Stormwater Collection System Modeling Report

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PRESENTED TO

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EXECUTIVE SUMMARY

In December 2012, the Michigan legislature authorized the SAW Grant program to provide funding for planning and design services for stormwater management, sanitary sewers, and wastewater treatment and the development or enhancement of an asset management program (AMP). In 2017, the City of Grand Rapids was awarded funding through the SAW Grant program to create, calibrate, and simulate a numerical model of its stormwater collection system among other tasks. As part of the project, Tetra Tech coordinated data collection of flow and rainfall data, including a radar-rainfall dataset, and an impervious cover analysis, built and calibrated the model, and performed a capacity analysis. The purpose of this report is to document the modeling approach and the capacity analysis results.

Introduction

The City of Grand Rapids is 45 square miles in size and has more than 500 miles of stormwater conveyance infrastructure, including both storm sewers and channels, which discharge to the Grand River or one of its tributaries. The City operates nine stormwater pump stations, six of which are located along the Grand River to remove water from the collection system when the Grand River stage exceeds the elevation of the storm sewer. There are also eight large stormwater control facilities providing detention and/or infiltration within the City that are owned by the City or Kent County and numerous smaller stormwater control and green infrastructure facilities.

Flow and Rainfall Monitoring

Flow meters were installed at 71 locations in the storm sewer collection system, of which 63 were used for calibration of the model. The meters measured flow rate, velocity, and depth collected in 5-minute increments.

The City operates a network of 14 rain gauges, which record rainfall in 5-minute increments. The ground-based rain gauge data were not used directly in the model but, along with four other public rain gauges in the area, were used to develop a radar rainfall dataset for calibration.

During the May 1 through October 31, 2018 flow monitoring period, there were 21 rainfall events in which the rainfall across the City (as measured at the City's rain gauges) exceeded 0.25 inches. These rainfall events provided the data for the model calibration. Smaller rainfalls occurred during the monitoring period but were not used for model calibration. Some of the more significant rainfalls included:

- August 26, which was between the 5- and 100-year rainfall citywide and had an embedded peak hour rainfall of up to the 2-year event.
- September 2, up to the 2-year total rainfall and 25-year peak hour rainfall in some areas
- September 20, up to the 5-year total rainfall in some areas
- September 29, up to the 5-year total rainfall in some areas

Impervious Cover Analysis

An impervious cover analysis (ICA) defining the locations and types of impervious areas was created for the entire City. The types of impervious areas that are uniquely defined in the ICA dataset include: alleys, buildings (roofs), driveways, parking lots, patios/decks, railroads, roads, and sidewalks. The impervious cover analysis was used to define the imperviousness of each modeled subcatchment.

Model Development

The modeled collection system was imported from the City's stormwater collection system geodatabase. The entire collection system is contained in the model, but primarily only sewers that are 30 inches in diameter or larger are actively modeled, meaning that they have simulation results. The active portion of the model includes approximately 616,000 feet (117 miles) of storm sewer and channels, representing approximately 21 percent of the total length of the collection system.

The model also includes stormwater pump stations and stormwater detention or infiltration facilities that are downstream of sewers 30 inches in diameter or larger. Design or record drawings provide the basis for the representation of the pump stations and stormwater storage facilities. The model includes pump curves and controls provided by the City.

Rating curves were developed using data from USGS gauging stations to estimate the river stage during the flow monitoring period at each outfall along the Grand River and Plaster Creek.

Calibration and Validation

Calibration is the systematic process of adjusting the model inputs, so the model flow volume, rate, and depth reasonably match the measured data. For this project, the calibration used both manual and automated processes. Approximately 650,000 simulations were completed during the model calibration.

The quality of the calibration was evaluated using guidance based on the Wastewater Planning Users Group (WaPUG) *Code of Practice for the Hydraulic Modelling of Sewer Systems* (November 2002). While it is common in model calibration for individual data points to fall outside of the calibration tolerances, the average trend lines should be within the calibration tolerances. For this model, all the peak flow rate and volume trends are within one and seven percent, respectively, of a perfect calibration and 94 percent of the depth data points fall within the calibration tolerance. Therefore, the model represents the measured peak flow rate, volume, and depth well. Fifty-seven (57) and 58 percent of all individual calibration and validation data points for the peak flow rate and volume, respectively, fall within the calibration tolerances.

Five of the rainfall events during the monitoring period were withheld from the calibration to be used as validation events. Validation events are independent of the calibration and are used to demonstrate the validity of the model. Forty-eight (48) and 42 percent of the peak flow rate and volume validation events, respectively, fall within the calibration tolerance. There is not a specific standard that defines the percentage of validation events that should fall within the calibration tolerance, but since the validation events were not specifically calibrated, it is expected that a lower percentage of the validation events would fall within the calibration tolerance when compared to the calibration events.

Capacity Analysis

A capacity analysis compares projected flow rates, volumes, and hydraulic grade line elevations to the City's targeted level of service. The capacity analysis was completed for the 10-year, 24-hour design storm (3.83 inches) and a long-term simulation, including 53 years of hourly rainfall records from the NOAA rain gauge at Gerald R. Ford International Airport. Storm sewers, channels, pump stations, and detention facilities were evaluated as part of the capacity analysis.

The model predicted:

- Approximately five percent of the modeled manholes flooded more than five minutes during the 10-year, 24-hour design storm. The duration of the flooding varied widely with the longest duration of flooding at any manhole during any event being 9 hours.
- Approximately three percent of the modeled manholes were projected to flood more than five times during the long-term simulation, exceeding an average of once every 10 years.
- Five of the seven modeled pump stations meet the targeted level of service. The Indian Mill and Ken-O-Sha Pump Stations did not meet the targeted level of service. The Indian Mill Pump Station firm capacity is exceeded six times in the long-term simulation, which exceeds the frequency in the targeted level of service by one event. The Ken-O-Sha pump station firm capacity is exceeded five times per year, on average, during the long-term simulation, which is well in excess of the targeted level of service.

- All of the modeled detention basins meet the LOS. In fact, some of the facilities may be underutilized and could be used to store more water.

The most significant projected capacity restrictions include:

- Storm sewer reaches that are projected to flood at several manholes during the 10-year, 24-hour design storm and flood more frequently than five times during the long-term simulation, including:
  - The Palmer Separation Drain from Monroe Avenue to Ball Avenue.
  - The area within the flood hazard area behind the floodwall on the west side of the Grand River. In this area, it appears that the projected flooding is caused more by the river stage than the sewer capacity.
  - The 21- to 30-inch sewer along Plainfield Avenue between Quimby and Coldbrook Streets.
  - The 30- to 60-inch sewer along Graceland Street between Monroe and Plainfield Avenues.
  - One segment of the South Branch of Coldbrook Creek from Michigan Street to the main branch of Coldbrook Creek and the 30- to 36-inch sewer along Michigan Street between Fuller and Ball Avenues.
  - The 36-inch sewer discharging to Silver Creek at Blaine Avenue from Silver Creek to Burton Street.
  - A local low point at the intersection of College Avenue and Burton Street and along the 30- to 36-inch sewer along Eastern Avenue between Winchell and Burton Streets.
  - The 24- to 30-inch sewer along Eastern Avenue between Everglade and Mayhew Wood Drives.
  - West Leonard Drain (24- to 30-inch sewer) in multiple locations from Leonard Street to Indian Mill Creek.
- Ken-O-Sha Pump Station
- Culverts projected to flow under pressure during the design storm, including:
  - 30-inch circular culvert conveying Carrier Creek under the Carrier Creek Trail connecting Union Street between Hubert and Cedar Streets.
  - 30-inch circular culvert on Laraway Brooklyn Drain, on the west side of MacKay-Jaycees Park east of the intersection of Brooklyn Avenue and Walsh Street.

Recommendations

The recommendations are divided into categories to group similar types of recommendations.

Model maintenance recommendations:

- Maintain a master version of the model to provide to City staff and consultants for future projects
- Update the model annually and document the changes

Model improvement recommendations to the current active model extents:

- Update the City's GIS data to be compatible with modeling needs.
- Measure the dimensions of the weir downstream of Fisk Lake and add weir detail to the model.
- Collect additional survey cross-sections of channels in 300- to 500-foot intervals, except near culverts and inlet and outlet structures, which should have cross-sections within 50 feet of the culvert or structure.

Data collection recommendations in areas outside the current active model extents or as part of a City-wide effort:

- Conduct flow monitoring in areas that were not metered in 2018.
- Complete quality check measurements of the flow monitoring data as it is collected.
- Collect data for a high-resolution ground surface.

- Conduct flow monitoring to more accurately measure base flows at locations where water quality assessments are made.
- Supplement the impervious cover analysis with a pervious cover analysis to define the types of pervious cover, such as lawns, open park or recreational areas, and wooded areas.

Future modeling recommendations:

- Add detail to the model for smaller diameter sewers as necessary. Flow monitoring may be necessary to calibrate those areas if they are not upstream of meters used in the 2018 flow monitoring program.
- Add 2D model functionality in areas prone to overland flow, especially where the overland flow is outside the street. Inlet (catch basin) capacity should be added to the model with the 2D model functionality.

Infrastructure recommendations:

- Develop alternatives for the areas projected to have capacity limitations and add the infrastructure improvements to the City's infrastructure planning documents for prioritization.
- Evaluate Indian Mill and Ken-O-Sha Pump Station in more detail to assess whether or not the frequency at which the firm capacity is projected to be exceeded would cause upstream flooding more than the frequency set in targeted level of service.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEFINITIONS

Term	Definition
AMP	Asset Management Program
cfs	cubic feet per second
GARR	ground adjusted radar rainfall
ICA	impervious cover analysis
LOS	level of service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
SWMM	Storm Water Management Model
WaPUG	Wastewater Planning Users Group

1.0 INTRODUCTION

In December 2012, the Michigan legislature authorized the SAW Grant program to provide funding for planning and design services for stormwater management, sanitary sewers, and wastewater treatment, and the development or enhancement of an asset management program (AMP). An AMP is a program that identifies the targeted level of service at the lowest life cycle cost for rehabilitating, repairing, or replacing the assets. The intent of asset management is to ensure long-term sustainability of the collection system by maximizing the life of the City's infrastructure assets through proactive maintenance and financial planning for future repair and replacement expenditures.

In 2017, the City of Grand Rapids was awarded funding through the SAW Grant program to create, calibrate, and simulate a numerical model of its stormwater collection system among other tasks. The City plans to integrate the hydraulic output from the collection system model with condition assessments to prioritize improvements in the collection system and link the data to other models, such as those for the Grand River, to provide a holistic understanding of water volume and quality throughout the City.

The City of Grand Rapids is 45 square miles in size and has more than 500 miles of stormwater conveyance infrastructure, including both storm sewers and channels, which discharge to the Grand River or one of its tributaries. The City operates nine stormwater pump stations, six of which are located along the Grand River to remove water from the collection system when the Grand River stage exceeds the elevation of the storm sewer. There are also eight large stormwater control facilities providing detention and/or infiltration within the City that are owned by the City or Kent County and numerous smaller stormwater control or green infrastructure facilities. ***Figure 1-1*** shows an overview of the stormwater collection system. Details are included in the modeling and GIS datasets.

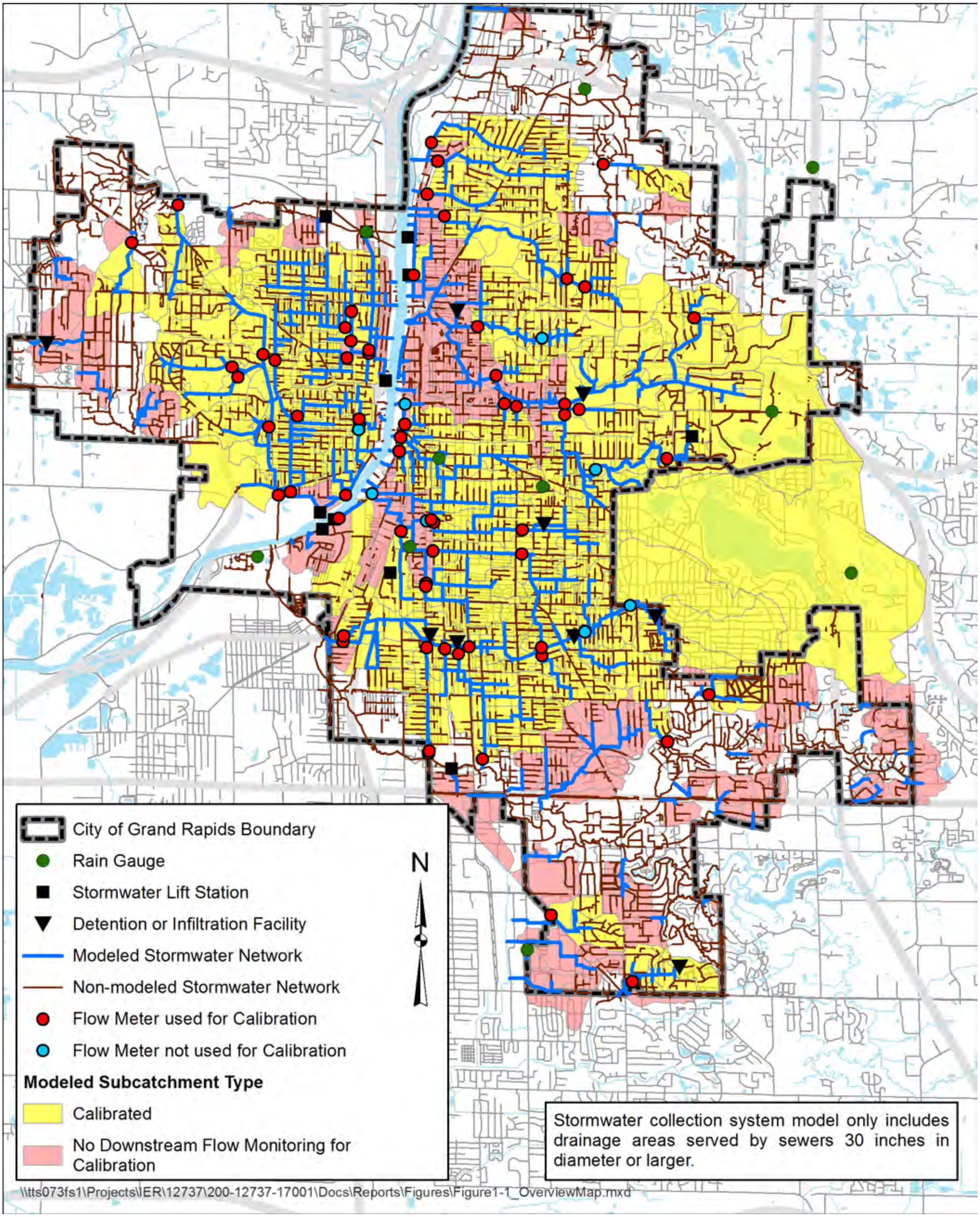
This report is intended to provide guidance to the City regarding the performance of the stormwater collection system based on currently available data. New or more refined information may inform the City to continue to follow, modify, or ignore the recommendations in this study. The purpose of this report is to provide a summary of the approach and results of the collection system modeling. The amount of data is extensive, so data supplemental to the report are provided electronically.

1.1 TASKS

The following tasks related to the collection system modeling were completed as part of this project:

- Flow and rainfall monitoring (as part of a separate contract between the City and another consultant)
- Radar-rainfall development
- Impervious cover analysis
- Model development primarily for the portions of the collection system that are equal to or greater than 30 inches in diameter
- Model calibration and validation
- Capacity analysis
- Report

Figure 1-1. Stormwater Collection System Overview



1.2 ELECTRONIC DATA

Much of the details and supporting data referenced in this report are provided electronically, including the items listed below (software and/or file format are listed in parentheses). File paths relative to the saved location of the report also are provided throughout the report.

- Collection system model input, output, and interface files (InfoSWMM and text files at …\Electronic Data\Hydraulic Model Files)
- GIS geodatabase that includes (…\Electronic Data\Geodatabase):
  - Modeled collection system element input data
  - Modeled collection system output data used for capacity analysis (loaded into geodatabase as a table from CSV file format)
  - Flow monitoring locations
  - Ground-based rain gauges and radar-rainfall grid
  - Impervious cover analysis
  - Surveyed channel cross-section and control points
  - Soil data
- Grand River and Plaster Creek stage rating equations for each outfall (PDF at …\Electronic Data\Monitoring Data\Outfall Boundary Condition Rating Curves)
- Temporary flow monitoring data (Excel at …\Electronic Data\Monitoring Data\Flow Monitoring)
- Ground-based rainfall data (Excel at …\Electronic Data\Monitoring Data\Rainfall\Rain Gauges)
- Maps of the individual flow monitoring locations (PDF at …\Electronic Data\Monitoring Data\Flow Monitoring Maps)
- Stormwater pump station operating status (on or off) and the number of pumps operating (Excel at …\Electronic Data\Monitoring Data\Pump Stations)
- Stormwater pump station performance curves (PDF at …\Electronic Data\Reference Data\Pump Curves)
- Stormwater pump station operating rules (image files at …\Electronic Data\Reference Data\Pump Operating Rules)
- Radar-rainfall data and *Radar Rainfall Analysis Report* prepared by Vieux and Associates (text files and PDF at …\Electronic Data\Monitoring Data\Rainfall\Radar Rainfall)
- Soil parameters (PDF at …\Electronic Data\Reference Data\Soil Data)
- Evaporation data (PDF at …\Electronic Data\Reference Data\Evaporation Data)
- Calibration and validation results (Excel and PDF at …\Electronic Data\Calibration Results)
- Capacity analysis maps for the 10-year, 24-hour design storm and a long-term simulation (PDF at …\Electronic Data\Capacity Analysis\Capacity Maps)
- Hydraulic profiles of a subset of sewers and overview of sewers including in the hydraulic profiles (PDF at …\Electronic Data\Capacity Analysis\Hydraulic Profiles)

2.0 MONITORING

Tetra Tech provided the City with preferred flow monitoring locations. EmNet then installed and maintained the meters for the City as part of a separate contract. The City also provided rainfall data from the City's permanent rain gauge network for use in the development of the radar rainfall. Monitoring was conducted from April through October 2018 for the model calibration data.

2.1 FLOW MONITORING

Flow meters were installed at 71 locations (up to 69 flow meters were installed concurrently). Of the 71 flow meters, 63 were used for calibration. A list of the manholes and pipes in which the flow meters were installed is shown in ***Table 2-1***. The manholes and pipes are listed based on their facility identification in the City's GIS database. The flow meters not used for calibration did not have adequate data to which to calibrate. The monitoring sites were selected to maximize the portion of system that could be calibrated or to provide flow data for specific land use types (e.g., primarily residential, industrial, etc.). ***Figure 1-1*** shows the flow monitoring locations, including those that were not used for calibration. Smaller scale overview and location maps of the individual flow monitoring sites are provided in the electronic data.

Flow rate, velocity, and depth were collected in 5-minute increments.

Supplemental flow monitoring data and relative file paths:

- Flow meter locations in GIS format …\Electronic Data\Geodatabase
- Flow meter locations in PDF format …\Electronic Data\Monitoring Data\Flow Monitoring Maps
- Flow monitoring data in Excel format …\Electronic Data\Monitoring Data\Flow Monitoring Data

Table 2-1. List of Manholes and Sewers in which Flow Meters Installed

Manhole Facility ID	Sewer Facility ID		Manhole Facility ID	Sewer Facility ID		Manhole Facility ID	Sewer Facility ID
6492	9469		438	6476		3506	2724
6547	6512		636	5696		812	1562
1656	8001		3590StormMH	2951		20818	2059359
6203	8712		5753	5176		9301	2202810
3751	4339		44162†	66562		9476	2095813
5017†	6332		118	2096022		5657	8106
4738	3846		5417†	3634		4337	5352
4938	5222		7787	8609		4430	3394
3952	3878		5338	2096241		2199131	6162
3925	577		48962	2203264		2040425	2040895
8392StormMH	11085		6999	6880		72967	106895
5228†	6425		4336	3651		8441	32643
75525	110087		4281	4470		872	3579
5089	103683		5473	8101		41281	2202992
2061493†	2061496		7812	33309		1364	5668
2062088	2062086		2555	6804		1009	3187
2040356	2040819		24033	3736		1013†	3191
2060600	2061053		1149	6681		2058473	2058465
61126StormMH†	91844		1089	6790		8386StormMH	11068
3703	7624		46408	69132		3973	4653
3697	3521		46403	69123		2780†	9853
536	2940		2475	6785		1007	3183
304	294		3437	11096		2061519	2061539
40003	2438		3462	6462			

† Not used for calibration.

2.2 RAINFALL MONITORING

The City operates a network of 14 rain gauges, which are shown in ***Figure 1-1***. Ten (10) of the rain gauges are within the city limits or the modeled drainage areas. Rainfall data are recorded in 5-minute increments. The ground-based rain gauge data were not used directly in the model but, along with four other public rain gauges in the area, were used by Vieux and Associates to develop a ground adjusted radar rainfall (GARR) dataset. GARR data provides a more accurate representation of the temporal and spatial rainfall patterns. The GARR dataset includes a time series rainfall for 250- by 250-meter pixels across the City. For the purposes of the modeling, an area-weighted rainfall for each modeled subcatchment was created. The *Radar Rainfall Analysis Report*, which includes the methodology used to create the GARR dataset and maps and tables of individual rain events, is provided electronically.

During the May 1 through October 31 flow monitoring period, there were 21 rainfall events in which the rainfall across the city (as measured at the City's rain gauges) exceeded 0.25 inches. These rainfall events provided the data for the model calibration. Smaller rainfalls occurred during the monitoring period but were not used for model calibration. ***Table 2-2*** lists the rainfall events, the date on which the rainfall began, the duration of rainfall as it moved across the City (individual rain gauges had shorter rainfall durations than the total duration), and the range of the total and peak hour rainfall. Some of the significant rainfalls include:

- August 26, which was between the 5- and 100-year rainfall citywide and had an embedded peak hour rainfall of up to the 2-year event. The ground-based rainfall and GARR for this event are shown in ***Figure 2-1***.
- September 2, up to the 2-year total rainfall and 25-year peak hour rainfall in some areas
- September 20, up to the 5-year total rainfall in some areas
- September 29, up to the 5-year total rainfall in some areas

Supplemental rainfall monitoring data and relative file paths:

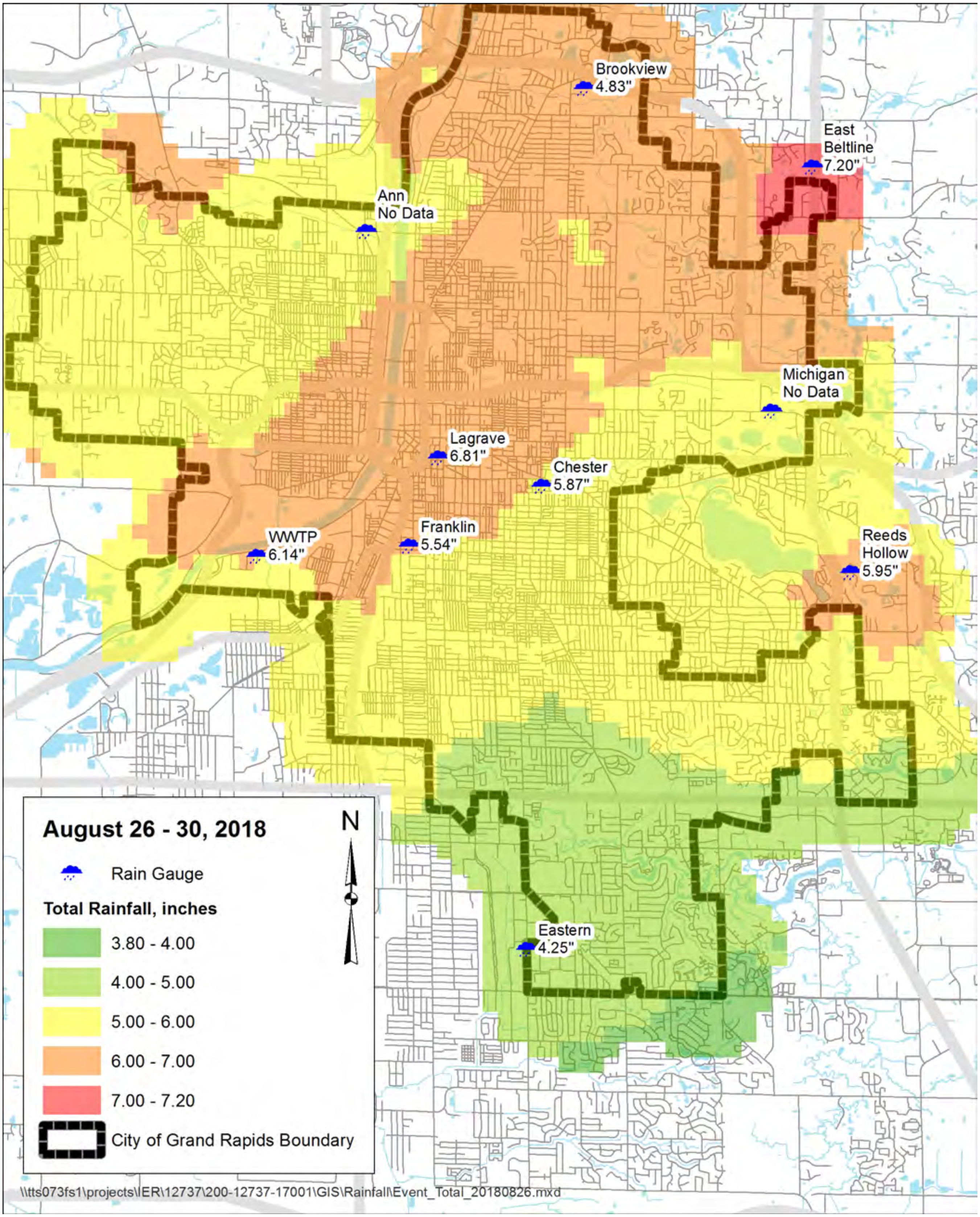
- Rain gauge locations in GIS format …\Electronic Data\Geodatabase
- Rain gauge data in Excel format …\Electronic Data\Monitoring Data\Rainfall\Rain Gauges
- Radar rainfall grid in GIS format and ground adjusted radar rainfall data in text format …\Electronic Data\Monitoring Data\Rainfall\Radar Rainfall\Data
- *Radar Rainfall Analysis Report* …\Electronic Data\Monitoring Data\Rainfall\Radar Rainfall\Report

Table 2-2. Rainfall Events with Ground-Based Rainfall used for Model Calibration

Event†	Start Date	Duration, hours	Total Rainfall Range, inches	Peak Hour Rainfall Range, inches
3	May 2	17	0.31 - 0.55	0.09 - 0.25
4	May 3	6	0.20 - 0.55	0.11 - 0.36
5	May 9	11	0.10 - 0.45	0.06 - 0.42
6	May 11	26	0.51 - 1.08	0.13 - 0.27
7	May 12	7	0.13 - 0.37	0.09 - 0.20
8	May 14	21	0.37 - 1.18	0.14 - 0.59
9	May 18	17	0.52 - 0.83	0.11 - 0.46
10	May 21	37	0.27 - 0.70	0.03 - 0.23
11	May 30	54	0.00 - 1.79	0.00 - 0.93
12	June 2	20	0.00 - 0.72	0.00 - 0.34
13	June 27	9	0.39 - 0.83	0.14 - 0.36
14	July 20	40	0.39 - 1.62	0.16 - 0.64
15	August 6	7	0.22 - 0.52	0.15 - 0.26
16	August 26	67	4.25 - 7.20	0.73 - 1.27
17	September 1	4	0.28 - 1.07	0.16 - 0.81
18	September 2	13	0.84 - 2.49	0.64 - 2.08
19	September 20	10	1.50 - 2.93	0.46 - 0.87
20	September 29	60	1.81 - 3.68	0.30 - 0.46
21	October 5	30	0.31 - 0.75	0.10 - 0.26
22	October 10	10	0.66 - 1.07	0.14 - 0.26
23	October 30	17	0.74 - 1.39	0.22 - 0.50

† Meter installation began in April 2018. Events 1 and 2 occurred in April 2018 but were discarded because of snow and ice precipitation and melting snow after they had been numbered.

Figure 2-1. Total Rainfall August 26 – 30, 2018



3.0 MODEL DEVELOPMENT

The collection system model was built using InfoSWMM version 14.6, which is compatible with the EPA SWMM version 5.1.012 calculation engine. The collection system model files are located at …\Electronic Data\Hydraulic Model Files.

3.1 HYDROLOGY

The modeled wet weather hydrology uses EPA SWMM's non-linear reservoir method where each subcatchment (drainage area) in the model has inflow components, most commonly rainfall, and outflow components, such as evaporation, infiltration, and runoff. Runoff only occurs from the subcatchment once the rate of rainfall exceeds the infiltration and evaporation rates and the depression storage volume is filled. The runoff rate is calculated using a form of Manning's equation where the depth of the runoff is spread uniformly across the subcatchment.

3.1.1 Subcatchments

In SWMM, runoff rate and volume are calculated by subcatchment. The modeled subcatchments (stored in a geodatabase at …\Electronic Data\Geodatabase) represent the drainage areas to groups of catch basins where runoff can enter the storm sewer. Processes that impact the flow or volume in the collection system, such as imperviousness, slope, infiltration, and evaporation among others are defined by subcatchment.

Subcatchments were delineated using 2-foot topographic contours for Kent County provided by the City. In SWMM, subcatchments are linked to nodes, and the sizes of the subcatchments vary orders of magnitude depending on the active sewers near the subcatchment. The average surface slope also was derived from the 2-foot contours.

Many of the other variables that define subcatchments in SWMM were assumed to be uniform throughout the model or were varied as part of the calibration (see Section 4.0).

3.1.2 Dry Weather Flow

Dry weather flow (base flow) does not occur throughout the collection system and is a small component of the total flow rate and volume where it does exist. Where dry weather flow was measured, it was either entered into the model as a constant value or as a time series hydrograph if the dry weather flow varied during the flow monitoring period.

3.1.3 Impervious Cover Analysis

Prior to the modeling effort, Sanborn completed an impervious cover analysis (ICA) for the entire City of Grand Rapids by defining the location and type of impervious area. The ICA is stored in a geodatabase at …\Electronic Data\Geodatabase. The ICA was used to define the aggregate imperviousness of each modeled subcatchment. The Michigan Statewide Authoritative Imagery and LiDAR (MiSAIL) program orthoimagery from spring 2015 were used as the source data for the ICA. The ICA has a minimum mapping unit of 100 square feet.

The types of impervious areas that are uniquely defined in the ICA dataset include:

- Alleys
- Buildings (Roofs)
- Driveways
- Other
- Parking Lots
- Patios / Decks
- Railroads
- Roads and Highways
- Sidewalks

Figure 3-1. Sample of Impervious Cover Analysis

3.1.4 Infiltration

The Horton Infiltration Method was used. The initial infiltration values used in the model were median values downloaded from the Natural Resources Conservation Service (NRCS) Web Soil Survey and aggregated using a weighted area average by subcatchment. These initial infiltration parameters were adjusted during the calibration of the model (see Section 4.0).

Supplemental rainfall monitoring data and relative file paths:

- NRCS physical soil properties in PDF format at …\Electronic Data\Reference Data\Soil Data
- NRCS soil map in GIS format at …\Electronic Data\Geodatabase

3.1.5 Evaporation

In the model, evaporation occurs during dry periods between rain events as one of the processes that decreases the water held in surface storage in the subcatchments. Therefore, evaporation only impacts the simulation with multiple rain events and has little impact on design storm simulations. The evaporation in the model uses data for Grand Rapids found in Table II in the National Oceanic and Atmospheric Administration (NOAA) Technical Report NWS 34 *Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States* and multiplied by an adjustment factor cited on page 3 of Technical Report NWS 34 defined on Map 4 of NOAA Technical Report NWS 33 *Evaporation Atlas for the Contiguous 48 United States*. The adjustment factor is 0.77 for Grand Rapids. The evaporation rates used in the model are presented in ***Table 3-1***.

Both reports are located electronically at … Electronic Data\Reference Data\Evaporation Data.

Table 3-1. Daily Evaporation Rates by Month

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0.02	0.02	0.05	0.10	0.15	0.18	0.18	0.15	0.10	0.07	0.04	0.02

Note: All units are in inches per day.

3.1.6 Fisk Lake Discharge

The discharge from Fisk Lake into a branch of Coldbrook Creek is uniquely represented in the model due to the lack of precise physical data, lack of flow monitoring data, and the size of the drainage area. The area discharging from Fisk Lake is outside the City of Grand Rapids, so there was no impervious cover analysis for the subcatchment and no details of the channel and culvert dimensions. Flow monitoring data were available downstream, but not at the discharge location. Furthermore, upstream of Fisk Lake is Reeds Lake, which is larger than Fisk Lake. The two lakes combine to cover approximately 11 percent of the 3.9 square mile subcatchment.

For the reasons above, the discharge from Fisk Lake was represented with a rating curve based on the meter in the downstream enclosed portion of the South Branch of Coldbrook Creek. The rating curve limits the discharge from Fisk Lake to 17 cfs to match the magnitude of the measured downstream flows.

In the model, all wet weather flows are routed through a node representing the estimated total volume of Fisk and Reeds Lakes. Evaporation from the surface area of the lakes (290 acres) is included in the model.

3.2 HYDRAULICS

The model uses the dynamic wave routing method to calculate the sewer flows in location and time. This method solves the complete one-dimensional St. Venant equations, which account for flow continuity and momentum. The dynamic wave routing method can account for channel storage, backwater, entrance and exit losses, flow reversal, and pressurized flow, all of which exist in the collection system.

3.2.1 Modeled Network

The collection system in the model was imported from the City's stormwater collection system geodatabase. Modifications were made to the modeled elements where data were missing from the City's geodatabase or appeared to be incorrect. The modeled links and nodes with their attributes are included in the electronic data so that the City may review differences between the modeled and original datasets (see Section 6.2 for more details).

The entire collection system is contained in the model, but primarily only sewers that are 30 inches in diameter or larger are actively modeled, meaning that they have simulation results. Sewers that are inactive are available to be added to the active set of modeled elements. Including additional sewers in the model may require adjusting the subcatchment hydrology. The active portion of the model includes approximately 616,000 feet (117 miles) of storm sewer and channels, representing approximately 21 percent of the total length of the collection system, and 3,400 drainage structures (primarily manholes, catch basins, and taps).

Supplemental model network and relative file paths:

- Entire model network in GIS format at …\Electronic Data\Geodatabase
- Active model network in GIS format at …\Electronic Data\Geodatabase
- Collection system model in InfoSWMM at …\Electronic Data\Hydraulic Model Files

3.2.2 Stormwater Pump Stations

In addition to the pipe and channel network, the model also includes stormwater pump stations. Record or design drawings provide the basis for the representation of the pump stations and stormwater storage facilities. The model includes pump performance curves and operational controls provided by the City.

The stormwater pump stations in the system are listed in ***Table 3-2***. Only the lift stations that are on sewers with a diameter of at least 30 inches have simulation results. Since the pump discharge is based on its pump curve, the discharge rate likely varies based on the hydraulic conditions and may not be the same as the rated firm capacity listed in the table.

Supplemental pump station data and relative file paths:

- Pump performance curves in PDF format at …\Electronic Data\Reference Data\Pump Curves
- Pump operational controls in an image format at …\Electronic Data\Reference Data\Pump Operating Rules

Table 3-2. Stormwater Pump Station Summary

Pump Station	Location	Discharge	Model Output Available	Number of Stormwater Pumps	Rated Firm Capacity, cfs
Caledonia	1401 Monroe Avenue NW	Grand River	Yes	3	18
Front-Scribner	600 Front Street NW	Grand River	Yes	6	560
Indian Mill	500 Ann Street NW	Indian Mill Creek	Yes	3	18
Ken-O-Sha	221 Ken-O-Sha Drive SE	Plaster Creek	Yes	3	18
Market	740 Market Avenue SW	Grand River	Yes	4	72
Palmer	60 Ann Street NW	Grand River	Yes	3	18
Wealthy	940 Wealthy Street SW	Grand River	Yes	10	1000
Academy	2255 Academy Drive NE	Remington Drain – Manhole 5861	No	2	1.7[†]
Albany	301 Albany Street NW	Buchanan Avenue Sewer – upstream of Manhole 514	No	2	3.1
Alpine	1905 Alpine Avenue NW	Indian Mill Creek	No	3	1.3[††]

† Rated firm capacity is not known and is estimated from the pump curve at the best efficiency point.

† Pump station is currently being re-designed. Future firm capacity is expected to be 5.3 cfs.

3.2.3 Storage and Infiltration Facilities

The model includes the engineered stormwater detention or infiltration facilities listed in ***Table 3-3***. Natural low points and lakes are not included in the table. All the modeled facilities are located near sewers 30 inches in diameter or larger. Those maintained by the Kent County Drain Commission are included in the model because they directly impact the flow rates and hydraulic grade line in the City's collection system. Smaller facilities were not included in the model. The numerous, but small green infrastructure practices that provide storage or infiltration are not directly modeled but are represented in the hydrologic calibration of the model. Infiltration rates for the basins were estimated during calibration of the model.

Table 3-3. Stormwater Storage Facility Summary

Facility	Location	Owner	Type	Storage Volume†, acre-feet
Brownwood	East of Brownwood Avenue, north of Woodglen Street	Grand Rapids	Detention	14.2
Calvin	Silver Creek west of Calvin Avenue, north of Ramona Street	Kent County	Detention	5.2
Corduroy Pond	Coldbrook Creek, south of I-196, east of Fuller Avenue	Kent County	Detention	83
Joe Taylor Park	East of Bemis Avenue, north of Baxter Street	Grand Rapids	Infiltration	0.8
Kreiser	Silver Creek, east of Kreiser Street, south of Hall Street	Kent County	Detention	5.5
Mary Waters Park	104 Lafayette Avenue NE	Grand Rapids	Infiltration	2.2
Otsego	Silver Creek, Division Avenue and Cottage Grove Street	Kent County	Detention	2.2
South Field	Silver Creek, south of Cottage Grove Street, east of Jefferson Avenue	Kent County	Detention	7.6

† Approximate. Based on volume below high water level on available design drawings. If no high water level is defined, this is the volume below the crown of the effluent sewer.

3.2.4 Boundary Conditions

Boundary conditions are defined in the model at locations where flows leave the modeled network at outfalls.

Outfalls that discharge to a minor watercourse without measured water surface elevation data were assumed to have a free discharge, meaning that the water surface elevation in the receiving watercourse does not impact the water surface elevation in the sewer.

The modeled boundary condition at each outfall along the Grand River and Plaster Creek where data were available to estimate a relationship between the river's discharge and depth is a time series of water surface elevations for the flow monitoring period created using an empirical rating curve. The model does not have the capability to directly use the rating curve as a boundary condition.

Along the Grand River, the discharges and water surface elevations used to develop the rating curves were estimated from a HEC-RAS model provided by the City. Each outfall's rating curve estimates the water surface elevation at the outfall from the discharge measured at USGS gauging station 04119000, located approximately 400 feet north of Fulton Street.

Along Plaster Creek, the discharges and water surface elevations used to develop the rating curves were estimated from a HSPF model provided by Limno Tech and documented in a March 2019 report prepared for the City titled *Development of a Watershed and Water Quality Model of the Lower Grand River*. The rating curves relate the discharge measured at USGS gauging station 04119055, located on 28th Street west of Eastern Avenue, to the creek's water surface elevation at each outfall.

Supplemental boundary condition data and relative file paths:

- Grand River and Plaster Creek River Stage Rating Curves by Outfall in PDF format at …\Electronic Data\Monitoring Data\Outfall Boundary Condition Rating Curves

4.0 CALIBRATION AND VALIDATION

Calibration is the systematic process of adjusting the model inputs, so the model flow volume, rate, and depth reasonably match the measured data.

Supplemental calibration data and relative file paths:

- Flow rate and volume calibration by meter and event in PDF format …\Electronic Data\Calibration Results\Flow Rate and Volume Event Plots
- Flow rate and volume calibration summary plots in PDF format …\Electronic Data\Calibration Results\Flow Rate and Volume Summary Plots
- Depth calibration summary in Excel format …\Electronic Data\Calibration Results\Depth Summary Table
- Calibration simulation in EPA-SWMM format …\Electronic Data\Calibration Results\Calibration Simulation

4.1 CALIBRATION PROCESS

For stormwater collection systems, the flow rate and volume are calibrated first, followed by the flow depth (hydraulic grade line).

For this project, the flow rate and volume were calibrated using both manual and automated processes. Some locations were calibrated using both methods to compare the results of the two methods. For sites that were only calibrated with the automated process, the results were reviewed and adjusted, if necessary, such that the combination of resulting model inputs were within ranges of commonly accepted values.

The automated calibration process used thousands of simulations to calibrate the flows at each flow monitoring location and scored the fitness of the results. Each subsequent generation of model simulations used earlier generations to identify variables within defined ranges that would improve the results from previous generations. A total of approximately 650,000 model simulations were completed during the model calibration and validation.

Only some of the variables that impact flow rate and volume in SWMM were adjusted during the calibration. Each variable that impacts runoff flow rate and volume is listed below with the adjustments that were allowed during the calibration process.

- Area: Not adjusted because the area is based on a map-based measurement.
- Imperviousness: Not adjusted because the ICA provided a map-based measurement of the imperviousness.
- Width: The initial width was estimated using the subcatchment shape, area, and longest flow path. The width tends to be a less precise input and, therefore, was allowed to vary over a wide range between 10 and 800 percent of the initial value. The width is used to calibrate flow rate.
- Slope: Not adjusted because it is a term in the same equation as the width and the available slope data are more accurate than the calculation of the width.
- Impervious and Pervious Area Manning Roughness: These variables were not changed. Roughness coefficients have a small impact on the results relative to the slope and width. The impervious and pervious area Manning roughness coefficients were set to 0.012 and 0.15, respectively, for all modeled subcatchments.
- Impervious Area Depression Storage: Allowed to vary between 0.01 to 0.10 inches, which is the range of recommended values in the SWMM guidance. It was allowed to vary to see if there was a correlation between depression storage and other subcatchment properties such as land use and slope. No correlations were found, and the variable was found to have little impact on the results.

- Pervious Area Depression Storage: Allowed to vary between 0.10 to 0.30 inches, which is the range of recommended values in the SWMM guidance. As with the impervious depression storage, no correlations were found between this variable and others, and the variable was found to have little impact on the results.
- Percent Impervious Area with Zero Depression Storage – This variable was not changed since the map-based ICA showed a city-wide average of 32 percent of the impervious area was roofs (pitched and flat). Pitched roofs, which are assumed to have zero depression storage, were assumed to comprise 75 percent of the roof. A uniform value of 25 percent was assumed for this variable. Furthermore, this variable is a term in the same equation as the impervious area depression storage which was already being adjusted.
- Subarea Routing: Set to Pervious for all subcatchments meaning that non-directly connected impervious areas (typically roofs) are routed to the pervious area where infiltration can occur in the model before being routed to sewer.
- Percent Routed: Allowed to vary between zero and 100 percent. This variable was used to calibrate flow rate and volume.
- Maximum and Minimum Infiltration Rates: The initial values were taken from the median values in the NRCS dataset. Initially, they were allowed to vary between 50 and 200 percent of the NRCS median values, which is the range of uncertainty listed in the NRCS data. However, after calibrating a few sites, the infiltration rates in many of the calibrated solutions were much lower than NRCS published values, so the range was adjusted downward to 10 to 150 percent of the NRCS median values to mitigate producing a solution that is limited at the lower bound of acceptable values. The urban characteristic of the soils (more likely to be compacted) may be a factor in infiltration rates less than those published by NRCS.
- Infiltration Decay Constant – Allowed to vary between 2 and 7 $hours^{-1}$, which is the range of typical values in the SWMM guidance.
- Infiltration Drying Time – Allowed to vary between 2 and 14 days, which is the range of typical values in the SWMM guidance.
- Maximum Infiltration Volume – The initial value is set to zero and was not used in the model.

The modeled depths were calibrated primarily by adjusting the Manning roughness coefficients of the pipes. In some instances, minor losses were added to the model during calibration of the depth, especially at junction chambers and flow control structures.

4.2 CALIBRATION CRITERIA

The quality of the calibration was evaluated using guidance based on the Wastewater Planning Users Group (WaPUG) *Code of Practice for the Hydraulic Modelling of Sewer Systems* (November 2002).

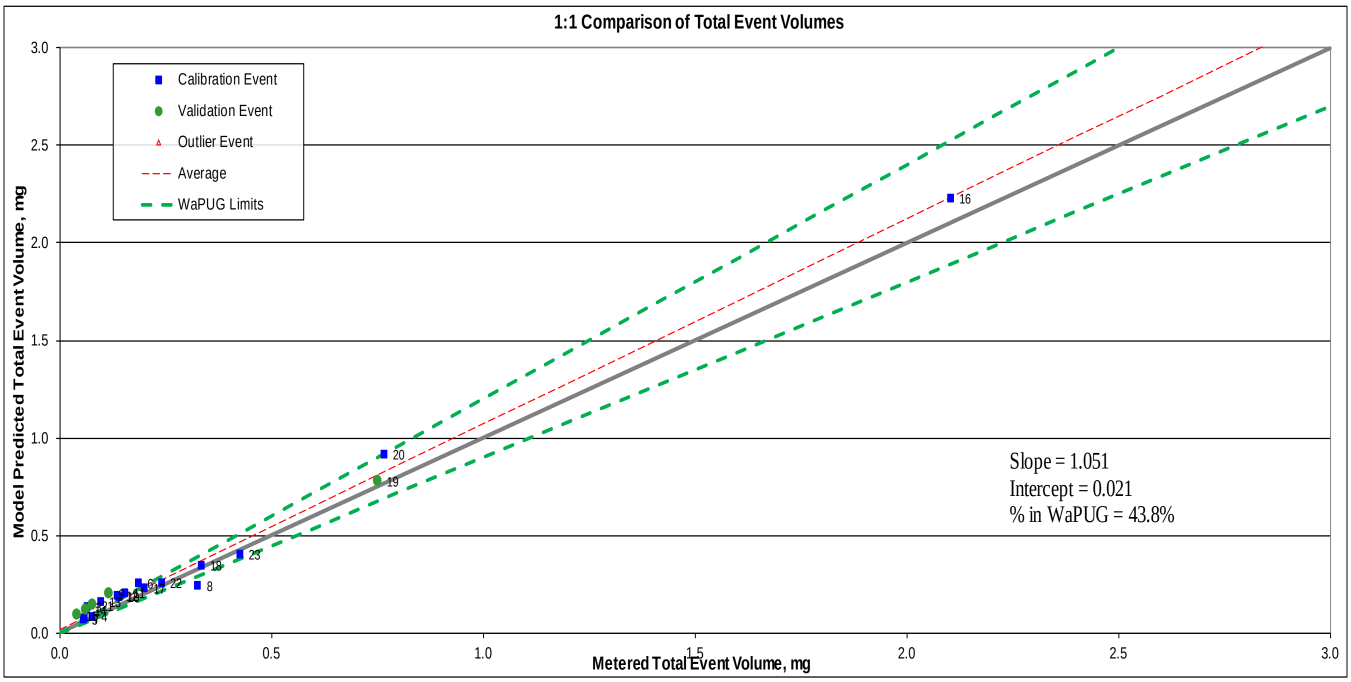
The calibration at each meter location was considered satisfactory when, on average:

- The modeled volume is +20 to -10 percent of the measured data.
- The modeled peak flow rate is +25 to -15 percent of the measured data.
- The shape of the modeled hydrograph resembles the measured hydrograph.
- If the measured depth is within the pipe, the modeled depth is within +/- 0.33 feet, and if the measured depth is above the pipe crown, the modeled depth is in the range of -0.33 feet to +1.5 feet of the measured depth.

Plots comparing the modeled and measured flow rate and volume were created to assess the quality of the calibration. ***Figure 4-1*** shows an example calibration plot. The electronic data includes the calibration plots, which have the following information:

- Table and plot of modeled and measured flow rate and volume for all calibration, validation, and outlier events (blue squares, green circles, and red triangles, respectively) and the number of calibration events that fall within the calibration limits.
- WaPUG calibration limits (green dashed lines). Even for a good calibration, it is likely some events will fall outside the limits.
- 1:1 line (grey line) showing where a perfect match between the modeled and measured data would fall. The model is overestimating events that fall to the left of the line and is underestimating events that fall to the right of the line.
- Average trend of calibration events (red dashed line) and statistics showing the slope and intercept of the line. Outlier events (events with poor quality measured data or measured data that did not match the data for other events) and validation events (see Section 4.3) were not calculated into the average used to assess the quality of the calibration.

Figure 4-1. Example Calibration Plot



4.3 SELECTION OF VALIDATION EVENTS

Validation events are those events that were part of the measured dataset but were not used to adjust the model inputs. In other words, they are independent of the calibration, and are used to show how well the model matches uncalibrated events.

Five (5) of the 21 events during the flow monitoring period were used as validation events and selected prior to the beginning of the model calibration. The validation events were selected to include one event in each quintile of rainfall volume and peak intensity (as an average of the available ground-based rain gauge data) and spread chronologically throughout the flow monitoring period. The validation events include:

- Event 9 (May). Volume rank = 10 (0.70 inches); Intensity rank = 12 (0.22 inches per hour)
- Event 14 (July). Volume rank = 7 (0.81 inches); Intensity rank = 8 (0.32 inches per hour)
- Event 15 (August). Volume rank = 18 (0.35 inches); Intensity rank = 14 (0.21 inches per hour)

- Event 19 (September). Volume rank = 3 (2.10 inches); Intensity rank = 3 (0.64 inches per hour)
- Event 21 (October). Volume rank = 13 (0.58 inches); Intensity rank = 20 (0.16 inches per hour)

4.4 SUMMARY CALIBRATION RESULTS

The peak flow rate, volume, and depth are well calibrated to the measurements based on the statistics below, which show, on average, that the calibrated peak flow rate, volume, and depth were within the calibration tolerances (see Section 4.2 for calibration criteria). Every calibration and validation event for the peak flow rate, volume, and depth are shown as ***Figure 4-2***, ***Figure 4-3***, and ***Figure 4-4***, respectively.

- On average, the peak flow rate is within one point of the 1:1 line, which represents an exact match between the modeled and measured flow. Forty-nine (49) percent of the peak flow rate calibration events lie above the 1:1 line (model overestimates peak flow rate) and 51 percent lie below the 1:1 line (model underestimates the peak flow rate), suggesting that the model almost evenly over- and underestimates the individual events. Fifty-seven and five-tenths (57.5) percent of the calibration event peak flow rates fall within the calibration tolerance including 72 percent of the largest 100 measured peak flow rate data points. Approximately 48 percent of the validation event peak flow rates also fall within the calibration tolerance.
- On average, the modeled volume, as measured by the slope of the trendline, is within the calibration tolerance, but is still above the 1:1 line, which means that the model overestimates volume, on average. Fifty-seven (57) percent of the volume calibration events lie above the 1:1 line. Fifty-eight (58) percent of the calibration event volumes fall within the calibration tolerance, including 80 percent of the largest 100 measured volumes. Approximately 42 percent of the validation event volumes also fall within the calibration tolerance.
- Fifty-nine (59) of the 63 depth calibration points met the calibration criteria. Where flow rate is over or underestimated, the depth should be expected to be over or underestimated as well, which factored into the decision to leave the remaining sites with depth calibrations outside of the calibration limits. Another consideration to leaving these sites outside the calibration limits was the impacts to the calibration of other meters, the reasonableness of the inputs needed to calibrate the model, site-specific configurations that SWMM may not be able to be able to represent well, and the extent of the impact of the calibration on the upstream collection system.

Figure 4-2. Peak Flow Rate Calibration Summary

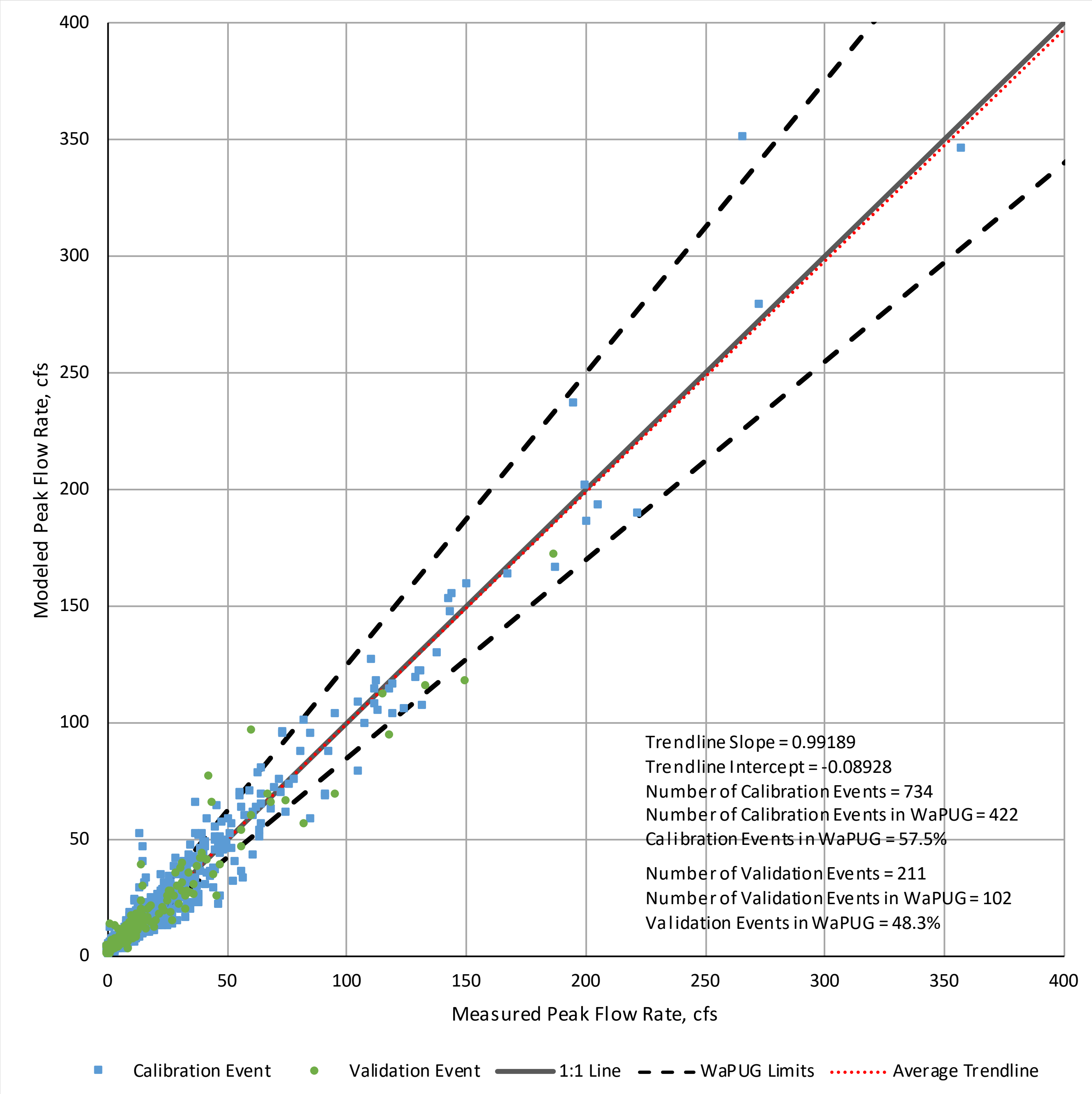


Figure 4-3. Volume Calibration Summary

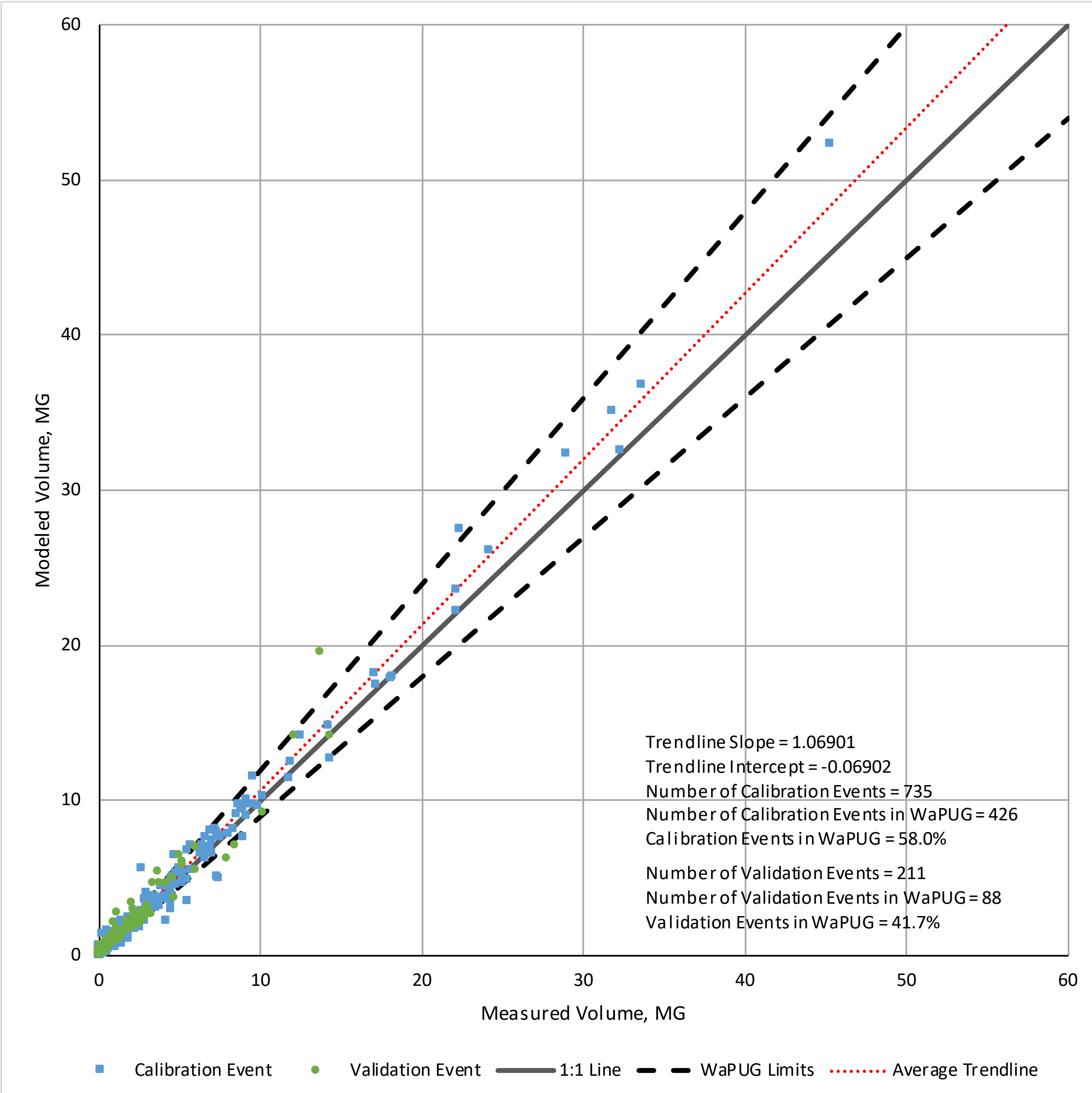
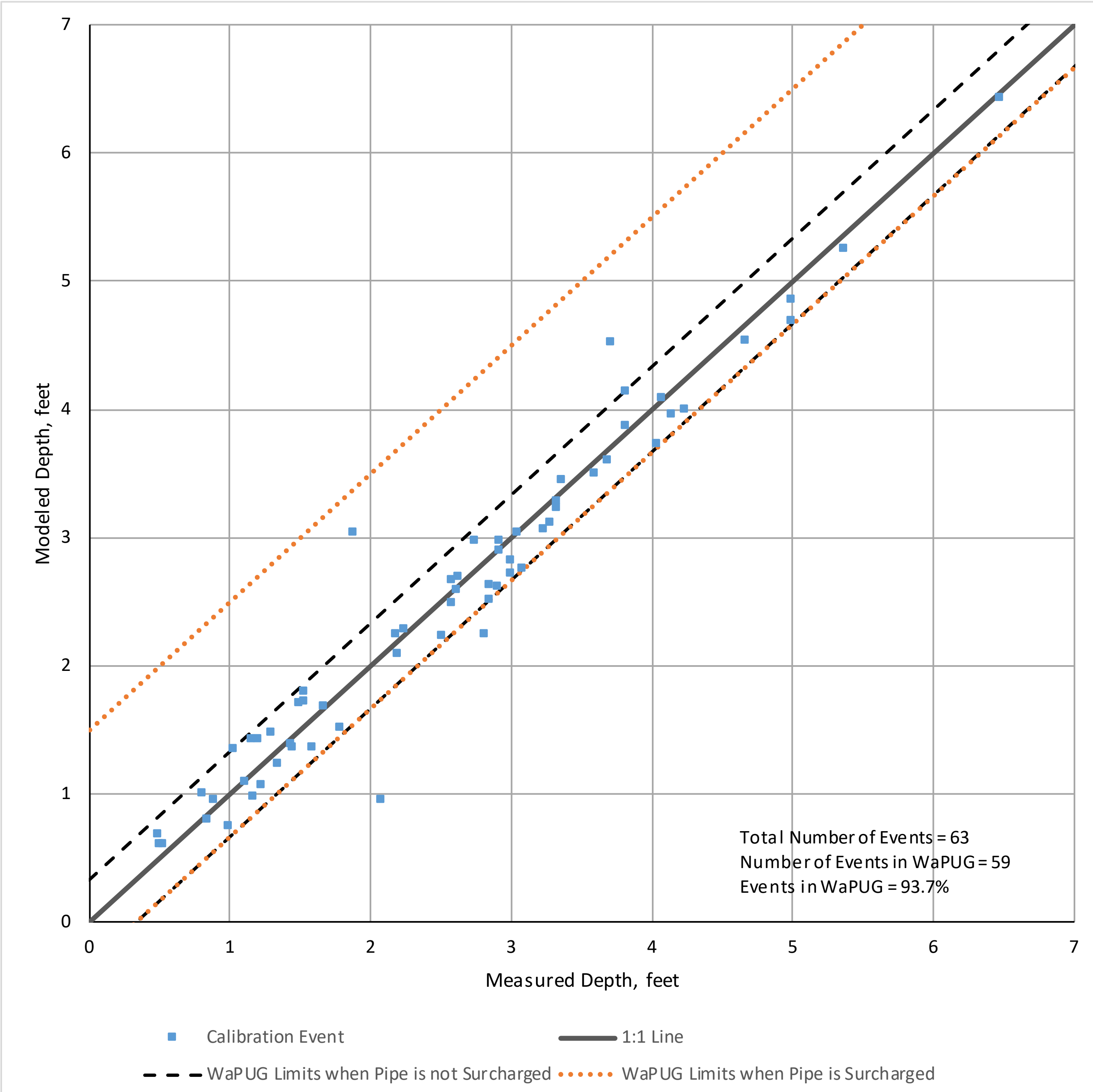


Figure 4-4. Depth Calibration Summary



5.0 CAPACITY ANALYSIS

A capacity analysis compares projected flow rates, volumes, and hydraulic grade lines to the City's targeted level of service (LOS). The LOS may contain other standards, but since the capacity analysis focuses on the hydraulic capacity of the collection system, this report focuses on the LOS provided to convey stormwater. Many communities have a stormwater collection system LOS that will convey the 10-year design storm without flooding, but the LOS for new systems may be different than those of existing systems, which were constructed in eras with less stringent design standards (e.g., use of smaller design storms or smaller rainfall volume and intensity for the same design storm) and fewer tools to demonstrate the interconnectedness of each new sewer branch.

Supplemental model output data and relative file paths:

- 10-year, 24-hour design storm and long-term simulation model output in Excel format at …\Electronic Data\Capacity Analysis\Model Output (this data can be joined with the GIS data using the Facility ID)
- Capacity maps in PDF format at …\Electronic Data\Capacity Analysis\Capacity Maps
- Hydraulic profiles in PDF format at …\Electronic Data\Capacity Analysis\Hydraulic Profiles

5.1 DESIGN STORMS AND CONDITIONS

The capacity analysis was completed for the 10-year, 24-hour design storm with the following details:

- Total rainfall from NOAA Atlas 14 = 3.83 inches
- MSE 4 rainfall distribution. The MSE distribution nests shorter duration design storms within longer duration design storms. The peak rainfall intensity for this distribution is 3.47 inches per hour (peak 5-minute duration) and 1.69 inches for the peak hour.

Other design conditions include:

- Dry weather flow rates similar to the largest that occurred during the flow monitoring period.
- Boundary conditions representing the 2-year flood stage on the Grand River and Plaster Creek. Outfalls with a free discharge continue to have a free discharge.

A long-term simulation also was completed using hourly rainfall data from NOAA rain gauge 20-3333 at Gerald R. Ford International Airport. The model was used to simulate flows in the stormwater collection system during the 53-year period between December 1963 and June 2016. The results of the long-term simulation were used to estimate the frequency of flooding at each manhole in the system. For the long-term simulation:

- The dry weather flow is the same as that used for the design storm simulation.
- The boundary condition was set to a free discharge for all outfalls to distinguish capacity in the collection system from limitations caused by the boundary condition. Pump station capacity was assessed using the flow in the pipe immediately upstream of the pump station.

5.2 DESIGN CRITERIA

The capacity analysis is based on the following design criteria:

- Sewers that are not projected to surcharge to the ground surface (flood) during the 10-year, 24-hour design storms meet the LOS. The nominal capacity (the flow rate that a pipe flowing full can convey without surcharging) may be less than the projected peak flow during the 10-year, 24-hour design storm and still meet the LOS.
- Channels meet the LOS if the projected water surface elevation during the 10-year, 24-hour design storm is more than 1 foot from a building or the edge of a road.

- Stormwater pump stations that have a firm capacity (sum of the individual capacities of the pumps assuming the largest pump is out of service) greater than the projected flow rate of the 10-year, 24-hour design storm or that is not exceeded by the projected flow rate more than five times during the long-term simulation meet the LOS.
- Detention and infiltration facilities that do not exceed 90 percent of the available volume during the 10-year, 24-hour design storm meet the LOS.

5.3 RESULTS SUMMARY

The total length of modeled sewer and the number of modeled manholes are compared, respectively, to sewers projected to have a lack of capacity and manholes projected to flood and are provided in ***Table 5-1***. ***Figure 5-1*** also shows a map of the City with each sewer's nominal capacity relative to the projected peak flow rate and the projected magnitude of manhole flooding during the 10-year, 24-hour design storm. Specific sewers and manholes shown on the map are in the model output provided electronically and can be joined to the GIS data using the Facility ID.

Table 5-1. Collection System Capacity Summary Results

Total Length of Modeled Collection System, feet	Length of Modeled Collection System with Projected 10-year, 24-hour Design Storm Peak Flow Rate more than 110% of Nominal Capacity	Total Number of Modeled Drainage Structures	Number of Modeled Drainage Structures Projected to Flood during 10-year, 24-hour Design Storm
616,000	175,000 (28%)	3,462	187 (5%)

Ninety-seven (97) of the modeled drainage structures in the system (3 percent of the total number of modeled drainage structures) were projected to flood more than five times during the long-term simulation, exceeding an average of once every 10 years. The locations of the 97 drainage structures and others that are projected to flood five times or fewer during the 53-year long-term simulation are provided in the electronic model output data. The duration of the flooding varied widely, with the longest duration of flooding at any manhole during any event being 9 hours. The projected frequency of flooding during the long-term simulation is shown in ***Figure 5-2***. Specific manholes shown on the map are in the model output provided electronically and can be joined to the GIS data using the Facility ID.

Figure 5-1. 10-year, 24-hour Design Storm Capacity Analysis Overview

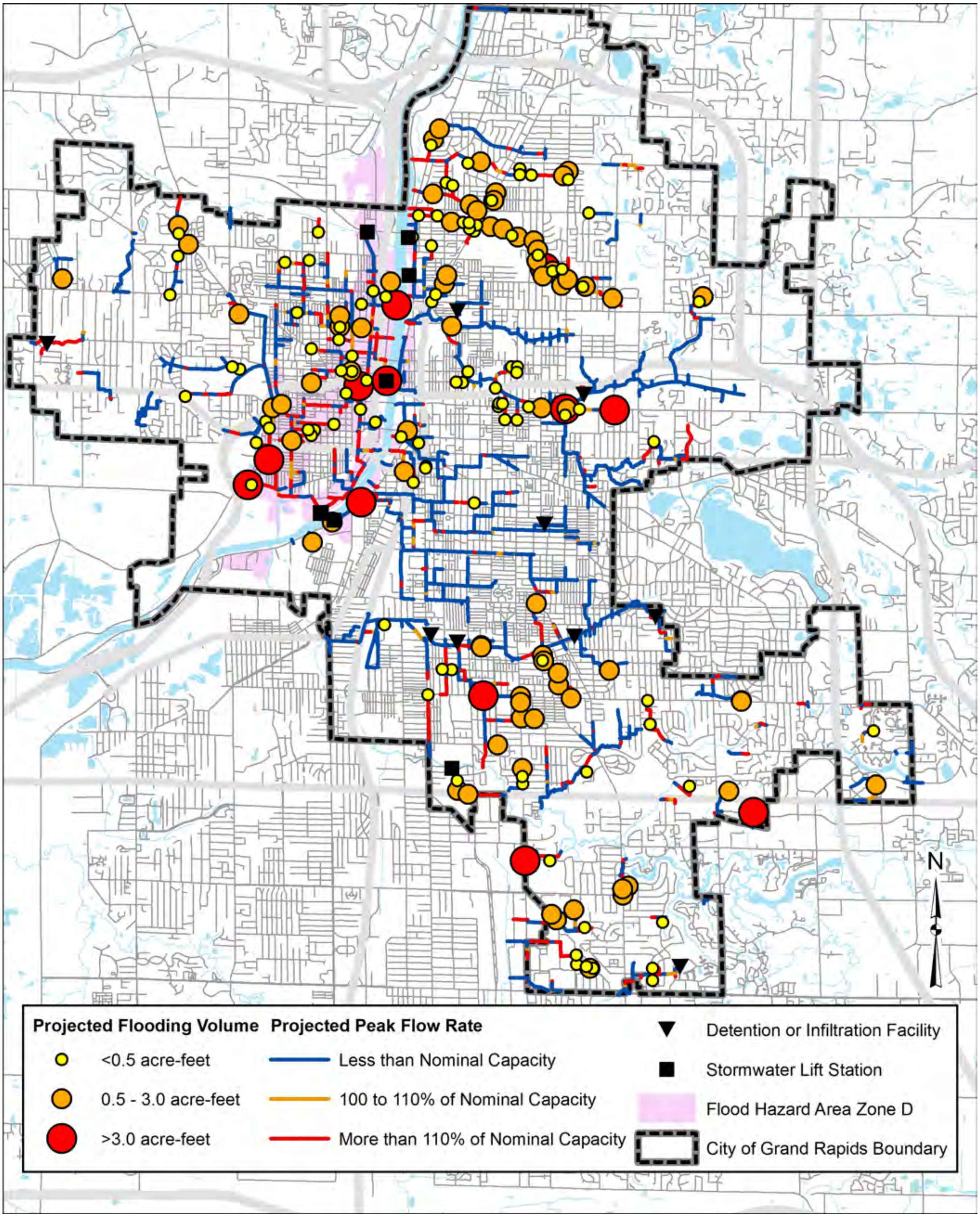
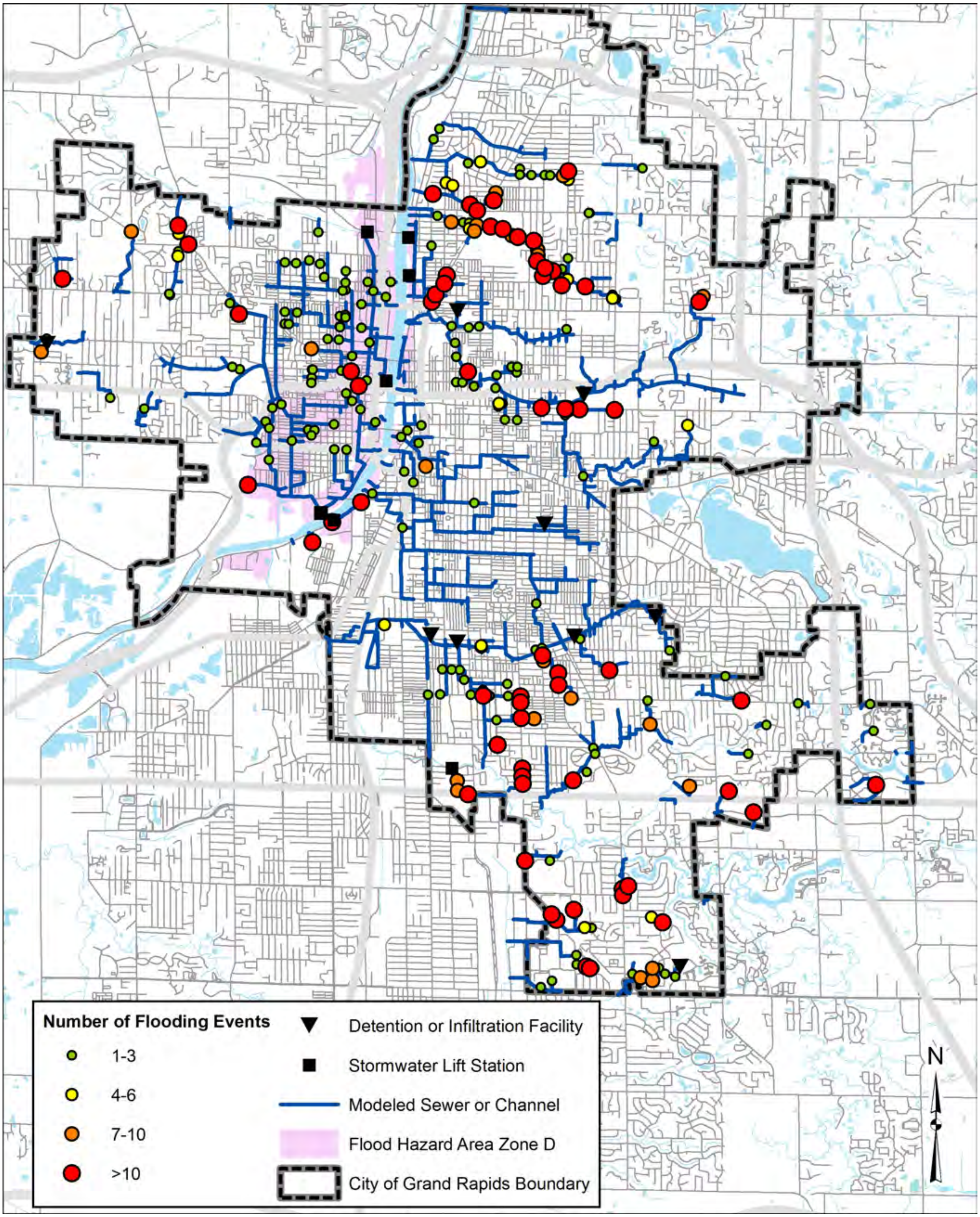


Figure 5-2. Long-term Simulation Flooding Frequency Overview



The model predicts that only one of the seven modeled pump stations has a firm capacity that exceed the projected 10-year, 24-hour design storm peak flow rate. However, five of the pump stations still meet the level of service criteria since the peak flow rate was projected to exceed the pump station firm capacity no more than five times during the long-term simulation. ***Table 5-2*** shows the firm capacity of each stormwater pump station, the projected peak flow rate during the design storms, and the frequency the firm capacity was exceeded during the long-term simulation.

Table 5-2. Pump Station Capacity Analysis Results

Pump Station	Firm Capacity, cfs	Projected 10-year, 24-hour Design Storm Peak Flow Rate, cfs	Number of Times Firm Capacity exceeded by Influent Flow during Long-term Simulation	Provides Targeted LOS
Caledonia	18	18	0	Yes
Front-Scribner	560	660	3	Yes
Indian Mill	18	32	6	No
Ken-O-Sha	18	62	286	No
Market	72	110	4	Yes
Palmer	18	19	0	Yes
Wealthy	1000	1100	0	Yes

The model predicts that all eight of the modeled detention basins have adequate volume for the design storm and meet the LOS. In fact, some of the facilities may be underutilized and could be used to store more water. It is possible that some of the basins were designed for larger design storms (such as the 100-year design storm), but in some instances, it unlikely that the 100-year flow rate can even be conveyed to the storage site.

Table 5-3 shows the volume of each storage facility and the projected maximum volume used during the 10-year, 24-hour design storm.

Table 5-3. Storage Facility Capacity Analysis Results

Facility	Available Volume, acre-feet	Projected 10-year, 24-hour Maximum Volume Used, acre-feet	Volume Used / Volume Available	Provides Targeted LOS
Brownwood Detention Basin	14.2	10.5	0.74	Yes
Calvin Detention Basin	5.2	7.1	0.73	Yes
Corduroy Pond	83	28.6	0.34	Yes
Joe Taylor Park Infiltration Basin	0.8	0.4	0.50	Yes
Kreiser Detention Basin	5.5	3.3	0.60	Yes
Mary Water Park Infiltration Basin	2.2	0.6	0.27	Yes
Otsego Detention Basin	2.2	0.5	0.23	Yes
South Field Detention Basin	7.6	3.2	0.42	Yes

The electronic files include maps showing sewers with a nominal capacity less than the design storm projected peak flow rate, drainage structures that are projected to surcharge and flood during the 10-year, 24-hour design storm, the frequency of flooding during the long-term simulation, and GIS data with the model output (…\Electronic Data\Capacity Analysis). An overview of the most significant projected capacity restrictions is shown in ***Figure 5-3***. ***Figure 5-4*** through ***Figure 5-8*** show the same areas in more detail with projected capacity and flooding information. Manholes projected to flood during the 10-year, 24-hour design storm or more than once in 10 years, on average, are labeled with the manhole's Facility ID from the City's GIS database. The most significant capacity restrictions include:

- Storm sewer reaches that are projected to flood at several manholes during the 10-year, 24-hour design storm and flood more frequently than five times during the long-term simulation:
    - Area 1 - The Palmer Separation Drain from Monroe Avenue to Ball Avenue is projected to flood at 21 percent of the manholes during the 10-year, 24-hour design storm. Many of the manholes upstream of Plainfield Avenue are projected to flood more frequently than 10 times in the 53.6-year long-term simulation.
    - Area 2 – The combination of the 2-year boundary condition and 10-year, 24-hour design storm caused the model to predict flooding at many manholes within the flood hazard area behind the floodwall west of the Grand River. During the long-term simulation, where a low boundary condition (free discharge) was assumed, the model predicted more than three flooding events at four manholes, all of which were at the upstream ends of the modeled system (see Section 6.1.3 for limitations of the model for areas upstream of the flow meter locations). In this area, it appears that the projected flooding is caused by the river stage more than the sewer capacity.
    - Area 3 – The 21- to 30-inch sewer along Plainfield Avenue between Quimby and Coldbrook Streets. No flow monitoring was completed on this reach. See Section 6.1.3 for limitations of the model for areas upstream of the flow meter locations.
    - Area 4 –The 30- to 60-inch sewer along Graceland Street between Monroe and Plainfield Avenues.
    - Area 5 - One segment of the South Branch of Coldbrook Creek from Michigan Street to the main branch of Coldbrook Creek and the 30- to 36-inch sewer along Michigan Street between Fuller and Ball Avenues. Flooding on the former reach may be impacted by energy losses where it discharges into the main branch of Coldbrook Creek. The latter reach is projected to flood during the design storm at 4 of the 8 manholes modeled.
    - Area 6 - The 36-inch sewer discharging to Silver Creek at Blaine Avenue from Silver Creek to Burton Street.
    - Area 7 – A local low point at the intersection of College Avenue and Burton Street due downstream conditions in the 60-inch sewer where it discharges into Silver Creek at South Field and the 66-inch sewer where it discharges into Plaster Creek near Godwin Avenue. Other flooding predicted by the model along the 30- to 36-inch sewer along Eastern Avenue between Winchell and Burton Streets also appears to be caused by the downstream conditions rather than local pipe capacity. While flooding is predicted by the model, the model overestimates the hydraulic grade line in the 66-inch sewer at the flow monitoring location, which also may cause an overestimation of the flooding.
    - Area 8 – The 24- to 30-inch sewer along Eastern Avenue between Everglade and Mayhew Wood Drives. No flow monitoring was completed on this reach. See Section 6.1.3 for limitations of the model for areas upstream of the flow meter locations.
    - Area 12 – West Leonard Drain (24- to 30-inch sewer) in multiple locations from Leonard Street to Indian Mill Creek.

- Area 9 – The projected design storm peak flow rate upstream of Ken-O-Sha Pump Station exceeds its firm capacity. The long-term simulation projects that the Ken-O-Sha Pump Station firm capacity is exceeded an average of five times per year. During the 6-month flow monitoring period, all three pumps operated concurrently on two occasions, which is an indicator that the firm capacity was exceeded. City staff have stated the limited firm capacity may be by design, as the pump station is only intended to supplement the gravity discharge when Plaster Creek is high.
- Culverts that are projected to flow under pressure during the design storm, including:
    - Area 10 – 30-inch circular culvert conveying Carrier Creek under the Carrier Creek Trail connecting Union Street between Hubert and Cedar Streets.
    - Area 11 – 30-inch circular culvert on Laraway Brooklyn Drain, on the west side of MacKay-Jaycees Park east of the intersection of Brooklyn Avenue and Walsh Street.

Figure 5-3. Areas with Projected Capacity Restrictions

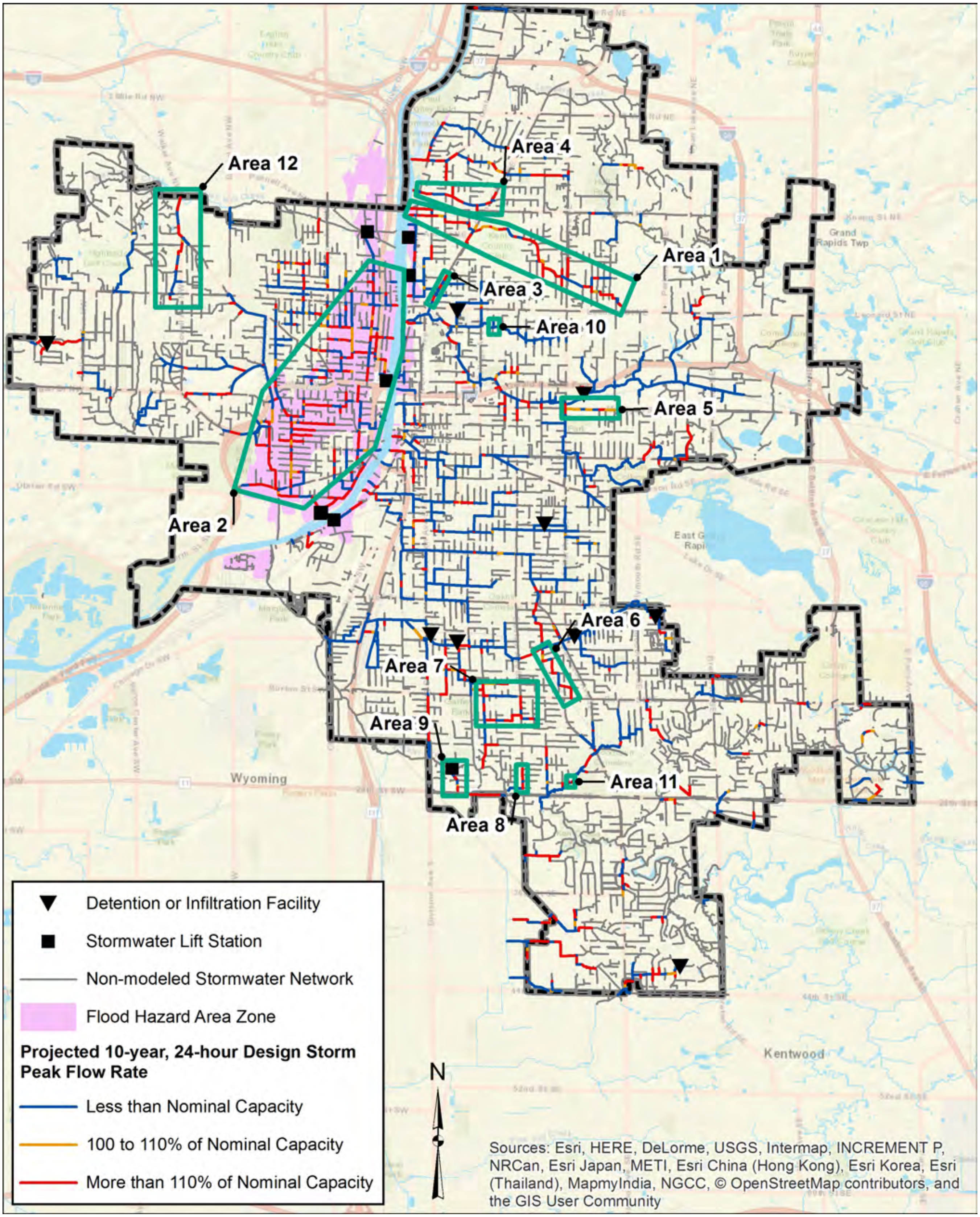


Figure 5-4. Projected Capacity Restrictions in Areas 1, 3, 4, and 10

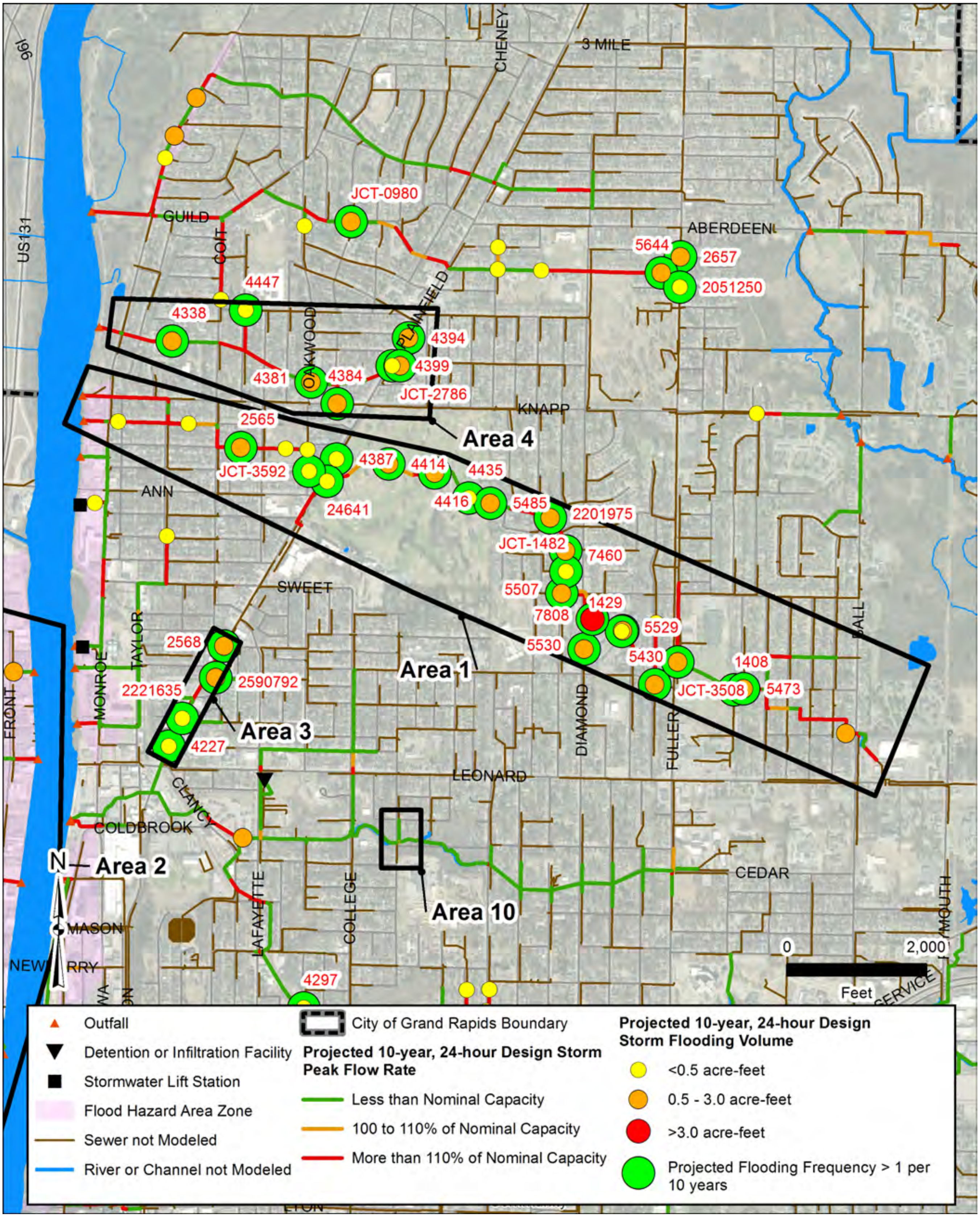


Figure 5-5. Projected Capacity Restrictions in Area 2

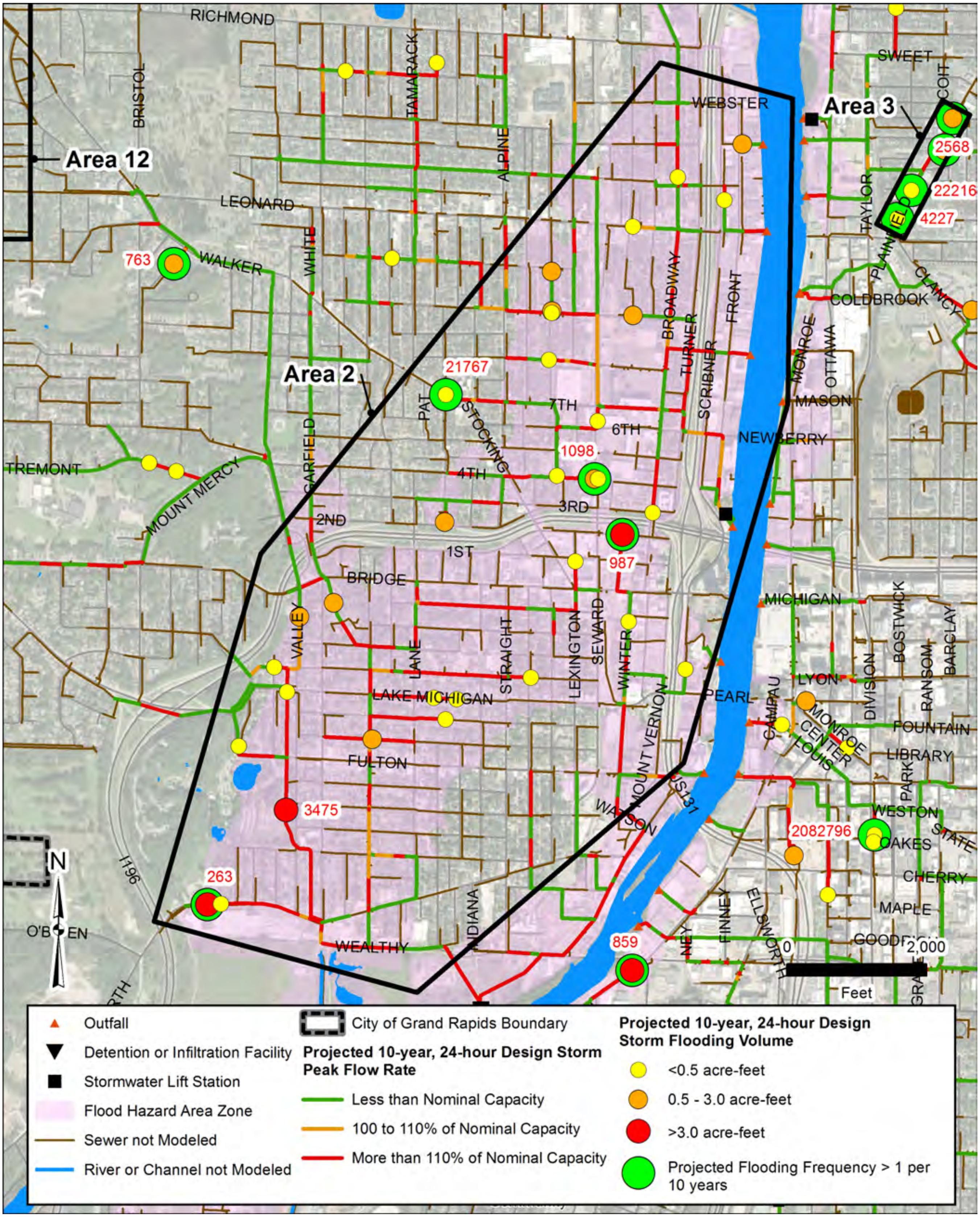


Figure 5-6. Projected Capacity Restrictions in Area 5

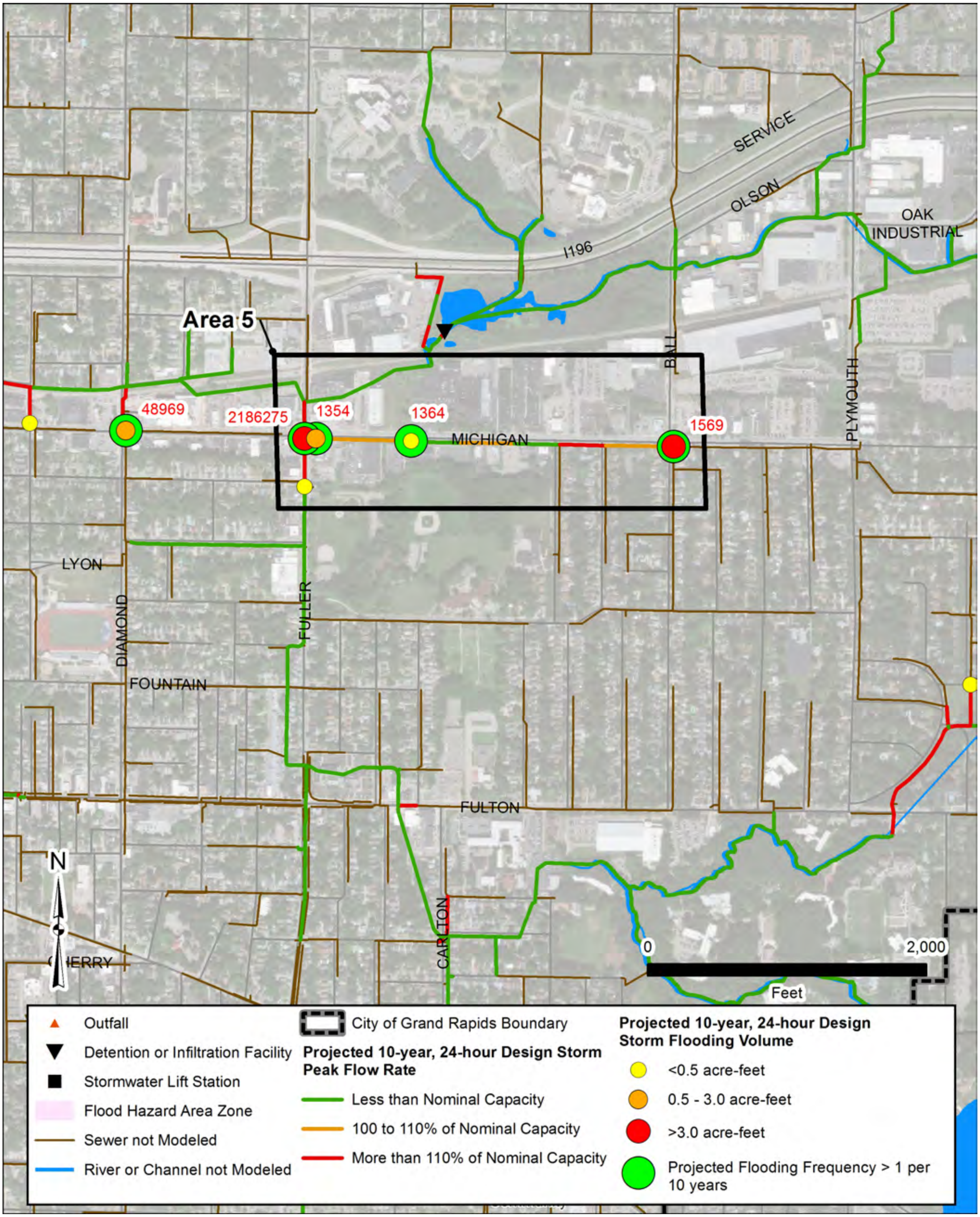


Figure 5-7. Projected Capacity Restrictions in Areas 6, 7, 8, 9, and 11

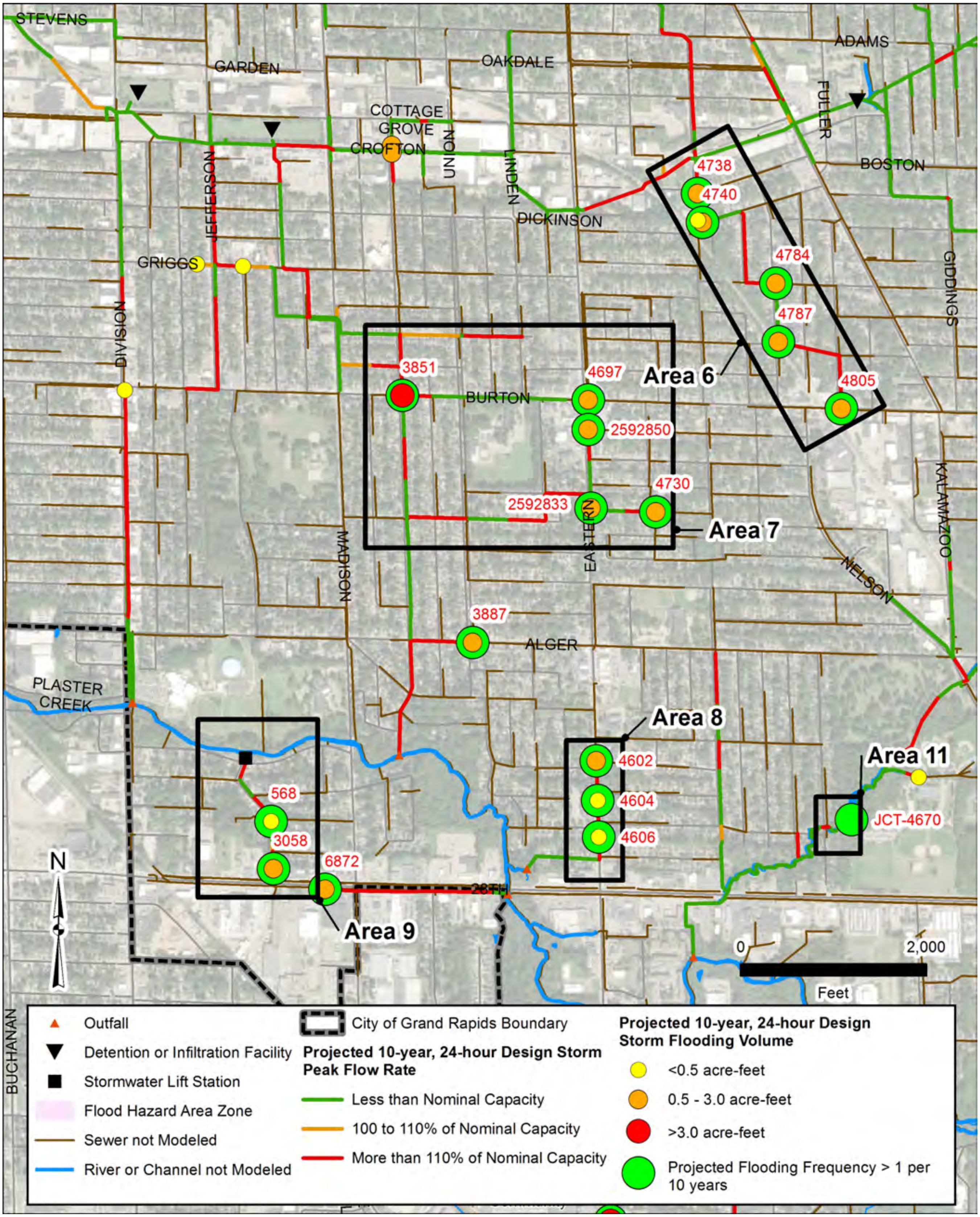
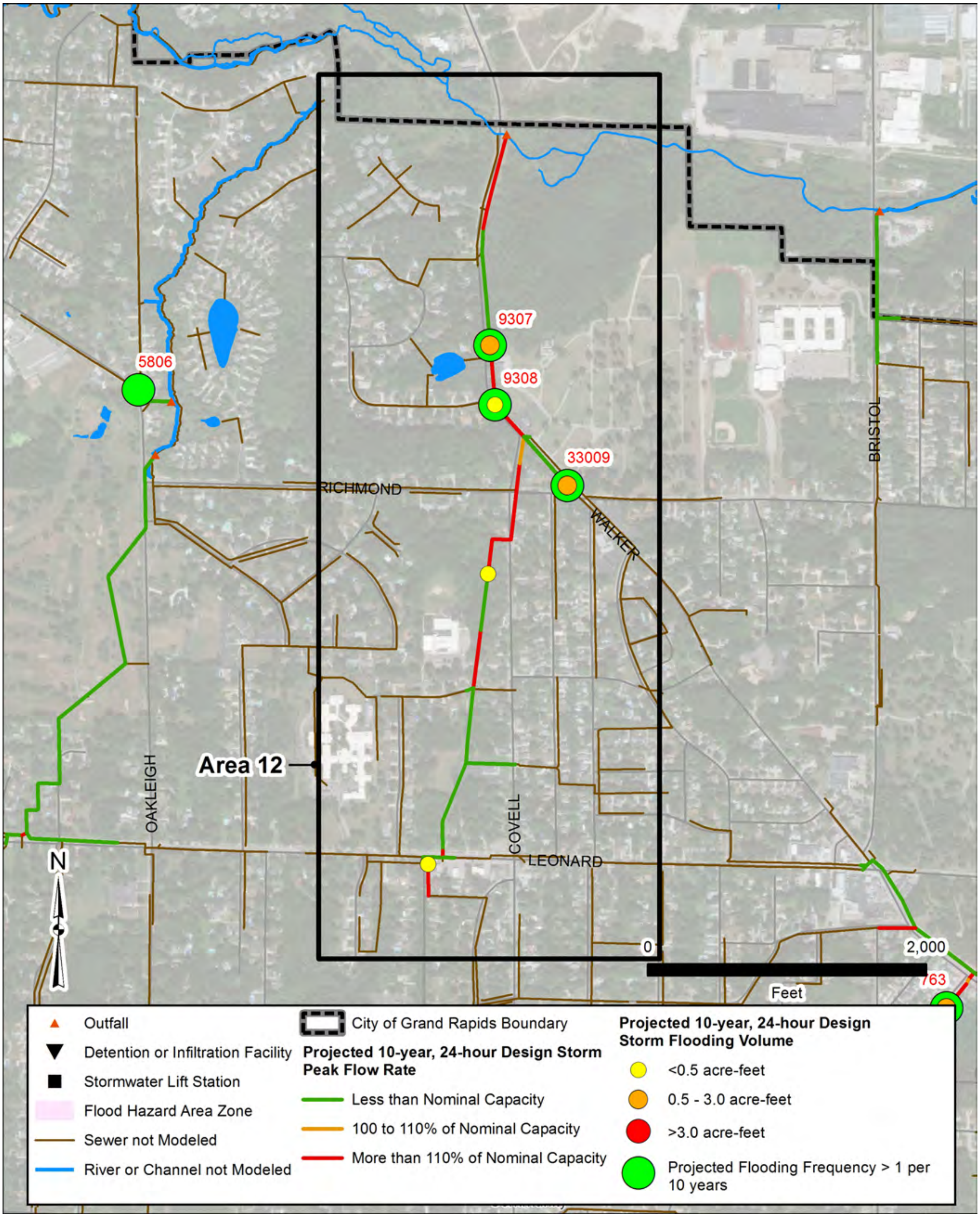


Figure 5-8. Projected Capacity Restrictions in Area 12



6.0 FUTURE MODEL USES

The model was developed to be a tool for the City to use and update periodically as the system changes; therefore, it is important for the user of the model to understand its limitations and intended uses.

6.1 MODEL LIMITATIONS

The model will provide results for any set of conditions, but not all conditions may be appropriate. Model limitations describe conditions which biased model results or may not be appropriate.

6.1.1 Software Limitations

Software limitations are those issues which are inherent to the modeling platform and its calculations.

- Some of the short pipes in the model cause numerical instabilities, so the conduit lengthening feature within SWMM was set to 5 seconds to reduce the calculation instabilities. While SWMM automatically accounts for the increased conduit length with a decreased roughness coefficient, artificially longer conduits add storage volume to the system and, therefore, may artificially reduce the HGL indirectly through a reduction in flow rate. For this project, the benefits of better model stability outweigh the additional storage volume because the volume added was small relative to the total volume passing through the pipe network. If the City chooses to clean the GIS data (see Section 6.2), merging unnecessary short pipes would reduce the need for artificial conduit lengthening.
- The inertial terms in the dynamic wave equation, which account for the momentum of the flow, were kept. The benefit of keeping the inertial terms and using a generally more accurate equation outweighed the risk of more numerical instability in some locations under some hydraulic conditions than dampening or ignoring the inertial terms.

6.1.2 Model Network Limitations

Model network limitations are caused by the extent to which the sewers and channels are represented in the model.

- Only sewers 30 inches in diameter and larger and those channels and facilities downstream of such sewers were actively modeled. The model contains the remaining conveyance network, but the dimensions and elevations of those inactive sewers and channels must be reviewed for accuracy before being activated in the model. Furthermore, if pipe network is added subcatchments may need to be divided and the calibration verified.
- The collection system was modeled as a one-dimensional (1D) system. InfoSWMM has two-dimensional (2D) modeling capabilities and portions or all of the model could be converted to a 2D model to simulate overland flow (overland flow contained to the street could be approximated in a 1D model). 2D modeling is most beneficial where there are overland flow concerns. While 2D models provide more data, including (but not limited to) predicting the magnitude and location of overland flow and the interaction between catch basins and the sewer system, they also require more effort to develop. A high-resolution ground surface is recommended, especially in flat areas of the City, where multiple overland flow paths are possible. Furthermore, in areas where 2D modeling is implemented the pipe network would have to be expanded to include every catch basin, since each catch basin is the connection between the overland and sewer flows. The catch basin inlet hydraulics would have to be defined based on common grate and inlet types that the City uses.
- Since overland flow was not considered, it is assumed that runoff is not restricted by the number and capacity of the catch basins and other inlet structures. Therefore, all runoff enters the collection system

(unless the conveyance network has enough energy losses to cause the hydraulic grade line to reach the ground surface). For this reason, the model may overestimate flows during simulations of large design storms because of inlet (catch basin) capacity restrictions that are not reflected in the model. Typically, inlets begin to restrict flow into the sewer for events larger than the 10-year design storm but may restrict flow into the sewer during smaller events if the number of catch basins are inadequate or they are clogged with debris.

6.1.3 Limitations Associated with Available Data and Calibration Steps

The lack of availability of precise data and the calibration methodology can create model limitations.

- The model was not calibrated for snow and ice precipitation or snowmelt events and should not be used to simulate those types of events without additional calibration.
- The depth in the sewer for larger events was preferentially calibrated. A variable roughness coefficient was not used, and the model may be less accurate at smaller depths.
- While only a small component of the flow, the meters had limited ability to measure dry weather flow. Flow meters typically are less accurate when depths are small, which occurs during low flow in large pipes. While this is not a concern for a capacity analysis, which typically looks at large design storms, it may be a limitation during the evaluation of water quality, which may require estimates of discharge during low flow conditions to estimate pollutant loadings in portions of the collection system that have base flows.
- The calibration of the model was completed using data from a six-month period. If the rainfall and antecedent moisture patterns deviate from the conditions during the monitoring period, the model may over- or underestimate flow rate, volume, and depth for those other conditions.
- The initial and calibrated saturated (minimum) infiltration rates exceeded the maximum measured rainfall intensity in some areas, making it impossible to define a saturated infiltration rate. The model may underestimate runoff during rainfall events larger than those that occurred during the flow monitoring period.
- Some areas were not calibrated (see ***Figure 1-1***) and were given input parameters based on neighboring areas with similar characteristics that were calibrated. Additional flow monitoring in the uncalibrated areas would decrease uncertainty of the flow rate, volume, and depth.
- Furthermore, flow rate, volume, and depth for sewers far upstream of meters were extrapolated from the nearest downstream meter. The further upstream of the meter location, the more uncertainty there is in the modeled flows. Additional monitoring in areas like the upstream reaches, particularly along Coldbrook Creek and Silver Creek, would provide more resolution in upstream reaches.
- Survey cross-sections of channels were obtained in many areas, but for detailed analysis additional cross-sections may be warranted. The cross-sections that were surveyed are provided in the electronic files (…\Electronic Data\Geodatabase).
- No measurements of the weir downstream of Fisk Lake were collected. Understanding the physical dimensions of the weir and monitoring the flow rate over it would help refine modeled flows entering Coldbrook Creek from Fisk Lake.
- The model calibration was completed using GARR, which provides more precise rainfall data than ground-based rain gauges. If the City wishes to model real rainfall events in the future, GARR data is more appropriate for the model setup, but also costlier to obtain.

6.1.4 Limitations When Reviewing Results

The model output must be reviewed, even for a well calibrated model. The user should be aware that the model simulates a particular condition and that the output is a projection of what may occur. Models are often the only source of identifying hydraulic capacity constraints for infrequent events, but if they do not agree with observations, the model results should be reviewed to understand the reasons and the model improved, if necessary.

- The model was calibrated using spatially-varying radar rainfall. The capacity analysis (both the design storm and long-term simulation) used a single rainfall for every subcatchment at every time step, which likely would not happen during a real rainfall. The movement of rainfall across an area the size of Grand Rapids may enhance or diminish flows in the sewer depending on location. Therefore, the capacity analysis is an approximation and real events of similar magnitude could produce higher or lower flow rates, hydraulic grade line, and flooding.

6.2 INTEGRATING A HYDRAULIC MODEL AND GIS DATA

Currently, the City's stormwater collection system database, while thorough, is designed more for mapping tasks than modeling tasks. Improvements can be made to the GIS database so that it provides good mapping and modeling functionality. One of the largest issues was that many portions of the City's GIS database did not have proper node and link connectivity and Tetra Tech had to split pipes and add junctions. There are also fields that have missing or inaccurate data. Also, several duplicate Facility IDs were found in the GIS database and the current Facility ID nomenclature is not user friendly because it was difficult to sort since the length of the Facility ID varied and the model treats numerical Facility IDs in GIS as text. Because of this, leading zeroes are often dropped when exporting the model input and output to a spreadsheet.

It is recommended that the City update their GIS database to a modeling compatible format and review differences in the data between the model and the GIS database. The modeled version of the collection system network is provided electronically (at …\Electronic Data\Geodatabase) so that the City staff can see the differences between the two datasets and make updates to the GIS or model data as appropriate. While the current naming convention works, adding a lettered prefix and fixing the length of the Facility ID to a common value would improve the efficiency of the modeler when evaluating inputs and post-processing the data.

6.3 HOW TO USE THE MODEL

City staff plan to continue to update its GIS data and collect flow and rainfall data, which could be used in conjunction with the collection system model. The following list identifies the modeling approach for possible future data collection tasks.

Data controls tasks include:

- Maintain a master model, which can be given to City staff or consultants for specific projects. The master model is intended to maintain the accuracy of the model and address physical changes to the collection system due to development or infrastructure improvements or corrections to the GIS database. Having a single party responsible for maintaining a master model will allow a consistent modeling approach and ensure that current modeling conditions are not unintentionally modified during project-specific tasks that often look at alternatives.
  - Update GIS. It is helpful to maintain a date edited field to flag recent changes to the database.
  - Import GIS data into the model and prepare for future modeling. Record drawings are helpful, particularly where more complex infrastructure, such as pumps, detention, weirs, and non-circular pipes need to be represented in the model.
  - Annual updates are recommended or as needed to support infrastructure design.
  - After changes are made, the calibration should be rechecked and adjusted as appropriate to maintain consistency with the calibration.

- Modeling to support infrastructure design:
  - Update the master model as necessary within the proposed project area and adjacent areas. Updates may be necessary to the subcatchment boundaries.
  - If the project is in a previously uncalibrated area, flow monitoring and calibration of that area may be beneficial prior to design to better understand hydrologic and hydraulic conditions.
  - The engineer for the design project should obtain the current version of the master model from the City for use on the project.
  - No edits to the master model should be made until construction is complete unless an error is identified in an area not changed by the construction.
  - After construction, update GIS, then import the GIS data into the model.
- Flow monitoring at outfalls and along sewers larger than 30 inches in diameter.
  - From a wet weather flow standpoint, flow monitoring can be used to calibrate previously uncalibrated areas or update the calibration in areas where the hydrology has changed due to development, green infrastructure, or environmental factors.
  - From a dry weather flow standpoint, the model can be updated (if the data is collected) to include a more precise representation of the dry weather flows, which were difficult to capture in the wet weather flow monitoring because of the low flow depth.
- Flow monitoring in upstream areas or smaller diameter systems can be used to expand the portion of the model that is calibrated.
  - Update the master model and actively model the proposed flow monitoring area. Updates to the subcatchment boundaries would be likely for this type of work.
  - Recalibrate the master model within the proposed flow monitoring area.
  - Ensure that the calibration at downstream meter locations remains accurate.

7.0 RECOMMENDATIONS

The purpose of the recommendations varies from maintaining and improving the model to the results of the capacity analysis. Specific infrastructure recommendations are not provided since modeling of alternatives to mitigate projected flooding was not completed as part of the capacity analysis.

Model maintenance recommendations:

- Maintain a master version of the model to provide to City staff and consultants for future projects
- Update the model annually and document the changes

Model improvement recommendations to the current active model extents:

- Update the City's GIS data to be compatible with modeling needs.
- Measure the dimensions of the weir downstream of Fisk Lake and add weir detail to the model.
- Collect additional survey cross-sections of channels, in 300- to 500-foot intervals, except near culverts and inlet and outlet structures, which should have cross-sections within 50 feet of the culvert or structure.

Data collection recommendations in areas outside the current active model extents or as part of a citywide effort:

- Conduct flow monitoring in areas that were not metered in 2018.
- Complete quality check measurements of the flow monitoring data as it is collected.
- Collect data for a high-resolution ground surface.
- Conduct flow monitoring to more accurately measure base flows at locations where water quality assessments are made.
- Supplement the impervious cover analysis with a pervious cover analysis to define the types of pervious cover, such as lawns, open park or recreational areas, and wooded areas.

Future modeling recommendations:

- Add detail to the model for smaller diameter sewers as necessary. Flow monitoring may be necessary to calibrate those areas if they are not upstream of meters used in the 2018 flow monitoring program.
- Add 2D model functionality in areas prone to overland flow, especially where the overland flow is outside the street. Inlet (catch basin) capacity should be added to the model with the 2D model functionality.

Infrastructure recommendations:

- Develop alternatives for the areas projected to have capacity limitations and add the infrastructure improvements to the City's infrastructure planning documents for prioritization.
- Evaluate Indian Mill and Ken-O-Sha Pump Station in more detail to assess whether or not the frequency at which the firm capacity is projected to be exceeded would cause upstream flooding more than the frequency set in targeted level of service.