequency shift, which indicates the estimated average flow velocity. The sensor is typically mounted at a manhole inlet to take advantage of smoother upstream flow conditions. The sensor may be offset to one side to lessen the chances of fouling and sedimentation where these problems are expected to occur. Manual level and velocity measurements were taken during installation of the flow meters and again when they were removed and compared to simultaneous level and velocity readings from the flow meters to ensure proper calibration and accuracy. Figure 2-1 shows a typical installation for a flow meter with a submerged sensor.

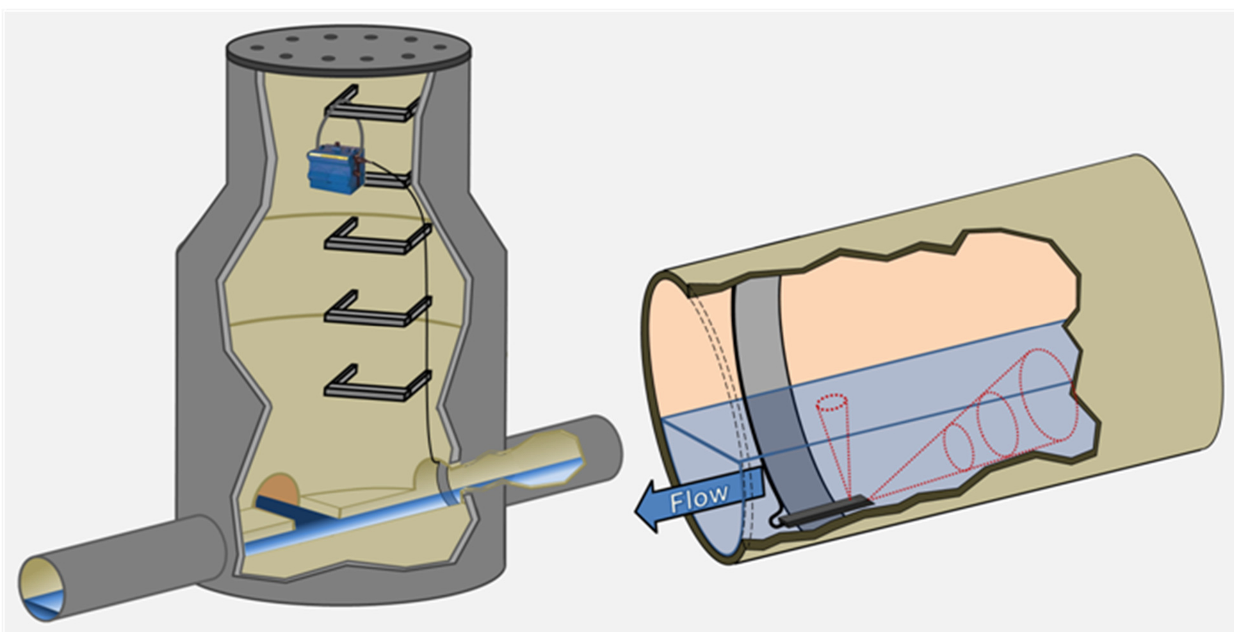

Figure 2-1. Typical Installation for Flow Meter with Submerged Sensor

2.3 Flow Calculation

Data retrieved from the flow meter was placed into a spreadsheet program for analysis. Data analysis includes data comparison to field calibration measurements, as well as necessary geometric adjustments as required for sediment (sediment reduces the pipe's wetted cross-sectional area available to carry flow). Area-velocity flow metering uses the continuity equation,

$$Q = v \cdot A = v \cdot (A_T - A_S)$$

where Q : volume flow rate
v: average velocity as determined by the ultrasonic sensor
A: cross-sectional area available to carry flow
A_T: total cross-sectional area with both wastewater and sediment
A_S: cross-sectional area of sediment.

For circular pipe,

$$A_T = \left[\frac{D^2}{4}\cos^{-1}\left(1-\frac{2d_W}{D}\right)\right]-\left[\left(\frac{D}{2}-d_W\right)\left(\frac{D}{2}\right)\sin\left(\cos^{-1}\left(1-\frac{2d_W}{D}\right)\right)\right]$$

$$A_S = \left[\frac{D^2}{4}\cos^{-1}\left(1-\frac{2d_S}{D}\right)\right]-\left[\left(\frac{D}{2}-d_S\right)\left(\frac{D}{2}\right)\sin\left(\cos^{-1}\left(1-\frac{2d_S}{D}\right)\right)\right]$$

where d_W: distance between wastewater level and pipe invert
d_S: depth of sediment
D: pipe diameter

2.4 Average Dry Weather Flow Determination

For this study, four distinct average dry weather flow curves were established for each site location:

- Mondays – Thursdays
- Fridays
- Saturdays
- Sundays

Flows for many sites differ on Friday evenings compared to Mondays through Thursdays. Starting around 7 pm, the flows are often decreased (compared to Monday through Thursday). Similarly, flow patterns for Saturday and Sunday were also separated due to their unique evening flow pattern. This type of differentiation can be important when determining I/I response, especially if a rain event occurs on a Friday, Saturday or Sunday evening.

Figure 2-2 illustrates a sample of varying flow patterns within a typical week dry week.

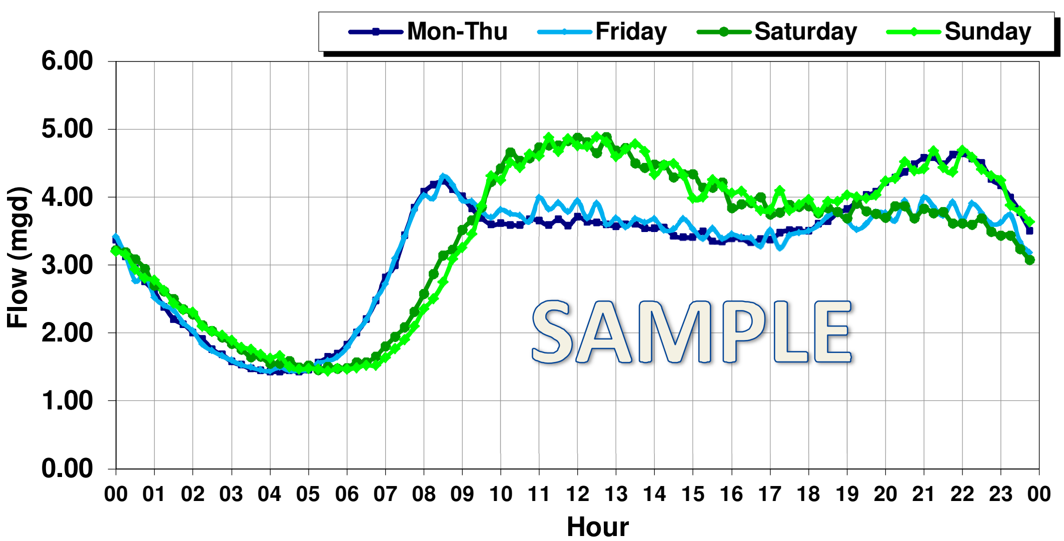

Figure 2-2. Sample ADWF Diurnal Flow Patterns

ADWF curves are taken from "Dry Days", when RDI had the least impact on the baseline flow. The overall average dry weather flow (ADWF) was calculated per the following equation:

$$ADWF = \left(ADWF_{Mon-Thu} \times \frac{4}{7}\right) + \left(ADWF_{Fri} \times \frac{1}{7}\right) + \left(ADWF_{Sat} \times \frac{1}{7}\right) + \left(ADWF_{Sun} \times \frac{1}{7}\right),$$

2.5 Flow Attenuation

Flow attenuation in a sewer collection system is the natural process of the reduction of the peak flow rate through redistribution of the same volume of flow over a longer period of time. This occurs as a result of friction (resistance), internal storage and diffusion along the sewer pipes. Fluids are constantly working towards equilibrium. For example, a volume of fluid poured into a static vessel with no outside turbulence will eventually stabilize to a static state, with a smooth fluid surface without peaks and valleys. Attenuation within a sanitary sewer collection system is based upon this concept. A flow profile with a strong peak will tend to stabilize towards equilibrium, as shown in Figure 2-3.

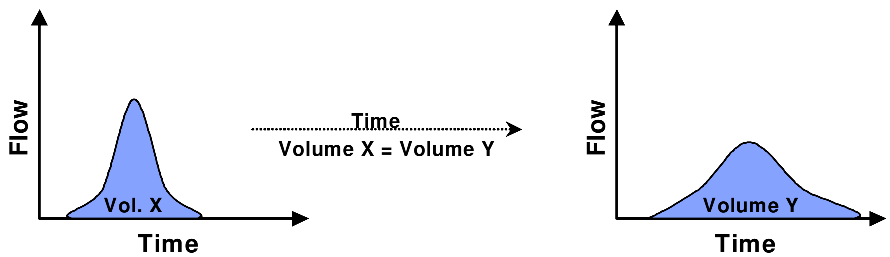

Figure 2-3. Attenuation Illustration

Within a sanitary sewer collection system, each individual basin will have a specific flow profile. As the flows from the basins combine within the trunk sewer lines, the peaks from each basin will (a) not necessarily coincide at the same time, and (b) due to the length and time of travel through the trunk sewers, peak flows will attenuate prior to reaching the treatment facility. The sum of the peak flows of the individual basins within a collection system will usually be greater than the peak flows observed at the treatment facility.

2.6 Inflow / Infiltration Analysis: Definitions and Identification

Inflow and infiltration (I/I) consists of storm water and groundwater that enter the sewer system through pipe defects and improper storm drainage connections and is defined as follows:

2.6.1 Definition and Typical Sources

- **Inflow:** Storm water inflow is defined as water discharged into the sewer system, including private sewer laterals, from direct connections such as downspouts, yard and area drains, holes in manhole covers, cross-connections from storm drains, or catch basins.
- **Infiltration:** Infiltration is defined as water entering the sanitary sewer system through defects in pipes, pipe joints, and manhole walls, which may include cracks, offset joints, root intrusion points, and broken pipes.

Figure 2-4 illustrates the possible sources and components of I/I.

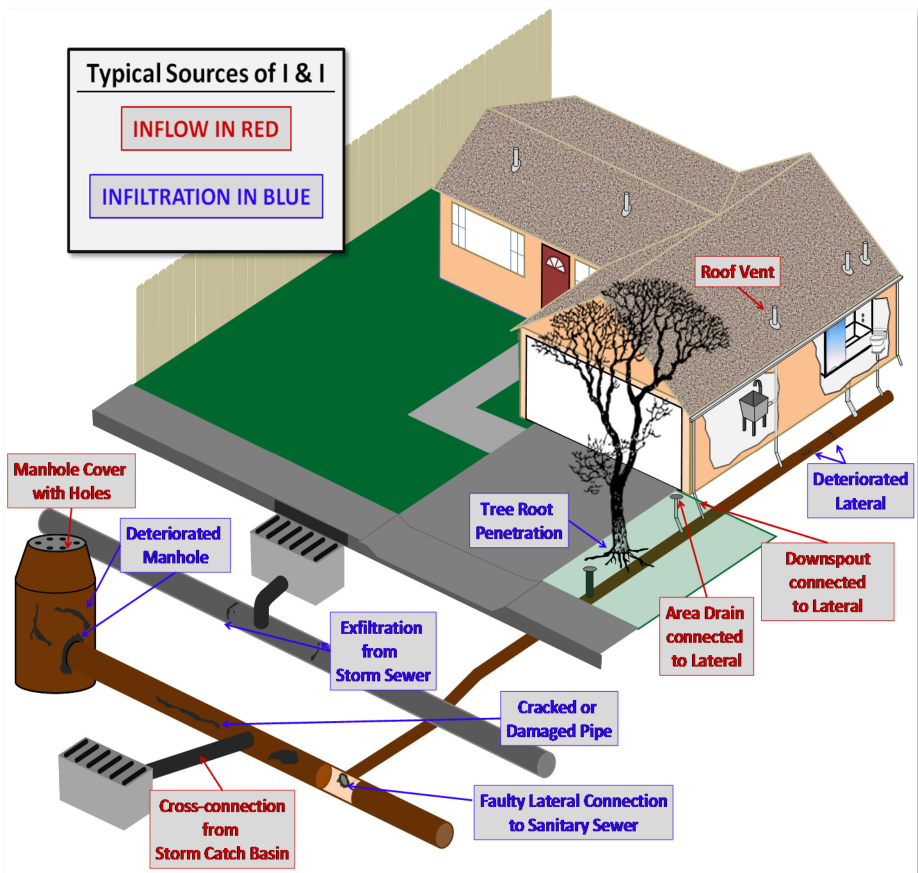

Figure 2-4. Typical Sources of Infiltration and Inflow

2.6.2 Infiltration Components

Infiltration can be further subdivided into components as follows:

- **Groundwater Infiltration:** Groundwater infiltration depends on the depth of the groundwater table above the pipelines as well as the percentage of the system submerged. The variation of groundwater levels and subsequent groundwater infiltration rates is seasonal by nature. On a day-to-day basis, groundwater infiltration rates are relatively steady and will not fluctuate greatly.
- **Rainfall-Dependent Infiltration:** This component occurs as a result of storm water and enters the sewer system through pipe defects, as with groundwater infiltration. The storm water first percolates directly into the soil and then migrates to an infiltration point. Typically, the time of concentration for rainfall-related infiltration may be 24 hours or longer, but this depends on the soil permeability and saturation levels.
- **Rainfall-Responsive Infiltration** is storm water which enters the collection system indirectly through pipe defects, but normally in sewers constructed close to the ground surface such as private laterals. Rainfall-responsive infiltration is independent of the groundwater table and reaches defective sewers via the pipe trench in which the sewer is constructed, particularly if the pipe is placed in impermeable soil and bedded and backfilled with a granular material. In this case, the pipe trench serves as a conduit similar to a French drain, conveying storm drainage to defective joints and other openings in the system. This type of infiltration can have a quick response and graphically can look very similar to inflow.

2.6.3 Impact and Cost of Source Detection and Removal

- **Inflow:**
  - **Impact:** This component of I/I creates a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows. Because the response and magnitude of inflow is tied closely to the intensity of the storm event, the short-term peak instantaneous flows may result in surcharging and overflows within a collection system. Severe inflow may result in sewage dilution, resulting in upsetting the biological treatment (secondary treatment) at the treatment facility.
  - **Cost of Source Identification and Removal:** Inflow locations are usually less difficult to find and less expensive to correct. These sources include direct and indirect cross-connections with storm drainage systems, roof downspouts, and various types of surface drains. Generally, the costs to identify and remove sources of inflow are low compared to potential benefits to public health and safety or the costs of building new facilities to convey and treat the resulting peak flows.

- **Infiltration:**
  - **Impact:** Infiltration typically creates long-term annual volumetric problems. The major impact is the cost of pumping and treating the additional volume of water, and of paying for treatment (for municipalities that are billed strictly on flow volume).

- **Cost of Source Detection and Removal:** Infiltration sources are usually harder to find and more expensive to correct than inflow sources. Infiltration sources include defects in deteriorated sewer pipes or manholes that may be widespread throughout a sanitary sewer system.

2.6.4 Graphical Identification of I/I

Inflow is usually recognized graphically by large-magnitude, short-duration spikes immediately following a rain event. Infiltration is often recognized graphically by a gradual increase in flow after a wet-weather event. The increased flow typically sustains for a period after rainfall has stopped and then gradually drops off as soils become less saturated and as groundwater levels recede to normal levels. Realtime flows were plotted against ADWF to analyze the I/I response to rainfall events. Figure 2-5 illustrates a sample of how this analysis is conducted and some of the measurements that are used to distinguish infiltration and inflow. Similar graphs were generated for the individual flow monitoring sites and can be found in *Appendix A*.

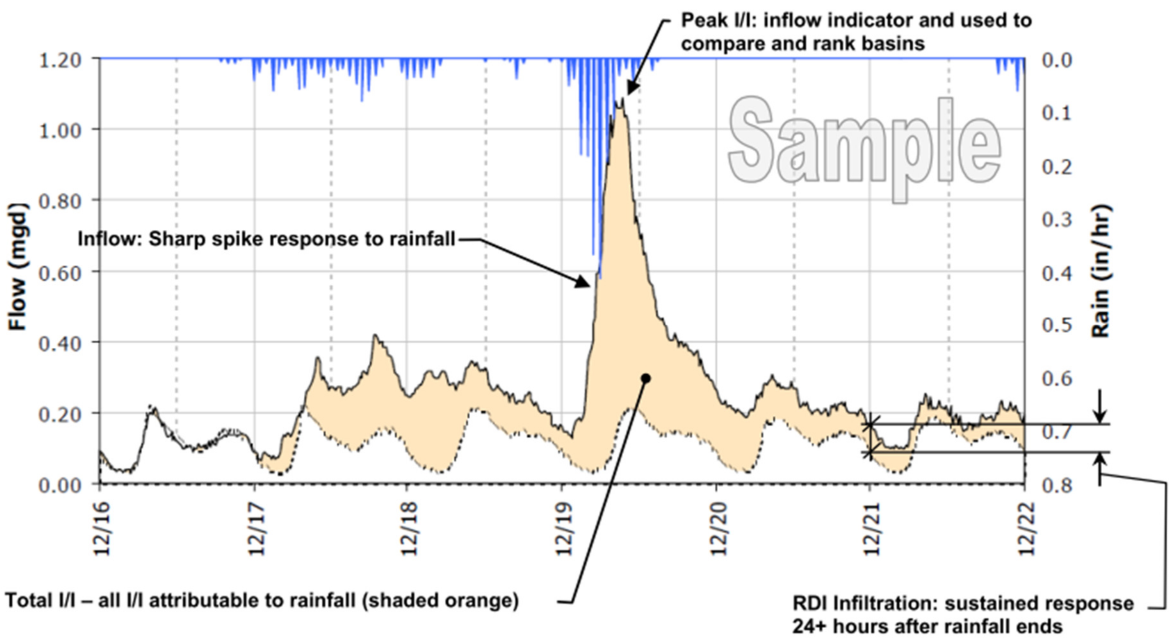

Figure 2-5. Sample Infiltration and Inflow Isolation Graph

Figure 2-6 shows sample graphs indicating the typical graphical response patterns for inflow and infiltration in a more detailed version.

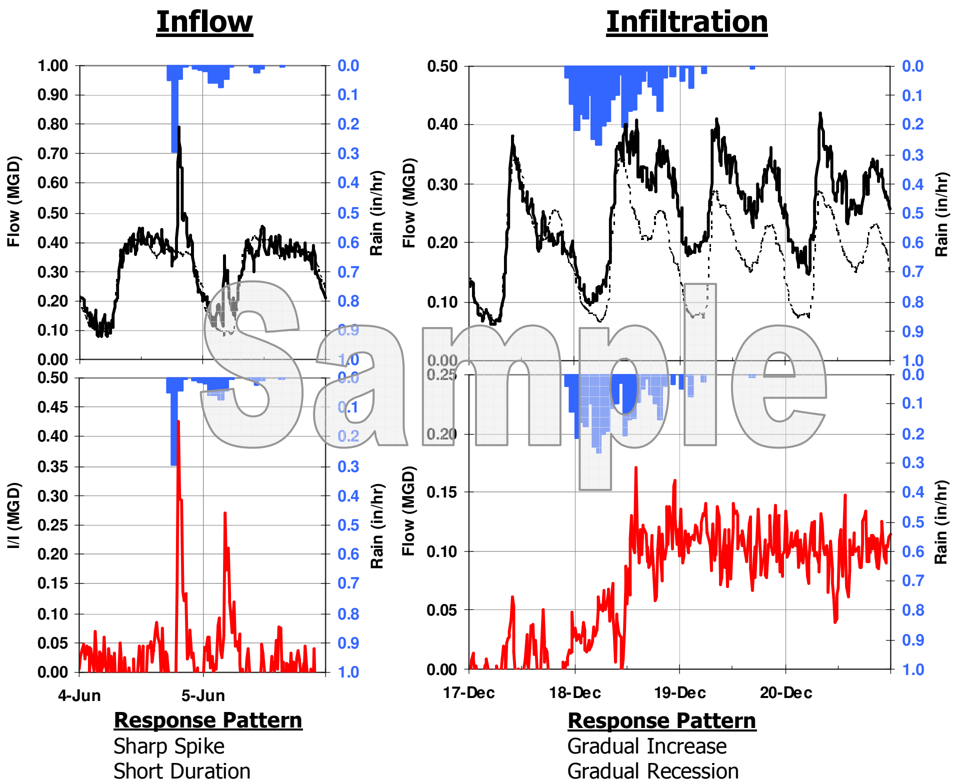

Figure 2-6. Inflow and Infiltration: Graphical Response Patterns

2.6.5 Analysis Metrics

After differentiating I/I flows from ADWF flows, various calculations can be made to determine which I/I component (inflow or infiltration) is more prevalent at a particular site and to compare the relative magnitudes of the I/I components between drainage basins and between storm events:

Inflow – Peak I/I Flow Rate: Inflow is characterized by sharp, direct spikes occurring during a rainfall event. Peak I/I rates are used for inflow analysis[3].

Groundwater Infiltration: GWI analysis is conducted by looking at minimum dry weather flow to average dry weather flow ratios and comparing them to established standards to quantify the rate of excess groundwater infiltration.

Rainfall-Dependent Infiltration: Infiltration occurring after the conclusion of a storm event is classified as rainfall-dependent infiltration (RDI). RDI Analysis is conducted by looking at the infiltration rates at set periods after the conclusion of a storm event. Depending on the particular collection system and the time required for flows to return to ADWF levels, different set periods may

[3] I/I flow rate is the real time flow less the estimated average dry weather flow rate. It is an estimate of flows attributable to rainfall. By using peak measured flow rates (inclusive of ADWF), the I/I flow rate would be skewed higher or lower depending on whether the storm event I/I response occurs during low-flow or high-flow hours.

be examined to determine the basins with the greatest or most sustained rainfall-dependent infiltration rates.

Total Infiltration: The total inflow and infiltration is measured in gallons per site and per storm event. Because it is based on total I/I volume, it is an indicator of combined inflow and infiltration and is used to identify the overall volumetric influence of I/I within the monitoring basin.

2.6.6 Normalization Methods

There are three ways to *normalize* the I/I analysis metrics for an "apples-to-apples" comparison amongst the different drainage basins:

- **per-ADWF:** The metric is divided by the established average dry weather flow rate and typically expressed as a ratio. *Peaking Factors* are examples of using ADWF to normalize data from different sites.
- **per-IDM:** The metric is divided by length of pipe (IDM [inch-diameter mile]) contained within the upstream basin. Final units typically are gallons per day (gpd) per IDM.
- **per-ACRE:** The metric is divided by the acreage of the upstream basin. Final units typically are gallons per day (gpd) per ACRE.

The infiltration and inflow indicators were normalized by the per-IDM and per-ADWF methods in this report. It is noted that future I/I rehabilitation and/or reduction efforts are typically budgeted per unit length of pipe.

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3.0 RAINFALL RESULTS

3.1 Rainfall Monitoring

There were two main rainfall events that occurred over the course of the flow monitoring period, as summarized in Table 3-1. These two rainfall events occurred very close to each other and can be considered part of the same storm system. Figure 3-1 shows rainfall activity in Lincoln over the flow monitoring period (RG North shown).

Table 3-1. Rainfall Events Used for I/I Analysis

Rainfall Event	RG North (in)	RG South (in)
Event 1: March 4 – March 7, 2016	3.79	2.34
Event 2: March 10 – March 14, 2016	3.31	2.72
Total Storm Duration: March 4 - March 14, 2016	7.11	5.07
Total over Monitoring Period	*9.91*	*6.90*

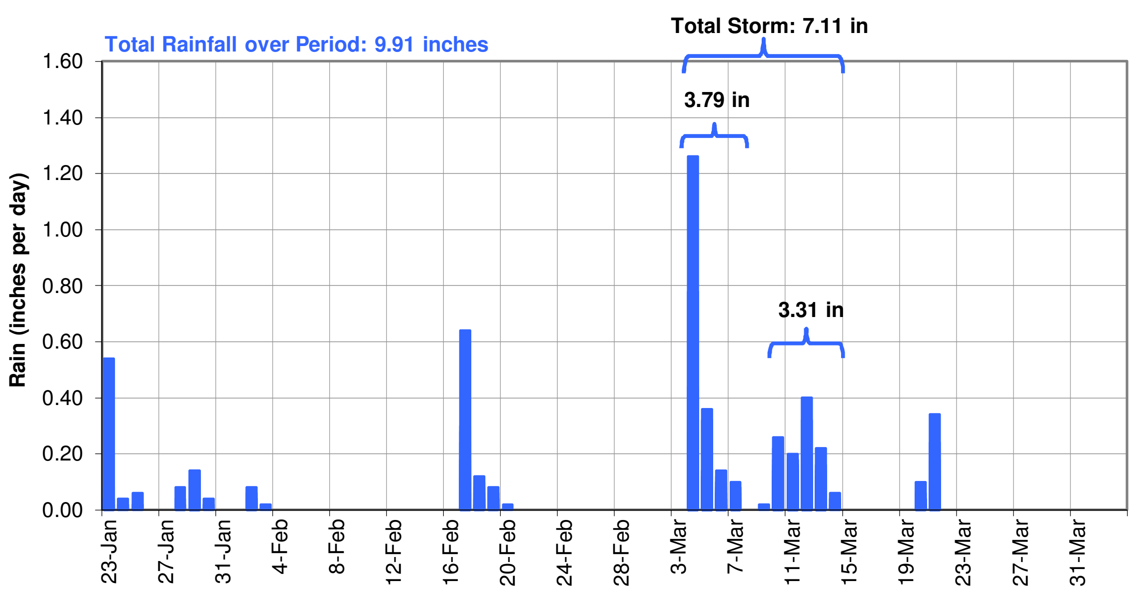


Figure 3-1. Rainfall Activity over Monitoring Period (RG North shown)

Figure 3-2 shows the rain accumulation plot of the period rainfall, as well as the historical average rainfall[4] in Lincoln during this project duration. The historical average rainfall was obtained using the inverse distance weighting method (Section 3.2 on Page 24) from stations in Rocklin and Marysville. Rainfall totals for Lincoln were at or above historical normal levels during this time period.

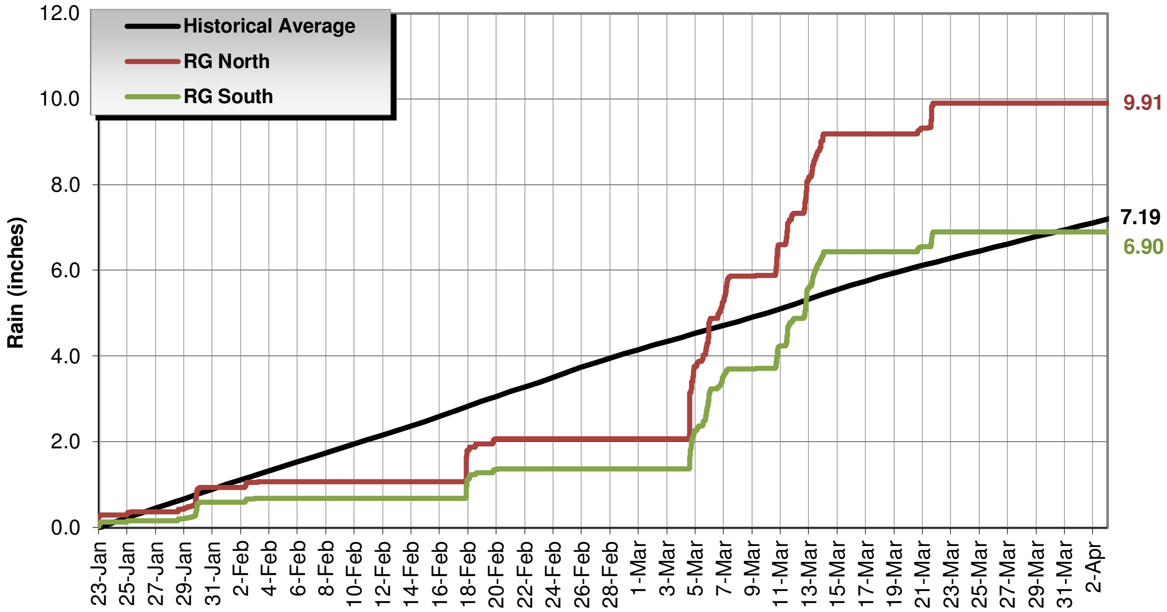


Figure 3-2. Accumulated Precipitation Monitored from Different Locations

[4] Historical data taken from the WRCC (Station 47516 in Rocklin and Station 45385 in Marysville): http://www.wrcc.dri.edu/summary/climsmnca.html

3.2 Rain Gauge Triangulation Distribution

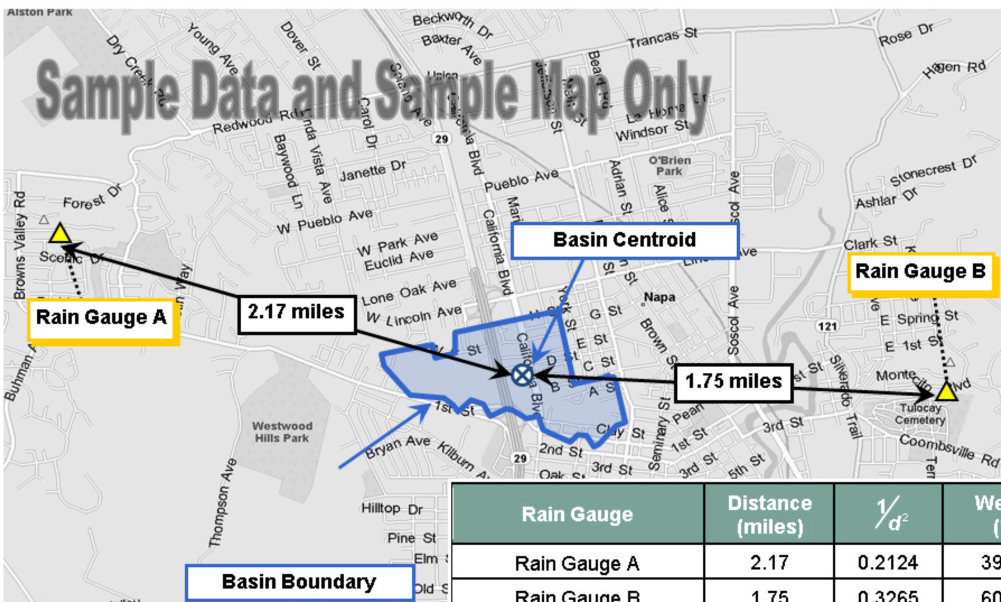
Since historic rainfall data was not available for the City of Lincoln, it was calculated based on the proximity to other nearby historic rain gauge stations. The inverse distance weighting (IDW) method is an interpolation method that assumes the influence of each rain gauge location diminishes with distance.

IDW is performed using the equation:

$$w = \frac{1/d^p}{\sum 1/d^p}$$

where the weight, *w*, depends on the distance, *d*, from the available rain gauge to the desired location and *p*, a user-selected power ($p > 0$). The most common choice of *p* in hydrological studies of watershed areas is 2.

Figure 3-3 illustrates the IDW method with sample data.



Rain Gauge	Distance (miles)	$1/d^2$	Weight (%)
Rain Gauge A	2.17	0.2124	39.4%
Rain Gauge B	1.75	0.3265	60.6%
Totals		**0.5389**	**100%**

Figure 3-3. Rainfall Inverse Distance Weighting Method

The IDW method was not used for the metered basins in this study as the sites were mainly located in two regions; north or south. The sites were associated with their respective rain gauges (RG North or RG South).

3.3 Rainfall: Storm Event Classification

It is important to classify the relative size of a major storm event that occurs over the course of a flow monitoring period in order to compare the observed flow response to that occurring during a design storm event (sanitary sewers are often designed to withstand I/I contribution to sanitary flows for specific-sized "design" storm events). Rainfall events are classified by intensity and duration. For example, the NOAA Rainfall Frequency Atlas shown in Figure 3-4 (NOAA Western U.S. Precipitation Frequency Maps Atlas 2, 1973: http://www.wrcc.dri.edu/pcpnfreq.html) classifies a 10-year, 24-hour storm event at RG North as 3.39 inches. This means that in any given year, at this specific location, there is a 10% chance that 3.39 inches of rain will fall in any 24-hour period.

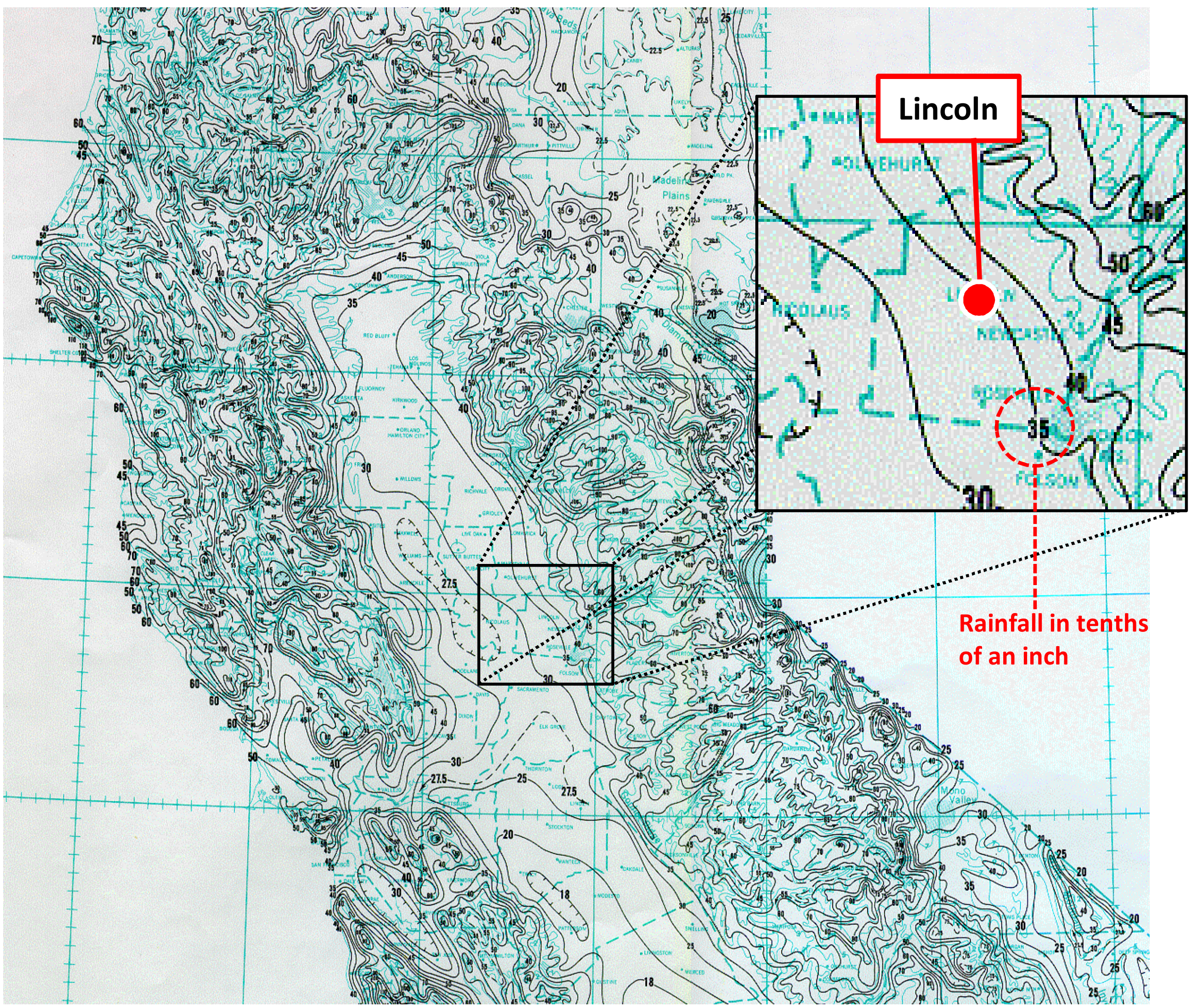


Figure 3-4. NOAA Northern California Rainfall Frequency Map (10-Year, 24-Hour IDF)

From the NOAA frequency maps, for a specific latitude and longitude, the rainfall densities for period durations ranging from 15 minutes to 60 days are known for rain events ranging from 1-year to 100-

year intensities. These are plotted to develop a rain event frequency map specific to each rainfall monitoring site. Superimposing the peak measured densities for all the rainfall events on the rain event frequency plot determines the classification of the storm event, shown in Figure 3-5 for RG North and Figure 3-6 for RG South. Table 3-2 summarizes the classification of the rainfall events that occurred during the flow monitoring period.

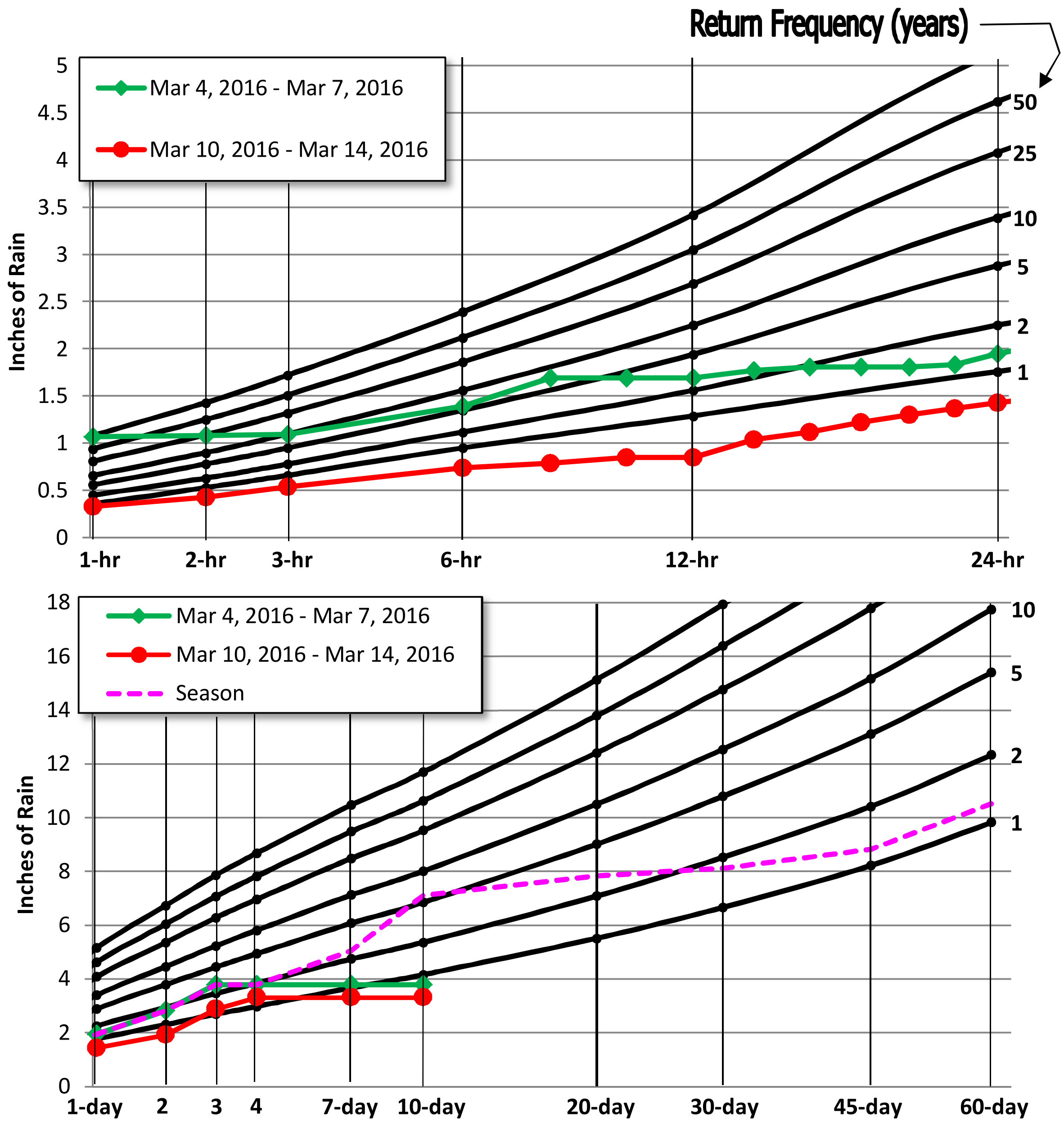


Figure 3-5. Rainfall Event Classification (RG North)

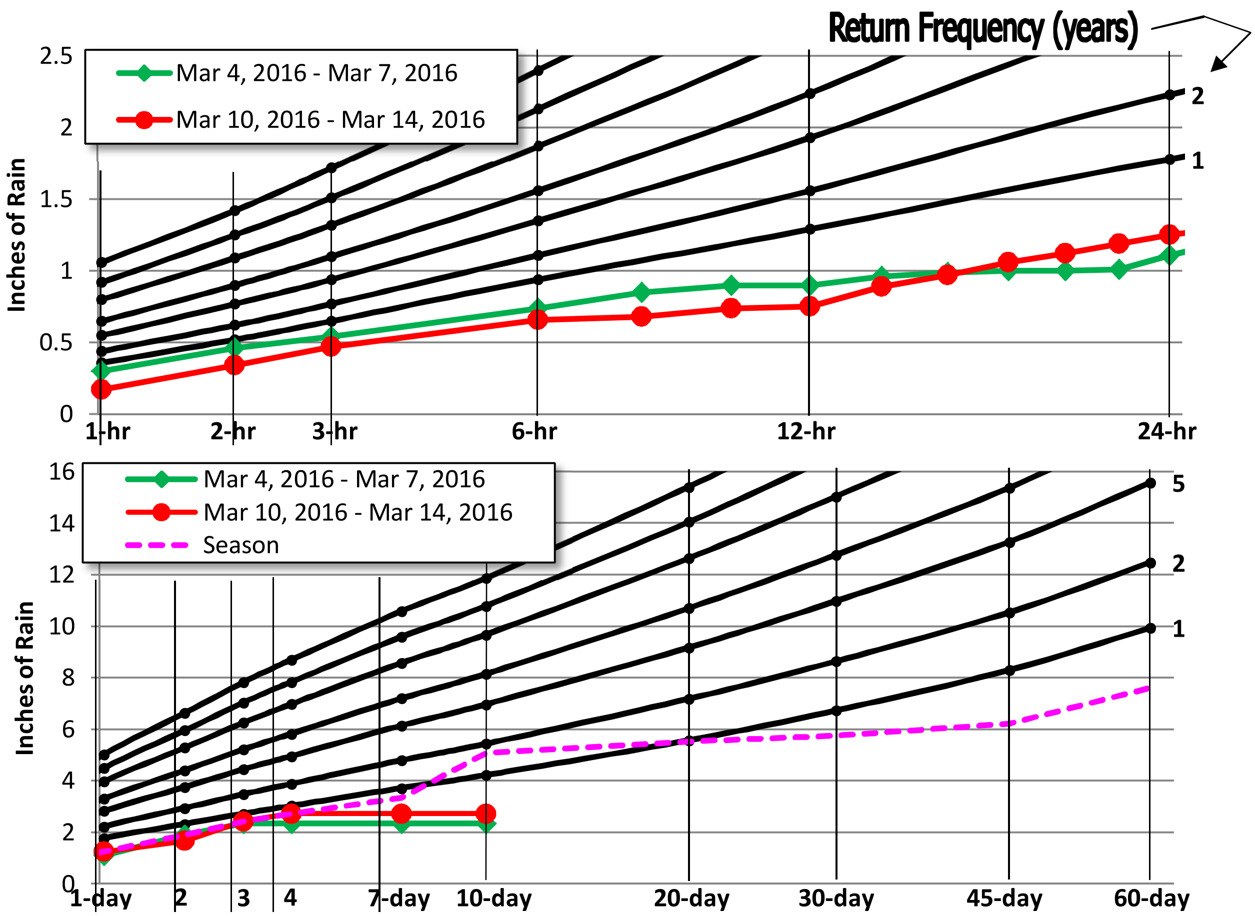


Figure 3-6. Rainfall Event Classification (RG South)

Table 3-2. Classification of Rainfall Events

Rainfall Event	RG North	RG South
March 4 – March 7, 2016	100-Year, 1-Hour 7-Year, 8-Hour 1-Year, 24-Hour 2-Year, 3-Day	<1-Year Event
March 10 – March 14, 2016	<1-Year, 24-Hour 1-Year, 4-Day	<1-Year Event
Total Storm Duration: March 4 - March 14, 2016	5-Year, 10-Day	2-Year, 10-Day

The following storm event classification items are noted:

- The March 4 - 7 rainfall was the largest classified rainfall event over the monitoring period.
- There was a very strong hour of rainfall in the northern region of Lincoln that registered as a 100-Year event, dropping 1.07 inches on March 4 from 1:45pm to 2:45pm.
- The 10 days of rainfall from March 3 – 14 was classified as a 5-Year, 10-Day storm event at RG North and as a 2-Year, 10-Day storm event at RG South.

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4.0 FLOW MONITORING RESULTS

4.1 Average Flow Analysis

ADWF curves were established when RDI had the least impact on the baseline flow. Table 4-1 summarizes the dry weather flow data measured for this study. ADWF curves for each site can be found in *Appendix A*. Figure 4-1 shows a schematic diagram of the average dry weather flows and flow levels.

Table 4-1. Dry Weather Flow

Monitoring Site	Sediment (inches)	Monday-Thursday ADWF (mgd)	Friday ADWF (mgd)	Saturday ADWF (mgd)	Sunday ADWF (mgd)	Overall ADWF (mgd)
Site 1	-	0.041	0.046	0.049	0.049	0.044
Site 2	-	0.008	0.007	0.009	0.008	0.008
Site 3	-	0.084	0.086	0.091	0.087	0.086
Site 4	-	0.015	0.017	0.016	0.017	0.016
Site 5	-	0.065	0.065	0.068	0.076	0.067
Site 6	0.5	0.159	0.164	0.173	0.208	0.169
Site 7	-	0.076	0.095	0.095	0.093	0.084
Site 8	-	0.016	0.017	0.018	0.019	0.017

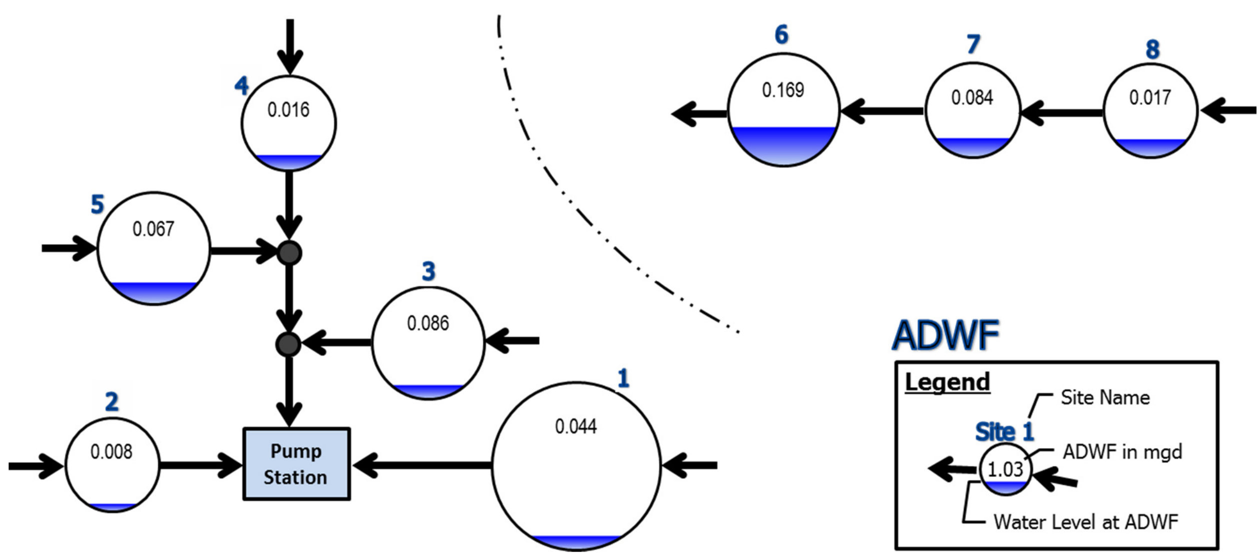

Figure 4-1. Dry Weather Flow Schematic

4.2 Capacity Analysis: Peaking Factor and d/D Ratio

Peak measured flows and the corresponding flow levels (depths) are important to understand the capacity limitations of a collection system. The peak flows and flow levels reported are from the peak measurements as taken across the entirety of the flow monitoring period. Peak flows and levels may not correspond to a rainfall event.

The following capacity analysis terms are defined as follows:

- **Peaking Factor:** Peaking factor is defined as the peak measured flow divided by the average dry weather flow (ADWF). Peaking factors are influenced by many factors including size and topography of tributary area, proximity to pump stations, and the amount and characteristics of I/I entering the collection system. Flow attenuation and flow restrictions will also affect the peaking factor. A peaking factor threshold value of 3.0 is commonly used for sanitary sewer design of new pipe; however, it is noted that this value is variable and subject to attenuation and the size of the upstream collector area. The City should follow its own standards and criteria when examining peaking factors.
- **d/D Ratio:** The d/D ratio is the peak measured depth of flow (d) divided by the pipe diameter (D). Standards for d/D ratio vary from agency to agency, but typically range between d/D ≤ 0.5 and d/D ≤ 0.75. The d/D ratio for each site was computed based on the maximum depth of flow for the flow monitoring study.

Table 4-2 summarizes the peak recorded flows, levels, *d/D* ratios, and peaking factors per site during the flow monitoring period. Results of note have been shaded in RED. Capacity analysis data are presented on a site-by-site basis and represents the hydraulic conditions only at the site locations; hydraulic conditions in other areas of the collection system will differ.

Table 4-2. Capacity Analysis Summary

Metering Site	ADWF (mgd)	Peak Measured Flow (mgd)	Peaking Factor	Pipe Diameter, *D* (in)	Max Depth, *d* (in)	*Max d/D* Ratio	Surcharge above Pipe Crown (ft)
Site 1	0.044	0.26	5.8	18	3.0	0.17	-
Site 2	0.008	0.18	23	10	2.3	0.23	-
Site 3	0.086	0.47	5.4	12	3.9	0.32	-
Site 4	0.016	0.15	9.7	10	4.8	0.48	-
Site 5	0.067	0.53	7.9	12	6.1	0.51	-
Site 6	0.169	0.55	3.1	12	6.4	0.53	-
Site 7	0.084	0.32	3.7	10	4.0	0.40	-
Site 8	0.017	0.054	3.1	10	3.6	0.36	-

The following capacity analysis results are noted:

- **Peaking Factor**
  - **Site 2:** The peak flow occurred on March 14 1:00, immediately after the last rainfall of the March 4 to 14 storm and appeared to be directly related to rainfall.
    - The ADWF of Site 2 was very low, potentially exaggerating the significance of the peaking factor. The peak measured flow was below average amongst these similar sized pipes.
    - It is noted that Site 2 has fluctuating and sporadic flows and flow spikes during the flow monitoring period, both before and after rainfall. The flows behave as though there is a holding basin with pump station upstream from the monitoring location. If so, the high peaking factors would also be explained by high flows resulting from a pump station discharge.
    - For a high peaking factor of 23, Site 2 had a relatively low max d/D ratio of 0.23.
  - **Sites 4 and 5** had high peaking factors.
- **d/D Ratio:** None of the sites had a maximum *d/D* ratio that exceeded a d/D value of 0.75. None of the sites reached a surcharged condition during this study.

Figure 4-2 shows a schematic diagram of the peak measured flows with peak flow levels. Figure 4-3 and Figure 4-4 show bar graphs of the capacity results.

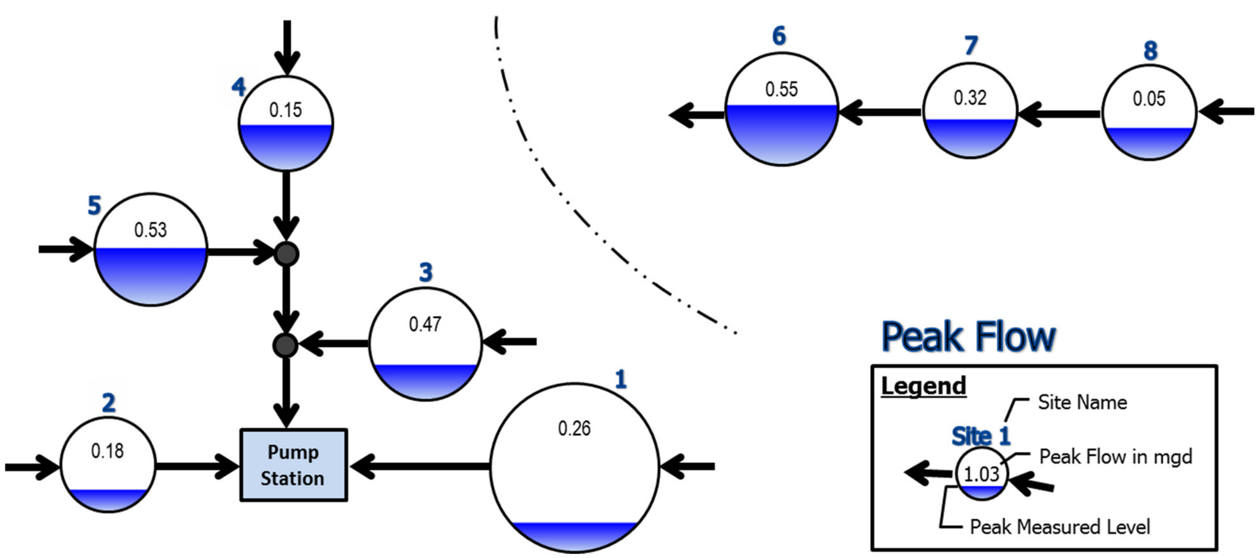

Figure 4-2. Wet Weather Flow Schematic

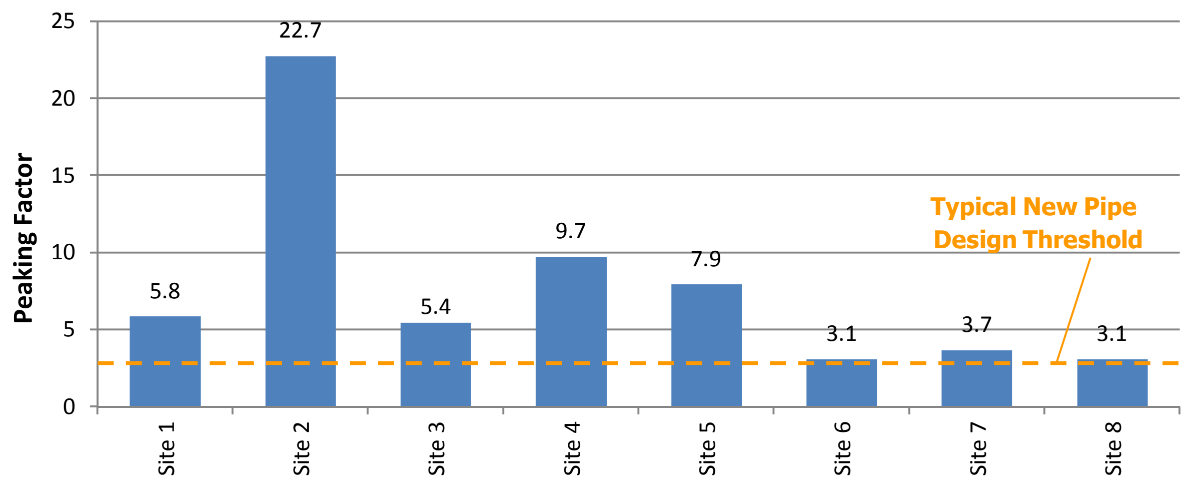

Figure 4-3. Capacity Summary: Peaking Factors

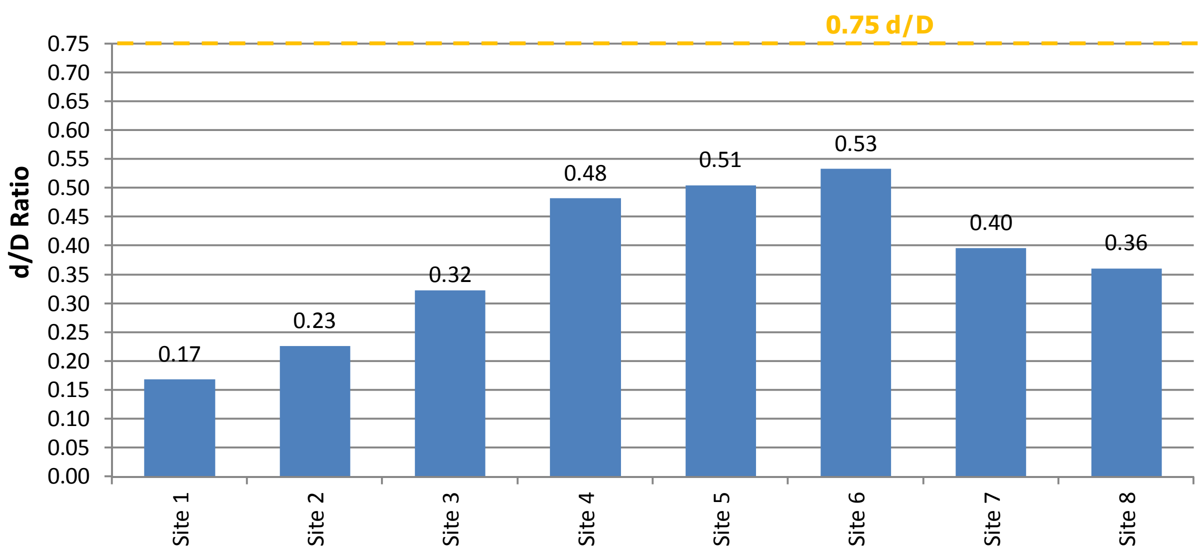

Figure 4-4. Capacity Summary: Max d/D Ratios

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5.0 Inflow and Infiltration Results

5.1 Preface

There are three items noted for the I/I analyses of this study:

- The I/I response to entirety of the rainfall from March 4 to 14 was evaluated for the I/I analyses of this study. Total infiltration was measured to March 20, 2016.
- Rankings: A basin was ranked “High” if it had high I/I factors when normalized by <u>both</u> “per-ADWF” and “per-IDM” methods. A basin was ranked “Medium” if it had high I/I factors for only one of the methods.
- Sites 1, 4 and 5, the I/I receded to baseline levels very slowly; taking up to two weeks after the conclusion of the rainfall event (see Figure 5-1).
- Site 2 has an atypical and non-residential service area resulting in ADWF rates that are low. Since ADWF is used as a divisor for the “per-ADWF” normalization method, the low Site 2 ADWF results in a potentially exaggerated Site 2 I/I result. Site 2 results I/I analyses should be reviewed with this in mind; the “per-IDM” normalization method should have stronger weighting for Site 2.

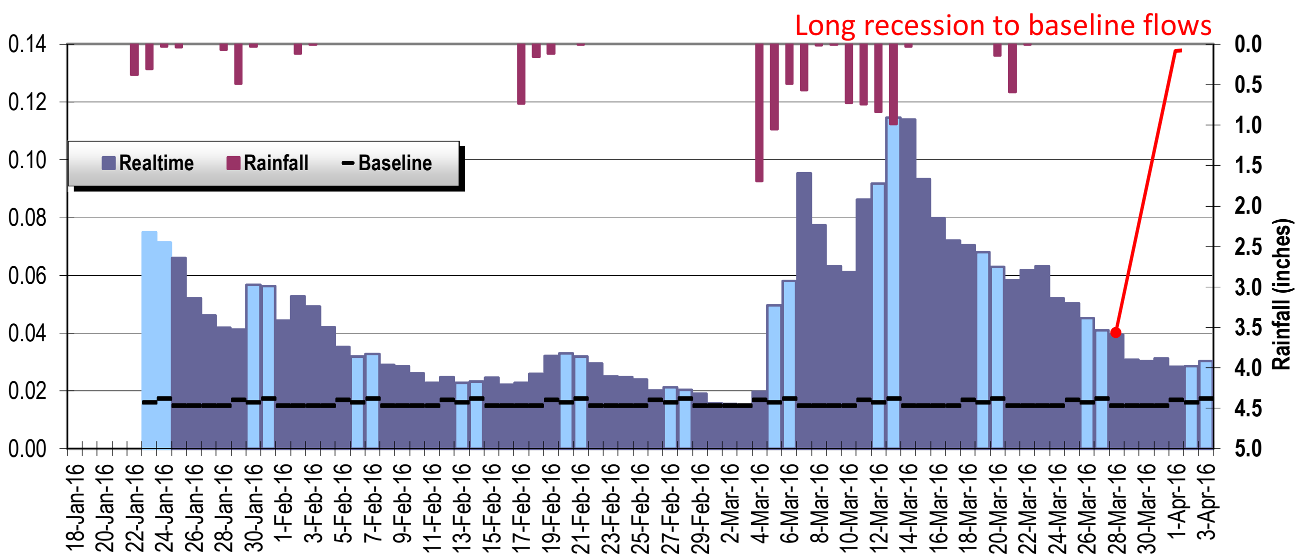


Figure 5-1. Daily Rainfall and Average Flow, Site 4

5.2 Inflow Results Summary

Inflow is storm water discharged into the sewer system through direct connections such as downspouts, area drains, cross-connections to catch basins, etc. These sources transport rain water directly into the sewer system and the corresponding flow rates are tied closely to the intensity of the storm. This component of I/I often causes a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows.

Table 5-1 summarizes the peak measured I/I flows and inflow analysis results. Results that are above relative system normals have been shaded in RED.

Table 5-1. Inflow Analysis Summary

Monitoring Basin	ADWF (mgd)	Peak I/I Rate (mgd)	Peak I/I per IDM (gpd/IDM)	Peak I/I per ADWF	INFLOW Ranking
Basin 1	0.044	0.18	7,900	4.1	Medium
Basin 2	0.008	0.18	6,500	21.8	High
Basin 3	0.086	0.35	8,300	4.1	Medium
Basin 4	0.016	0.12	5,400	7.7	Medium
Basin 5	0.067	0.44	7,300	6.5	High
Basin 6	0.169	0.10	2,000	1.2	Low
Basin 7	0.084	0.12	3,100	1.8	Low
Basin 8	0.017	0.031	4,200	1.8	Low

The following inflow analysis results are noted:

- Basins 2 and 5 had high normalized inflow contribution for both normalization methods.
  - **Site 2:** Also noted in the capacity analysis, it is interesting that often the spikes of inflow occur a couple hours removed from the actual rainfall event (note Feb 18). The inflow may be gathered into a holding area (wet well, tank, etc.) and then pumped into the sanitary sewer system. Also, the ADWF of Site 2 was very low, potentially exaggerating the significance of the Peak I/I normalized by ADWF; thus, it is useful to also normalize by IDM - one notices the Peak I/I is less exaggerated.
- Basins 1, 3 and 4 had high normalized inflow contribution for one of the normalization methods.

Figure 5-2 shows bar graph summaries of the inflow analyses.

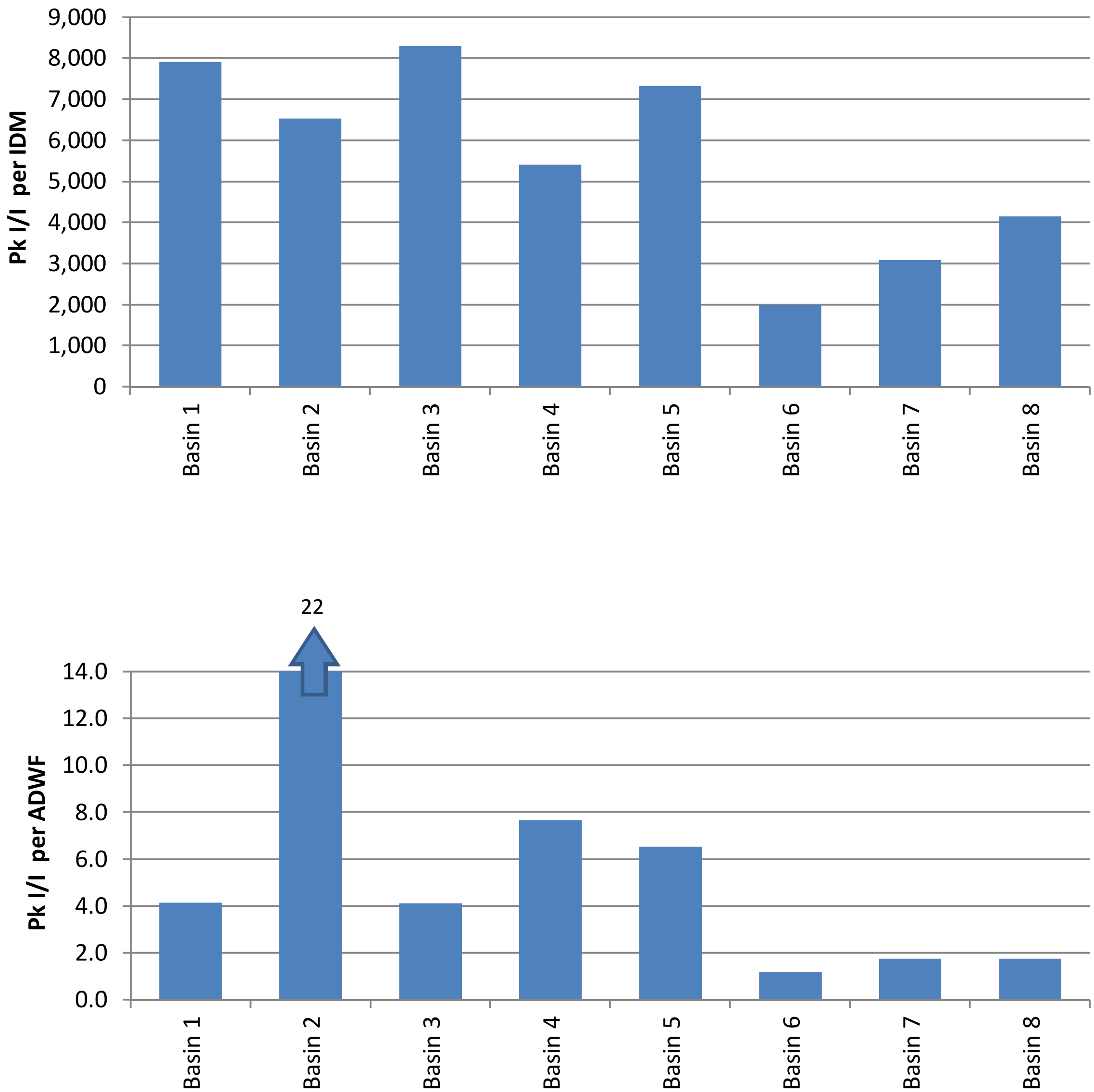


Figure 5-2. Bar Graph: Inflow Analysis Summary

5.3 RDI Results Summary

Infiltration is defined as water entering the sanitary sewer system through defects in pipes, pipe joints, and manhole walls, which may include cracks, offset joints, root intrusion points, and broken pipes. Increased flows into the sanitary sewer system are usually tied to groundwater levels and soil saturation levels. Infiltration sources transport rain water into the system *indirectly*; flow levels in the sanitary system increase gradually, are typically sustained for a period after rainfall has stopped, and then gradually drop off as soils become less saturated and as groundwater levels recede to normal. Infiltration typically creates long-term annual volumetric problems. The major impact is the cost of pumping and treating the additional volume of water, and of paying for treatment (for municipalities that are billed strictly on flow volume).

For this study, the RDI rate used for comparative analysis was measured as the average I/I rate from March 15 at 0:00 midnight to March 17 at 0:00 midnight (approximately 24 hours after the conclusion of the March 14 rain event). Figure 5-3 illustrates this for Site 5.

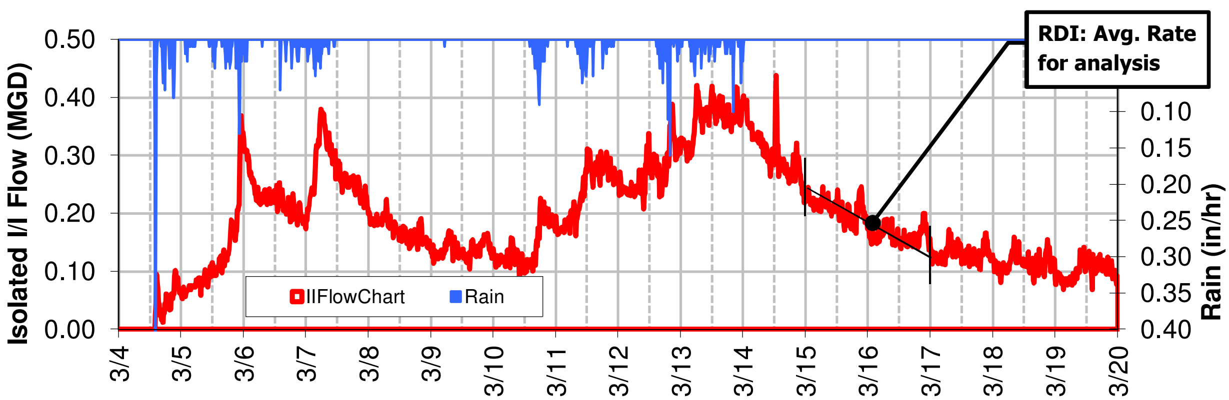


Figure 5-3. RDI Measurement, Site 5

Table 5-2 summarizes the calculated RDI flow rates. Results that are above relative system normals have been shaded in RED.

Table 5-2. Basins RDI Analysis Summary

Metering Basin	ADWF (mgd)	RDI Rate (mgd)	RDI per IDM (gpd/IDM)	RDI per ADWF	RDI Ranking
Basin 1	0.044	0.077	3,373	1.8	Medium
Basin 2	0.008	0.044	1,640	5.5	Medium
Basin 3	0.086	0.089	2,083	1.0	Low
Basin 4	0.016	0.071	3,206	4.5	High
Basin 5	0.067	0.185	3,098	2.8	High
Basin 6	0.169	0.013	1,298	0.2	Low
Basin 7	0.084	0.054	1,378	0.8	Low
Basin 8	0.017	0.001	72	0.0	Low

The following RDI analysis results are noted:

- Basins 4 and 5 had high normalized RDI contribution for both normalization methods and were given an RDI ranking of "High".
- Basins 1 and 2 had high normalized RDI contribution for one of the normalization methods and were given an RDI ranking of "Medium".

Figure 5-4 shows bar graph summaries of the RDI analyses.

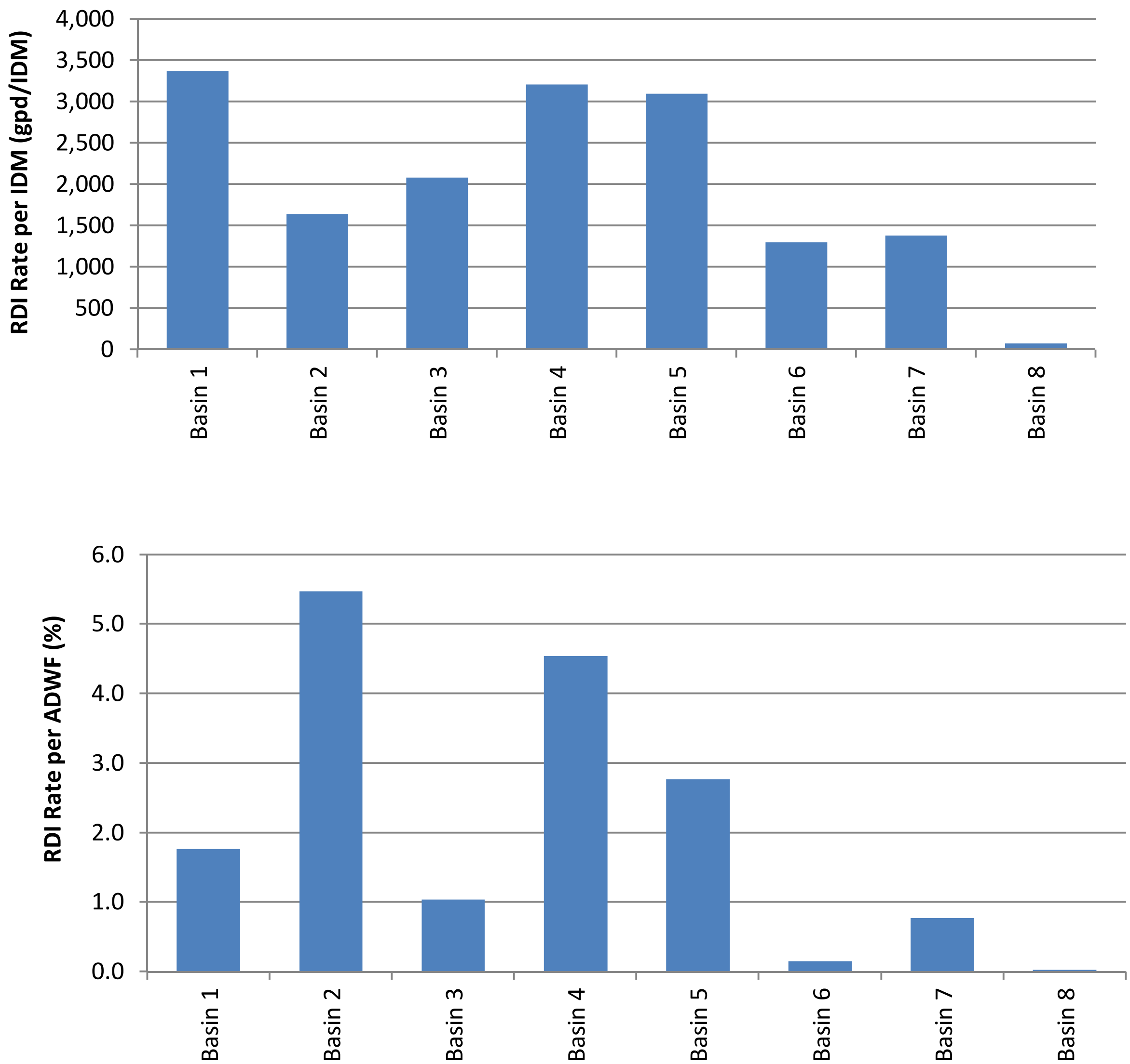


Figure 5-4. Bar Graphs: RDI Analysis Summary

5.4 Groundwater Infiltration Results Summary

Dry weather (ADWF) flow can be expected to have a predictable diurnal flow pattern. While each site is unique, experience has shown that, given a reasonable volume of flow and typical loading conditions, the daily flows fall into a predictable range when compared to the daily average flow. If a site has a large percentage of groundwater infiltration occurring during the periods of dry weather flow measurement, the amplitudes of the peak and low flows will be dampened[5]. Figure 5-5 shows a sample of two flow monitoring sites, both with nearly the same average daily flow, but with considerably different peak and low flows. In this *sample* case, Site B1 may have a considerable volume of groundwater infiltration.

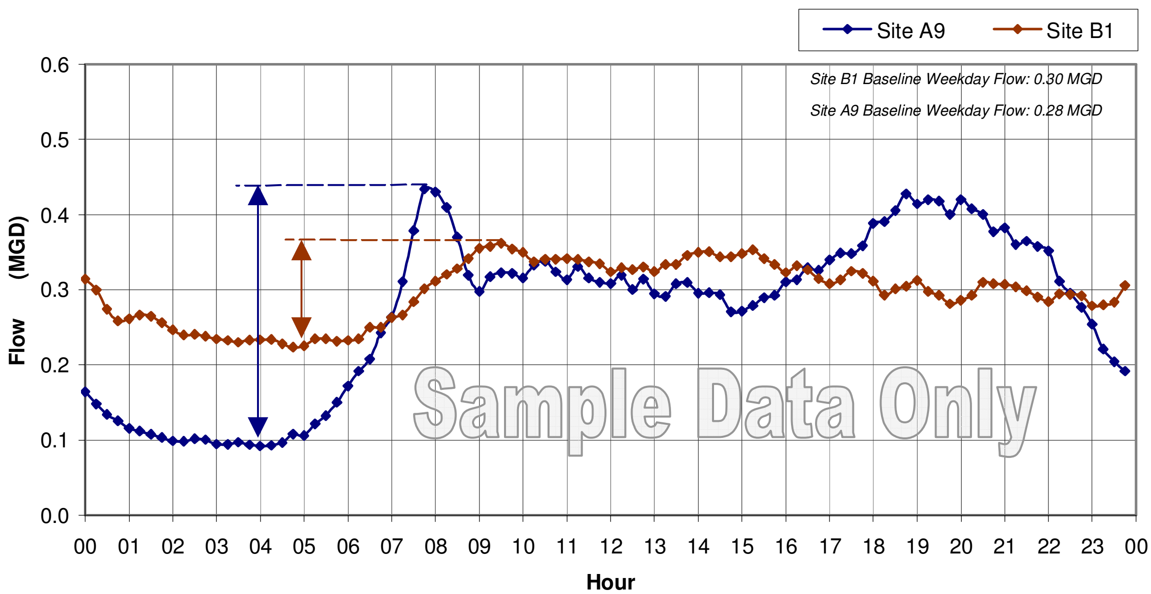


Figure 5-5. Groundwater Infiltration Sample Figure

It can be useful to compare the low-to-ADWF flow ratios for the flow metering sites. A site with abnormal ratios, and with no other reasons to suspect abnormal flow patterns (such as proximity to a pump station, treatment facilities, etc.), has a possibility of higher levels of groundwater infiltration in comparison to the rest of the collection system.

Figure 5-6 plots the low-to-ADWF flow ratios against the ADWF flows for the basins monitored during this study. The brown dashed line shows "typical" low-to-ADWF ratios per the Water Environment Federation (WEF)[6].

[5] In an extreme case, perhaps 0.2 mgd of ADWF flow and 2.0 mgd of groundwater infiltration, the peaks and lows would be barely recognizable; the ADWF flow would be nearly a straight line.
[6] WEF Manual of Practice No. 9, "Design and Construction of Sanitary and Storm Sewers."

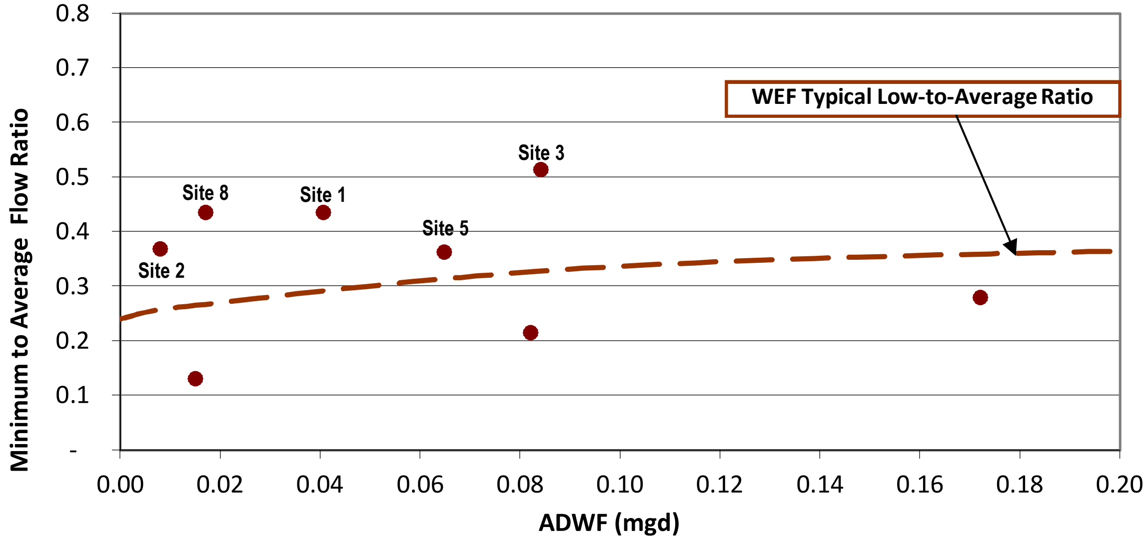


Figure 5-6. Minimum Flow Ratios vs. ADWF[7]

The graph suggests that GWI in the basins upstream from Sites 1, 2, 3, 5 and 8 above typical groundwater infiltration standards (as set forth by WEF). Site 2 is disregarded due to an atypical (non-residential) service area. Table 5-3 summarizes excess GWI that, if removed, would bring the above sites to within typical WEF Low-to-Average Ratios.

Table 5-3. Excess GWI per WEF

Metering Site	Excess GWI (mgd)	Excess GWI (gpm)
Site 1	0.008	5.6
Site 3	0.024	17
Site 5	0.004	3.0
Site 8	0.004	2.7

The following GWI results are noted:

- With the exception of Site 3, the rates of excess GWI are relatively low.
- A stream resides in Basin 3 and could be the source of groundwater infiltration.

[7] Due to attenuation, it should be expected that sites with larger flow volumes should not have quite the peak-to-average and low-to-average flow ratios as sites with lesser flow volumes, which is why the WEF typical trend lines slope closer to 1.0 as the ADWF increases, as shown in the figure.

5.5 Combined I/I Results Summary

Combined I/I analysis considers the totalized volume (in gallons) of both inflow and rainfall-dependent infiltration over the course of a storm event. Table 5-4 summarizes the combined I/I flow results for the entire storm of March 4 to 14, 2016. Results that are above relative system normals have been shaded in RED.

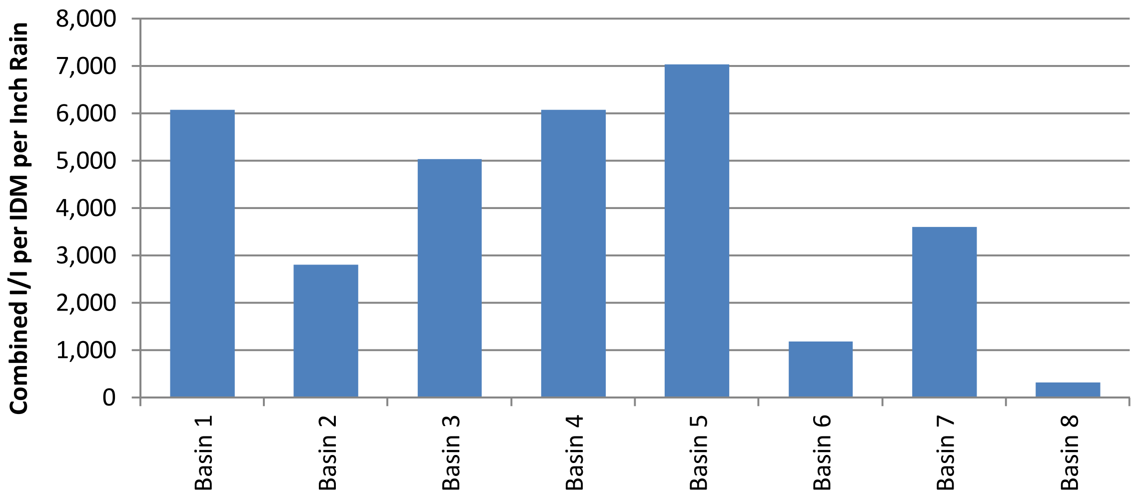
Table 5-4. Basins Combined I/I Analysis Summary

Metering Basin	ADWF (mgd)	Combined I/I (gallons)	Combined I/I per IDM per Inch Rain	Combined I/I per ADWF per Inch Rain	Combined I/I Rank
Basin 1	0.044	987,000	6,100	3.2	Medium
Basin 2	0.008	536,000	2,800	9.4	Medium
Basin 3	0.086	1,524,000	5,000	2.5	Medium
Basin 4	0.016	963,000	6,100	8.6	High
Basin 5	0.067	2,990,000	7,000	6.3	High
Basin 6	0.169	316,000	1,200	0.7	Low
Basin 7	0.084	722,000	3,600	2.0	Low
Basin 8	0.017	12,000	300	0.1	Low

The following combined I/I analysis are noted:

- Basins 4 and 5 had high normalized total I/I contribution for both normalization methods and were given a total I/I ranking of “High”.
- Basins 1, 2 and 3 had high normalized total I/I contribution for one of the normalization methods and were given a total I/I ranking of “Medium”.

Figure 5-7 shows bar graph summaries of the combined I/I analysis.



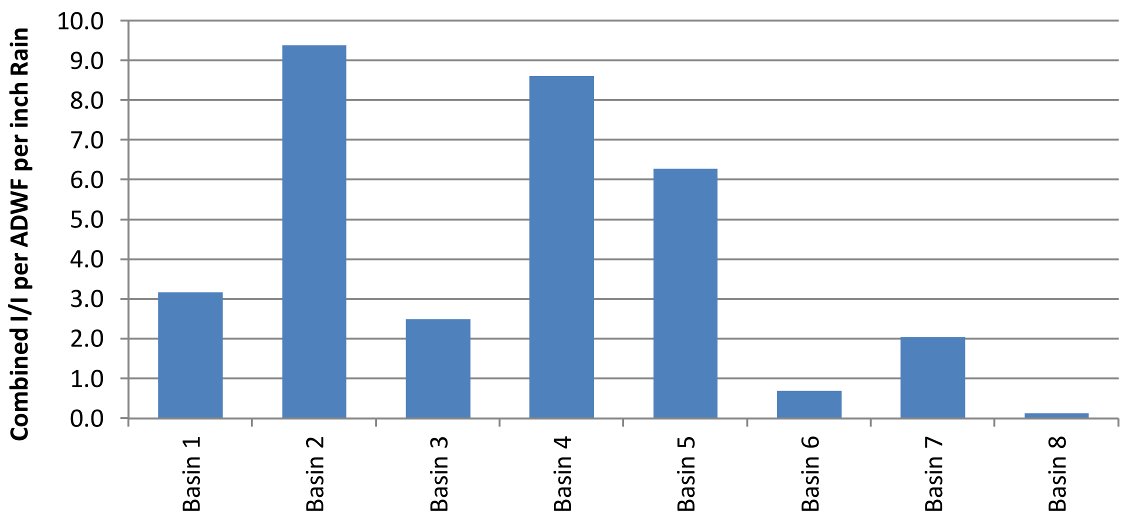


Figure 5-7. Bar Graphs: Combined I/I Analysis Summary

5.6 I/I Results Summary

Table 5-5 summarizes the flow monitoring and I/I results for the flow monitoring sites that were monitored during this study. I/I analyses were for conducted for the March 4 – 14 rainfall event. A basin was ranked "high" if it had high I/I factors when normalized by both "per-ADWF" and "per-IDM" methods. A basin was ranked "medium" if it had high I/I factors for one of the methods. Please refer to the *I/I Methods* section for more information on inflow and infiltration analysis methods and ranking methods.

Table 5-5. I/I Analyses Results Summary

Metering Basin	ADWF (mgd)	Peak I/I Rate (mgd)	Combined I/I (gallons)	Peak I/I Ranking	RDI Ranking	High GWI?	Combined I/I Rank
Basin 1	0.044	0.18	987,000	Medium	Medium	Low	Medium
Basin 2	0.008	0.18	536,000	High	Medium	N/A [A]	Medium
Basin 3	0.086	0.35	1,524,000	Medium	Low	High	Medium
Basin 4	0.016	0.12	963,000	Medium	High	None	High
Basin 5	0.067	0.44	2,990,000	High	High	Low	High
Basin 6	0.169	0.10	316,000	Low	Low	None	Low
Basin 7	0.084	0.12	722,000	Low	Low	None	Low
Basin 8	0.017	0.031	12,000	Low	Low	Low	Low

[A] Evidence that basin is a commercial/ industrial area and does not follow typical residential trends.

The following inflow/infiltration analysis results are noted:

- **Basin 5** was ranked "High" for all inflow/infiltration components except for groundwater infiltration.
- **Basins 3 and 4** also had strong inflow and infiltration rankings in all more most I/I categories. Basin 3 had the largest groundwater infiltration component.

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6.0 MODEL DESIGN STORM RESULTS

6.1 Synthetic I/I Hydrograph Development

In order to model the I/I response to the provided rainfall event, synthetic hydrographs were developed to approximate the actual RDI hydrograph shape in terms of the time to the peak and the recession coefficient. The actual RDI hydrograph was best matched with a synthetic hydrograph by separating the synthetic hydrograph into seven volume components (R1 through R7). The seven components represent different response times to the rainfall event and, therefore, different infiltration or inflow paths into the sewer system. R1 is characterized by a short response time (inflow) and R7 represents slower response and longer recession times (RDI). Levels of soil saturation are also considered. Using synthetic hydrograph analysis, appropriate time and recession parameters were estimated by a trial-and-error procedure until a good match was obtained. For example, the hydrograph and its component hydrographs for Site 5 is shown in Figure 6-1.

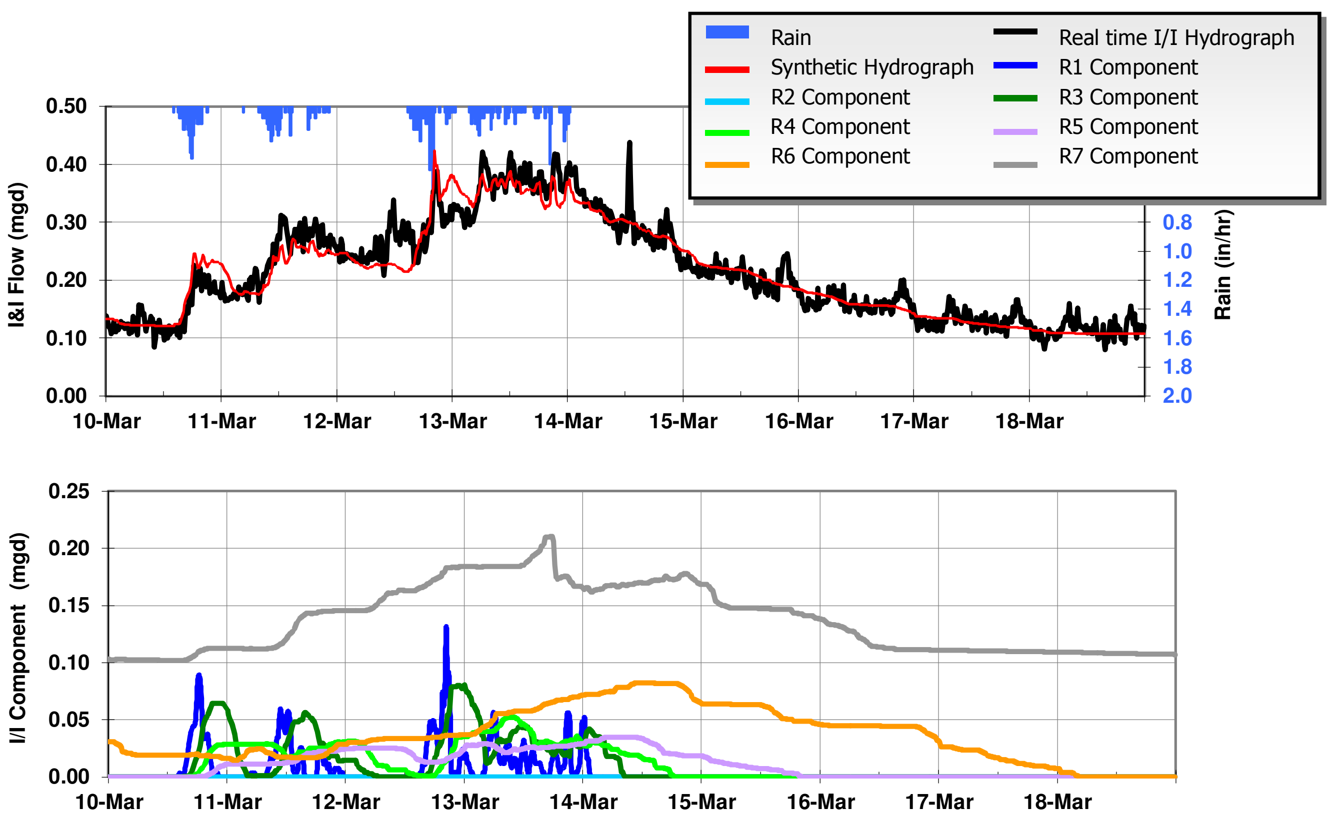

Figure 6-1. Synthetic Hydrograph Development (Site 5)

6.2 Design Storm Development

With the I/I response modeled by a synthetic hydrograph, design storms can be applied. This serves two functions: (a) predicted flows are based on the same storm event and are therefore normalized to each other, making for easier and better comparisons, and (b) the resulting I/I flows can be predicted for a design storm event. This helps to calibrate modeling efforts that will determine if the collection system has adequate capacity to handle very large storm events.

V&A used a 10-year, 24-hour design storm for this analysis. Storm events were taken from the NOAA Precipitation-Frequency Atlas of the Western United States. For example, Figure 6-2 summarizes the design storm magnitude and profile at Rain Gauge North. The 10-year, 24-hour design storm was developed for each flow monitoring site by taking data from the three rain gauges and using the inverse distance weighting (IDW) method. This particular profile distribution also fits the NOAA criterion for 2-hour and 6-hour durations, in addition to the 24-hour duration.

10-Year, 24-hour Design Storm	
Hour	**Inches of Rain**
1	0.009
2	0.023
3	0.234
4	0.140
5	0.047
6	0.014
7	0.201
8	0.115
9	0.161
10	0.057
11	0.029
12	0.011
13	0.118
14	0.331
15	0.039
16	0.125
17	0.125
18	0.327
19	0.607
20	0.250
21	0.125
22	0.095
23	0.158
24	0.047
Total:	**3.39**

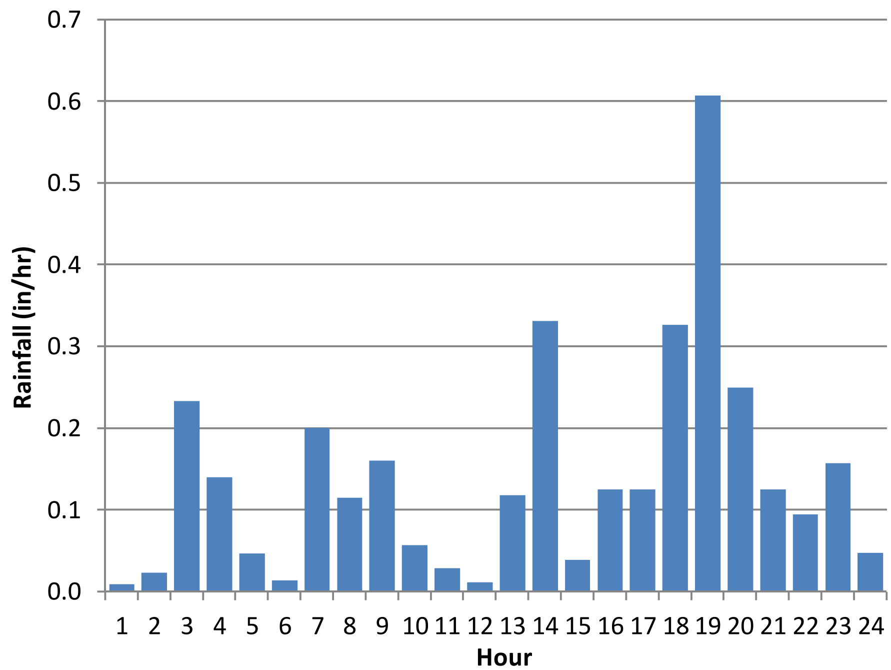

Figure 6-2. 10-Year, 24-Hour Design Storm Values and Profile

6.3 Design Storm Response Summary

The 10-year, 24-hour storm event was applied to the synthetic I/I hydrograph components developed for each flow monitoring site. This method produces the best estimated response to the design storm events. These results assume full ground saturation, and the peak I/I flows from the design storm coincide with peak sanitary flows to get a "worst-case" scenario of peak wet weather flows.

Table 6-1 summarizes the final results for each design storm on a site-by-site basis.

Table 6-1. Design Storm I/I Analysis Summary

Monitoring Site	Peak Dry Weather Flow (mgd)	Peak I/I Rate (mgd)	Peak Flow (mgd)
Site 1	0.127	0.224	0.351
Site 2	0.016	0.328	0.344
Site 3	0.158	0.550	0.708
Site 4	0.039	0.097	0.136
Site 5	0.127	0.599	0.726
Site 6	0.394	0.385	0.779
Site 7	0.161	0.278	0.439
Site 8	0.038	0.070	0.108

Note: It is possible that the peak flow rates predicted for a design storm event cannot be conveyed due to conveyance capacity limitations of the local collection system. A comprehensive dynamic model is required to determine the locations of the capacity issues and methods for relieving capacity.

Figure 6-3 shows the synthetic hydrograph response for the design storm event at Site 5.

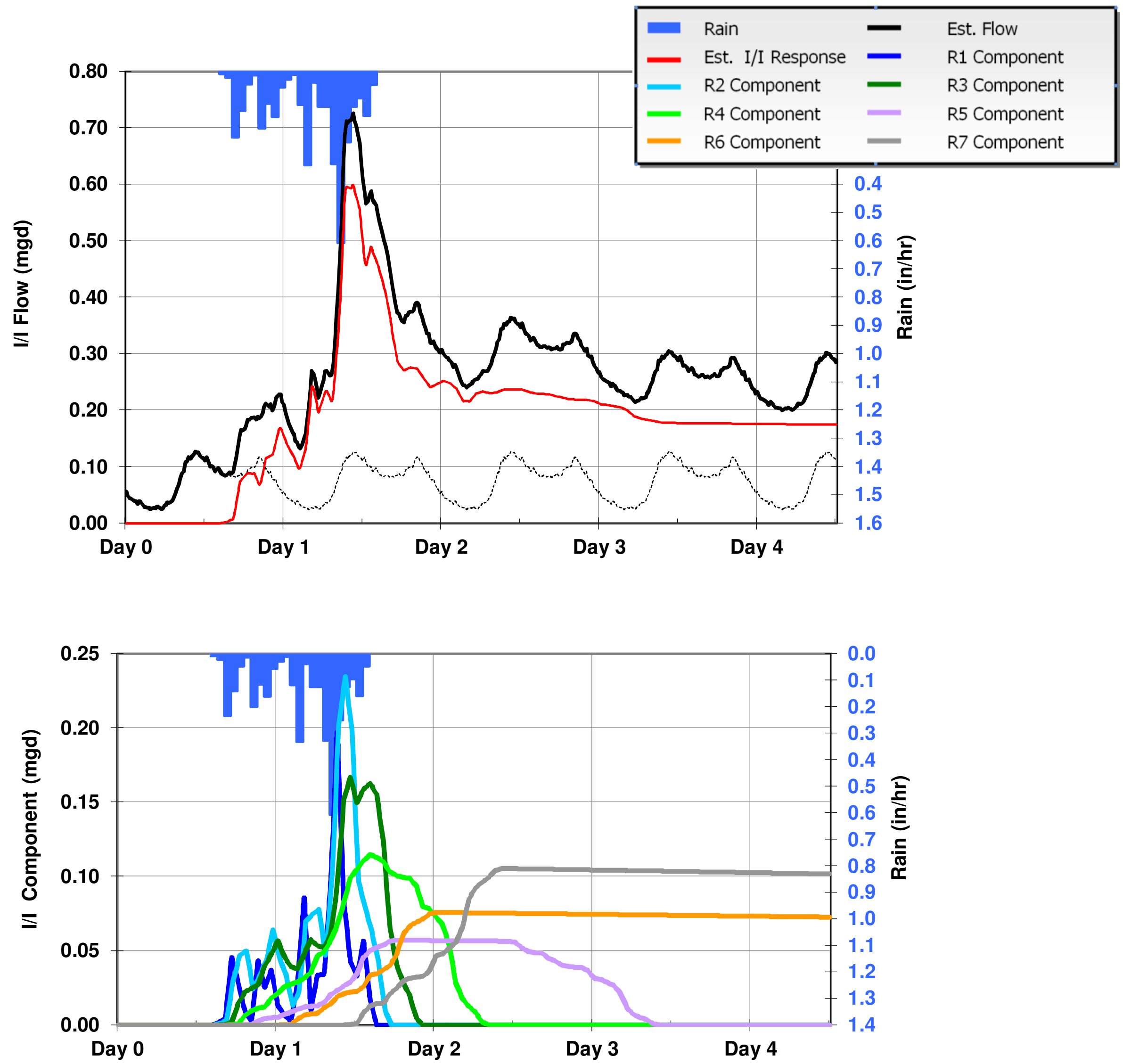

Figure 6-3. 10-Year, 24-Hour Design Storm: Estimated I/I Response at Site 5

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7.0 RECOMMENDATIONS

V&A advises that future I/I reduction plans consider the following recommendations:

1. **Determine I/I Reduction Program:** The City should examine its I/I reduction needs to determine a future I/I reduction program.
    a. If peak flows, sanitary sewer overflows, and pipeline capacity issues are of greater concern, then priority can be given to investigate and reduce sources of inflow within the basins with the greatest inflow problems.
    b. If total infiltration and general pipeline deterioration are of greater concern, then the program can be weighted to investigate and reduce sources of infiltration within the basins with the greatest infiltration problems.
2. **Basins 3, 4 and 5:** On an I/I contribution basis, the City should focus future I/I reduction efforts within Basins 3, 4 and 5, though it is noted that Basins 1 and 2 also had significant I/I contribution:
    a. Basins 3, 4 and 5 all ranked in the upper ranges of the system for normalized inflow, RDI and combined I/I contributions. Basin 3 also had higher than typical GWI rates.
3. **I/I Investigation Methods:** Potential I/I investigation methods include the following:
    a. Smoke testing: This method is typically used to locate inflow sources.
    b. CCTV inspection: This method is typically used to locate condition assessment defects linked to infiltration sources. This would need to take place immediately after a strong rainfall event when groundwater levels are high so as to try and capture the infiltration "in the act".
    c. Mini-basin flow monitoring: This method can be used to isolate smaller catchment areas in which to locate infiltration and inflow sources. This may be the most prudent course of action to try and better isolate the areas within Basins 3, 4 and 5 where the I/I is originating.
    d. Nighttime reconnaissance work to (1) investigate and determine direct point sources of inflow and (2) determine the areas and pipe reaches responsible for high levels of infiltration contribution.
4. **I/I Reduction Cost-Effectiveness Analysis:** The City may wish to conduct a study to determine which is more cost-effective: (1) locating the sources of inflow and infiltration and systematically rehabilitating or replacing the faulty pipelines or (2) continued treatment of the additional rainfall-dependent I/I flow.