BROADVIEW SEWER SYSTEM STUDY AREA

Modeling Report

Prepared for

Seattle Public Utilities

December 2009

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BROADVIEW SEWER SYSTEM STUDY AREA

Modeling Report

Prepared for

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Project Background

Seattle Public Utilities (SPU) is investigating alternatives to reduce the frequency of sewage backups in Broadview, located within the Carkeek Basin in northwest Seattle (Figure 1). Sewage backups in Broadview are caused by numerous factors, including high rates of inflow and infiltration (I/I), areas of low hydraulic capacity, and the low elevation of basements and finish floors relative to the mainline sewer.

In developing engineering alternatives to alleviate sewage backup, it is necessary to have an accurate model of the rainfall runoff processes and the routing of flows within the sewer pipe system. An Environmental Protection Agency Stormwater Management Model Version 5.0 (EPA-SWMM 5) was developed for this purpose.

SPU has retained Herrera Environmental Consultants (Herrera) to develop the flow monitoring Quality Assurance Project Plan, conduct flow data validation, develop a hydraulic model of the basin, analyze engineering alternatives, assist with community involvement, and prepare a project report with a recommended preferred alternative. SPU retained ADS Environmental Services (ADS) to perform flow and water level monitoring in the sewer pipe system.

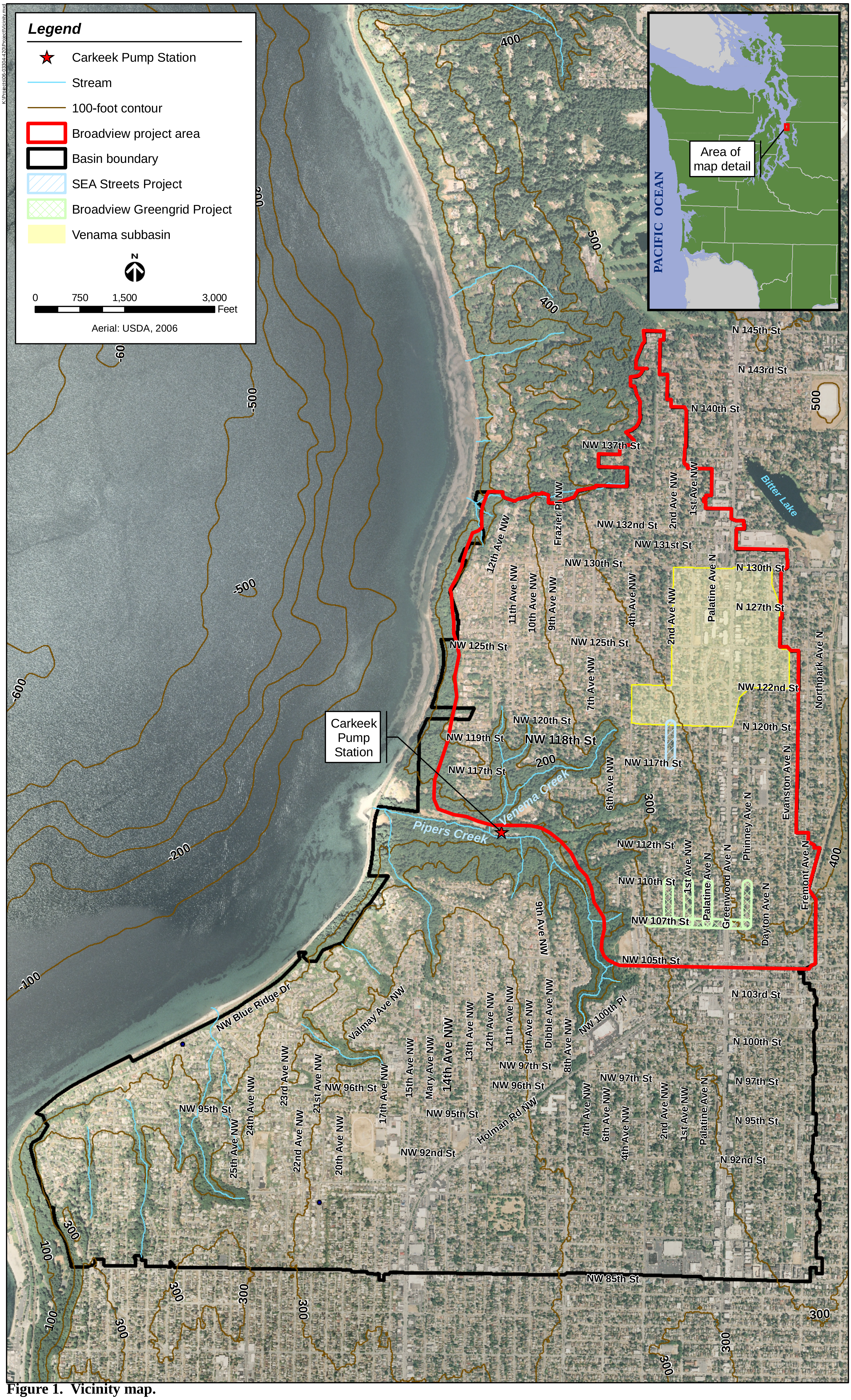


Figure 1. Vicinity map.

Purpose of this Report

The purpose of this report is to document the methods used and the results obtained from modeling of Broadview with the EPA-SWMM 5 modeling platform. The modeling performed investigates the causes of historical backups in the area and evaluates three engineering alternatives designed to reduce the likelihood and magnitude of potential future sewer backups.

The remainder of this report provides a brief overview of project background information, describes the Carkeek Basin and the smaller Broadview study area located in the northern portion of the basin referred to as Broadview. It also discusses the modeling objectives, data used, model calibration, model implementation, and analysis of model results to evaluate current and future conditions for various engineering alternatives.

Carkeek Basin and Broadview Description

The Carkeek Basin covers approximately 2,576 acres and is roughly bounded by Puget Sound to the west, North 145th Street to the north, Fremont Avenue North to the east, and Northwest 85th Street to the south. The Carkeek Park Pump Station, located at 855 NW 114th Place and owned and operated by King County Wastewater Treatment Division, pumps sewage south to the West Point Treatment Plant during normal flow conditions and to the co-located Carkeek Park Treatment Plant during wet weather conditions. The Carkeek Park Treatment Plant provides primary treatment of sewer flows before discharging to the Puget Sound.

SPU delineated a smaller study area within the Carkeek Basin based on historical sewer backup complaints by residents and businesses (Figure 2). The study area is located in Broadview, located in the northern portion of the Carkeek Basin. It covers approximately 990 acres. The northern, eastern, and western boundaries of the study area approximately overlap the respective boundaries of the Carkeek Basin, described above. Northwest 105th Street and the trunk of the sewer pipe system from Northwest 105th Street to the outfall to Puget Sound form the southern boundary of the study area. While the Carkeek Park Pump Station and Treatment Plant are not physically located within the study area, they provide the downstream boundary condition for the EPA SWMM 5 model, as described in greater detail below.

Both a sanitary sewer pipe system and a storm drainage system serve the study area. The sewer pipe system consists primarily of 3-foot sections of 6 to 12-inch-diameter concrete pipes with brick and mortar maintenance holes. The storm drainage system consists primarily of an informal network of roadside ditches and culverts (King County 2002).

Detailed modeling of the Broadview sanitary sewer pipe system including sanitary baseflows, rainfall runoff, and (I/I), was performed. Inflows to the Carkeek Park Pump Station and Treatment Plant from the remaining portions of the Carkeek Basin outside of the study area were represented as boundary condition model inputs. Storm drainage system modeling was not included as part of this study. A detailed description of the modeling methodologies and assumptions for the sewer pipe system is presented below.

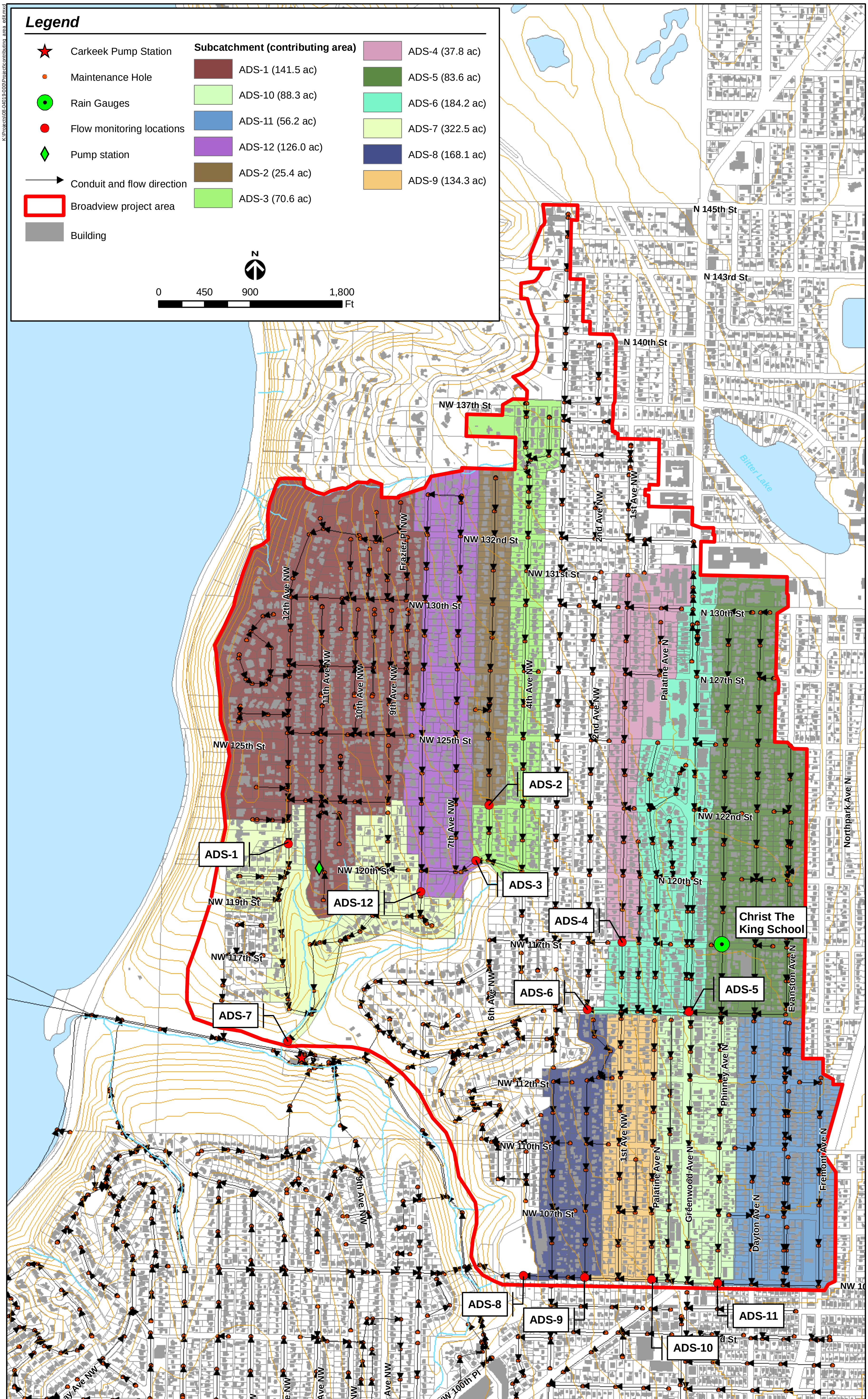


Figure 2. Broadview study area, subbasin delineation, gauges, and EPA-SWMM 5 model components.

Modeling Objectives

The main modeling objective is to evaluate engineering alternatives for reducing sewer backups in Broadview. Because the study area is located several hundred feet in elevation above the Carkeek Park Pump Station and Treatment Plant, it is assumed that the sewer backups are not affected by the operation of these facilities. However, the engineering alternatives could affect conveyance of sanitary sewer flows to these facilities. Therefore, a secondary objective of the modeling is to quantify additional flow to the Carkeek Park Pump Station and Treatment Plant.

Data Used in Modeling

This section provides a description of the data used in the modeling, including observed discharge and water level in the pipe network, precipitation, downspout connectivity, maintenance, and locations of historical sewer backups in the study area.

Discharge

Multiple sources of discharge data were used in the study (Table 1, Figure 2). The primary sources of flow data used for model calibration were the 12 ADS Flow Sharks that were installed around September 18, 2008. The ADS flow sensors collected data for a 5-month period and were removed on February 20, 2009. The locations of these flow sensors also provide the basis for the subcatchment delineation utilized in the EPA-SWMM 5 model (Figure 2). Further information on these sensors and the discharge data obtained from them can be found in the Broadview Flow and Water Level Monitoring Quality Assurance Project Plan (Herrera 2008) and the September 19, 2008 – March 1, 2009 Hydrologic Data Validation Review for the Broadview Flow Monitoring Project Memorandum (Herrera 2009a). Flow and water level data from the Carkeek Park Pump Station and Treatment Plant and the North Beach Pump Station were provided by King County and was used offline for additional model validation.

It was initially anticipated that King County Department of Assessment data, water consumption data, and demographic data would be used to assess baseline sanitary flows based on population and land use type; however, a 10-day dry period at the end of October 2008 made it possible to obtain baseline sanitary flows directly from the observed ADS flow data. Obtaining dry weather flow parameters directly from the observed flow data reduced the amount of required assumptions (e.g., population distribution, land use type, water demand, return flows, etc). Therefore, potential errors were reduced and allowed for a better comparison of dry and wet weather flows for partitioning out the I/I contribution. Further information on model calibration procedures used in this study can be found in the “Model Calibration” section below.

Precipitation

Two SPU precipitation gauges, RG1 and RG7 (Table 2, Figure 2), are used for model calibration, validation, and analysis of alternatives. SPU RG1 is located at Haller Lake Shop, and SPU RG7 is located at Whitman Middle School. Additional rainfall data from Christ the King School were also obtained for the period of interest but not used due to the exceptional quality of the RG1 and RG7 data. The rain gauge used in each subcatchment in the EPA-SWMM 5 model are shown in Table 3. The nearest rain gage to each subcatchment was used in the model (nearest neighbor interpolation). Different periods of the precipitation record are used for the different modeling steps (i.e., calibration, validation, and analysis of alternatives). The precipitation period used during each modeling step is given in table 2, as well as described in detail in the appropriate sections of this report.

Table 1. Discharge data used in this study.

Flow Meter Number [a, b, c]	Agency That Maintains the Meter	Maintenance Hole #	Location of Meter in Maintenance Hole	Timestep (minutes)	Intersection Streets
ADS-1	ADS, on behalf of SPU	224-025	North	5	12th Ave. NW, South of NW 121st St.
ADS-2	ADS, on behalf of SPU	224-042	North	5	6th Ave. NW, South of NW 122nd St.
ADS-3	ADS, on behalf of SPU	224-103	East	5	NW 120th St., Between 6th Ave. NW and 7th Ave. NW
ADS-4	ADS, on behalf of SPU	224-144	North	5	1st Ave. NW and NW 117th St.
ADS-5	ADS, on behalf of SPU	225-070	North	5	Greenwood Ave. N and N 115th St.
ADS-6	ADS, on behalf of SPU	224-197	East	5	2nd Ave. NW and NW 115th St.
ADS-7	ADS, on behalf of SPU	224-160	North	5	900 Block of NW Carkeek Park Rd.
ADS-8	ADS, on behalf of SPU	224-318	East	5	NW 105th St., Between 6th Ave. NW and 3rd Ave. NW
ADS-9	ADS, on behalf of SPU	224-331	East	5	2nd Ave. NW and NW 105th St.
ADS-10	ADS, on behalf of SPU	224-341	North	5	Palatine Ave. N and NW 105th St.
ADS-11	ADS, on behalf of SPU	232-002	East	5	Phinney Ave. N and N 105th St.
ADS-12	ADS, on behalf of SPU	224-097/415	North	5	8th Ave. NW and North of NW 118th St.
CK-TP, CK-PS	King County	N/A	N/A	N/A [c]	Carkeek Park Pump Station and Treatment Plant, 855 NW 114th Pl.
NB-PS	King County	N/A	N/A	N/A [c]	North Beach Pump Station
CRK-4	King County	224-097	North	5	8th Ave. NW and North of NW 118th St.
CRK-5	King County	224-067	North	5	12th Ave. NW and North 119th St.

N/A Not available

[a] ADS flow meters installed around September 18, 2008 and removed on February 20, 2009.

[b] King County flow meters CRK-4 and CRK-5 have a period of record of 2/12/1999-3/2/1999 and 2/11/1999 – 9/9/1999, respectively.

[c] Data for Carkeek Park Pump Station and Treatment Plant (CK-PS and CK-TP) and North Beach Pump Station (NB-PS) provided by King County.

Table 2. Precipitation data used in this study.

Rain Gauge ID	Period	Timestep	
SPU RG1 & RG7	9/18/2008 – 2/18/2009	5-minute	Calibration
SPU RG1 & RG7	100-year event, 12/3/2007	10-minute	Validation
SPU RG1 & RG7	6-month to 100-year events	10-minute	Model Analysis

Table 3. Rain gauge used in each subcatchment based on nearest neighbor method.

Subcatchment	Rain Gauge ID
ADS-1	SPU RG7
ADS-2	SPU RG1
ADS-3	SPU RG1
ADS-4	SPU RG1
ADS-5	SPU RG1
ADS-6	SPU RG1
ADS-7	SPU RG7
ADS-8	SPU RG7
ADS-9	SPU RG7
ADS-10	SPU RG1
ADS-11	SPU RG1
ADS-12	SPU RG1
Upper Basin	SPU RG1
Lower Basin	SPU RG7

Impervious Area Connectivity

The Broadview smoke testing analysis performed by SvR (SvR 2008) and the King County downspout connectivity study was used to estimate the area of impervious surfaces directly connected to the sewer system. This analysis was used to determine connectivity to be incorporated into the EPA-SWMM 5 model and to evaluate Alternative 2 Inflow Reduction. In preparing the Alternative 2 Inflow Reduction modeling parameters, smoke test results were analyzed along with additional information to determine what percent of roof downspouts could be disconnected to the sewer system. Further details on this analysis are provided under section "Analysis of Alternatives / Alternative 2, Inflow Reduction".

Pipe Conditions and Maintenance

Herrera obtained SPU maintenance records and CCTV inspection of pipe upstream and downstream of reported flooding locations to determine the existing condition of the pipes adjacent to sewer backups. The maintenance logs were used to determine a correlation between reported sewer problems and repeated maintenance issues. CCTV was used to analyze the current condition of the pipe. Results of maintenance records analysis are presented in the Problem Identification Technical Memorandum (Herrera 2008b). CCTV results are presented in Figure 3.

Historical Sewer Backup Locations

The locations of historical sewer backups in the study area are based on SPU GIS data and are shown in Figure 2. Additional information on these sites can be found in the Problem Identification Technical Memo (Herrera 2008b); however, a brief description below highlights the locations of the most frequent sewer backups.

1st Avenue NW to the north of NW 115th Street

Three homes on 1st Avenue to the north of NW 115th Street have experienced sewer backups on July 19th 1992, December 30th 1996, and December 3rd 2007. The 1992 backup occurred at one home and on a day with no precipitation. The reported backups in 1996 and 2007 occurred at three homes and were associated with storms of return intervals greater than 100 years. All three homes that experienced sewer backups are located on the low side of the street (west side) which is a contributing factor to sewer backups in their basements. A visual inspection of the maintenance hole downstream from these homes (maintenance hole 224-201, corner of 1st Avenue NW and NW 115th Street) showed signs of surcharge to a depth near the maintenance hole rim. Estimates performed in the field at this time indicated that the elevation of the surcharging in maintenance hole 224-201 was at or near the level of the basements of the homes that have had historic sewer backups. The nearby homes that have not experienced backups generally have basement elevations that are located above the elevation of the surcharge mark in maintenance hole 224-201.

6th and 7th Avenue NW north of NW 120th Street

Several homes near the intersections of 6th and 7th Avenue NW and NW 120th Street have experienced sewer backups in the past. Backups in five homes on 6th Avenue NW occurred on December 30th 1996 and December 3rd 2007, which were both 130-year events. Similar to the situation on 1st Avenue, the homes along 6th Avenue that experienced backups are on the low side of the street and have basements at elevations near the high water surcharge mark in the downstream maintenance hole. Four homes on 7th Avenue NW experienced backups in the 1996 event, while only one home experienced a backup in the 2007 event. The reduction in the number of homes along 7th Avenue experiencing sewer backups during the 2007 event compared to the 1996 event is attributed to the upsizing of the downstream sewer conduit from an 8 inch to a 15 inch in 1998.

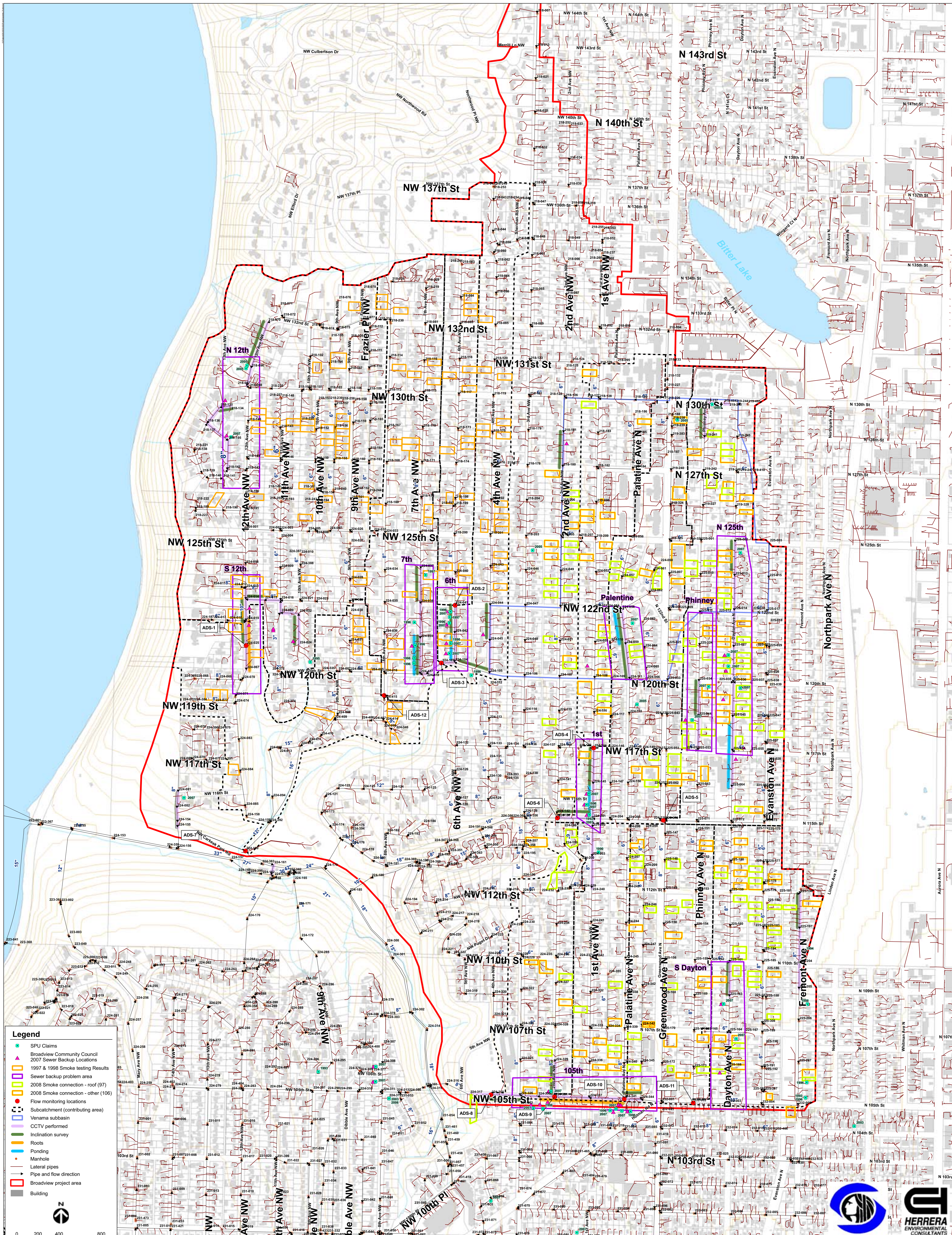


Figure 3. Sewer backup locations, smoke testing, inclination and CCTV for the Broadview area.

12th Avenue NW

A handful of homes along 12th Avenue NW have reported sewer backups in the past. SPU claims data and information gathered from the Broadview Community Action Group show the backup locations to be quite spread out, ranging from north of NW 130th Street to NW 120th Street. Conversations with residents during a site visit performed in the fall of 2008 indicate that additional sewer backups occurred on 12th Avenue NW between NW 120th and NW 122nd Street that are not reflected in either the aforementioned data sets. This information, along with the precipitation record showing no precipitation on the dates of the backups for the homes north of NW 130th Street, have narrowed the focus for an engineered solution to the area of 12th near NW 120th and NW 122nd Street.

NW 105th Street to the east of Greenwood Avenue

Sewer backups have been reported at two locations along NW 105th Street. The further east location is near the intersection of Palatine Avenue N, while the western location is at the intersection of 2nd Avenue NW. Both locations have four homes that experienced backups on December 3, 2007, and one to two homes that experienced backups on December 30, 1996.

Dayton Avenue NW between NW 117th Street and NW 122nd Street

A cluster of homes centered on NW 120th Street and Dayton Avenue N experienced sewer backups during the December 3, 2007 storm event. SPU and Broadview Community Action Group data show seven home experienced backups on this day. However, conversations with residents along Dayton Avenue N indicate that the number of impacted homes may actually be significantly higher. Residents pointed out six or more additional homes that experienced backups that are not reflected in the claims or community group data. These residents also relayed that the sewer backups were caused by debris in the pipe near Christ the King School, and that when maintenance crews showed up and removed the blockage that the surcharging in the maintenance holes and sewer backups ceased immediately. The information about the blockage, however, is not contained in the SPU maintenance records and there is some uncertainty as to whether or not this blockage actually existed.

EPA-SWMM 5 Model

An existing EPA-SWMM Version 5.0 Model (EPA-SWMM 5) of the basin was provided by SPU. The model covers the entire Carkeek Basin (approximately 2,576 acres), including over 1,900 pipes, 4 pump stations, and 2 outfalls. A separate model of Broadview was extracted from this basin model. Within the study area, there are two subbasins, 224-161 and 224-316, which cover approximately 345 acres and 604 acres, respectively (Figure 1 and 2). Below is a description of the subcatchments, pipes (or links), and nodes (or maintenance holes and structures) that make up the study area model. Also provided below is a description of the upstream tributary areas and the conduit QA/QC that was performed.

Subcatchments

The study area was delineated into 14 subcatchments, based on the location of the flow monitors installed and operated by ADS (Figure 2, Table 4). The contributing area of each of the 12 flow monitors is a subcatchment, and the remaining land area not captured by flow monitors is divided into two additional subcatchments. Subcatchment name, outlet maintenance hole number, area of subcatchment, number of nodes, and area per node are shown in Table 4. The purpose of delineating the smaller subcatchments is to allow for better spatial characterization of the parameters that influence the basin's dry weather flow as well as response to rain events.

Table 4. Subcatchment area, outlet maintenance hole number, number of nodes, and area per node for the study area.

Subcatchment	Outlet	Area (acres)	Nodes	Area per node (acres)
ADS-1	224-019	141.5	110	1.29
ADS-2	224-041	25.4	13	1.95
ADS-3	224-104	45.2	28	1.61
ADS-4	224-116	37.8	17	2.22
ADS-5	225-071	83.6	54	1.55
ADS-6	224-201	62.8	48	1.31
ADS-7	224-159	55.0	36	1.53
ADS-8	224-326	33.8	24	1.41
ADS-9	224-337	46.0	19	2.42
ADS-10	224-344	32.1	26	1.23
ADS-11	232-003	56.2	42	1.34
ADS-12	224-416	55.4	28	1.98
Upper Basin	224-126	148.3	83	1.78
Lower Basin	224-153	70.6	103	.69
Total	N/A	893.7	631	N/A

Upstream Tributaries

There are no upstream drainage areas that are tributary to Broadview.

Downstream Boundary Conditions

The downstream boundary for the EPA-SWMM 5 model is the Carkeek Park Pump Station and Treatment Plant. This allows for the analysis of potential impacts of the engineering alternatives on Carkeek Park Pump Station overflows and Treatment Plant flows. Consistent with the primary goal of the modeling, as described in the Modeling Methodologies Memorandum (Herrera 2008c), detailed modeling was performed for Broadview only. The inflows to the Carkeek Park Pump Station and Treatment Plant from the study area were evaluated with respect to potential increases in discharges to the pump station due to the engineered alternatives.

Pipe Network

The EPA-SWMM 5 model of the study area represents the modeled sewer pipe system in the form of nodes and links. The locations of the nodes and links in the network are based on Geographic Information System (GIS) data provided by SPU. A detailed Quality Assurance/Quality Control (QA/QC) check was performed on the attributes of the nodes and links in the GIS data before they were used in modeling. The QA/QC process is described in the “Conduit QA/QC” section below, while details on the pipe network changes that were made are contained in Appendix A.

Links

Links are the conveyance components of a sanitary and drainage system and always lie between a pair of nodes. Links can consist of conduits (pipes) and pumps. The EPA-SWMM 5 model for Broadview consists of 400 conduits generally ranging from 6 to 36 inches in diameter. The total length of the conduits is 17.2 miles. One pump unit is located upstream of the Carkeek Park Pump Station and Treatment Plant, which is associated with the storage unit 224-271.

Nodes

Nodes in the EPA-SWMM 5 model consist of junctions, outfalls, flow dividers, and storage units. Junctions are sanitary and drainage system nodes where links join together and usually take the form of maintenance holes. The model of the study area has 630 junctions, and one storage unit.

Pipe Network QA/QC

During the model construction process, QA/QC was preformed to ensure that the EPA-SWMM 5 model to be used for analysis of engineering alternatives was an accurate representation of the sewer pipe system in the study area. The QA/QC steps include:

1. Ensure that the most up to date data are used, such as GIS, as-builts, survey, and observations recorded during field reconnaissance.

2. Fill-in missing data and correct incorrect data. This included interpolating invert elevations and conduit slopes and filling in information with the data sources noted above. Continuity checks were performed to insure no conduits had negative slopes and that no outgoing conduits are higher than incoming conduits. Closed Circuit Television (CCTV), SPU's Virtual Vault, and As-Builts were used in this portion of the QA/QC process.

3. CCTV inspection and inclination data was used to adjust pipe slope in regions where significant settling has occurred.

Routing

Flow routing within a conduit link in EPA-SWMM 5 model is performed by the Dynamic Wave Routing Module, which is governed by the conservation of mass and momentum equations for steady, gradually varied, and unsteady flow. Dynamic Wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. These equations consist of the continuity and momentum equations for conduits and a volume continuity equation at nodes.

With the Dynamic Wave Routing Module it is possible to represent pressurized flow when a closed conduit becomes full, such that flows can exceed the full normal flow value. Flooding occurs when the water depth at a node exceeds the maximum available depth, and the excess flow is either lost from the system or can pond atop the node and re-enter the drainage system.

Dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal, and pressurized flow. Because it couples together the solution for both water levels at nodes and flow in conduits it can be applied to any general network layout, even those containing multiple downstream diversions and loops. It is the method of choice for systems subjected to significant backwater effects due to downstream flow restrictions and with flow regulation via weirs and orifices. This generality comes at a price of having to use much smaller time steps, on the order of a minute or less. In the EPA-SWMM 5 model of Broadview routing timestep was set at 10 seconds to provide the greatest accuracy and model stability.

Model Calibration

Discharge in the Broadview sewer system originates from two different sources; dry weather inflow and wet weather inflow. Dry weather inflows are continuous inflows that reflect the contribution from sanitary sewage along with the base flow in the pipes. Wet weather inflows are stormwater flows that enter sanitary or combined sewers due to "inflow" from direct connections of downspouts, sump pumps, foundation drains, etc. as well as "infiltration" of subsurface water through cracked pipes, leaky joints, poor maintenance hole connections, etc. The combination of I/I.

The model calibration for Broadview was divided into two steps: First the Dry Weather Flow (DWF) calibration and then the Wet Weather Flow (WWF) calibration. Both calibration processes are performed at the flow monitoring subcatchment scale. The following sections describe the calibration procedures used for both processes.

Dry Weather Flow Calibration

It was originally anticipated that King County Department of Assessments data, water consumption data, demographic data, land use data, population estimates, and per capita flow estimates would be used to generate a dry weather flow pattern; however, the ADS discharge monitoring period included a 10 day period of no precipitation which allowed for the direct usage of observed flow monitoring data to generate the dry weather flow patterns. The 10 day period of dry weather covered the period from October 21 through October 30, 2008. The first three days of this period are discarded to reduce the inflow from prior precipitation events, and the flow data from the remaining seven days are used to determine the magnitude and pattern of the dry weather flow for each subcatchment. The methodology used in the dry weather flow calibration process is described below, while dry weather flow calibration figures are shown Figures 1-12 in Appendix B. Additionally, Appendix B also contains a comparison between SPU estimates of Dry Weather Flow (based on population, landuse, etc) against the observed dry weather flows used in the EPA-SWMM model.

Dry Weather Flow Calibration Steps:

The dry weather flow calibration process was carried out in a series of steps that build upon each other. The steps are as follows:

Step 1: Calculate the minimum, average, and maximum discharge at each ADS flow sensor for the weekday portion of the dry weather flow calibration period (October 24 & October 27-30). The average weekday dry weather flows are given in Table 1 of Appendix B.

Step 2: Distribute the average weekday dry weather flow calculated at each ADS flow sensor evenly between all nodes upstream of that sensor. For example, if ADS-1 recorded an average dry weather flow of 0.1 cfs and there were 10 nodes upstream of it, then each node would contribute 0.01 cfs, for a total of 0.1 cfs.

Step 3: Generate 24 hourly factors to impose a diurnal cycle on the average dry weather flow at each flow sensor location. The hourly factors are used to reflect that weekday dry weather flow is at a minimum around 4 a.m., peaks around 9 a.m., dips during the middle of the day, has a secondary peak around 10 p.m., and then drops off during the night. The hourly factors are calculated by 1) averaging the 5-minute flow data for the five day weekday period into one day of average hourly values (one value for each hour of the day for a total of 24 values), and then 2) dividing each of these values by the average value calculated in step 1. For example, if ADS-1 recorded a daily average dry weather flow of 0.1 cfs and the average flow at 9 a.m. was 0.2 cfs, then the peaking factor for 9 a.m. would be 2. The peak hour factors used for each subcatchment are shown in Table 2 of Appendix B.

Step 4: The monitoring period of record was short and therefore did not capture dry weather flows over the whole year. However, an effort was made through the use of monthly peaking factors to simulate that dry weather flows are typically slightly higher in the wetter winter months. These monthly peaking factors, along with a 12 day baseflow recession from the Unit Hydrographs (discussed in the Wet Weather Calibration section) are used to account for the ground becoming saturated and continuing to discharge into the sewer system as infiltration for days or weeks after a storm has passed. The observed dry weather flow after a prolonged period of ground saturation (January 13 – January 20) was compared against the baseline dry period (October 24 – October 30). The monthly dry weather peaking factors generated from this comparison and are shown in Table 3 of Appendix B, while the monthly peaking factor is given in Table 4 of Appendix B.

Step 5: Generate two sets of weekend peaking factors that when multiplied against the weekday factors reflect the dry weather weekend pattern of flow. The weekend pattern consists of a peak flow slightly later in the day than the weekday pattern as well as higher midday flows. The two sets of peaking factors that were generated are called "Weekend01" and "Weekend02." The peaking factor used in each subcatchment is given in Table 4 of Appendix B with peaking factors presented in Table 5 of Appendix B.

Comparison of ADS observed versus SPU estimated Dry Weather Flow

It was originally anticipated that the Dry Weather Flow calibration for the EPA-SWMM 5 model would utilize estimates of sewer flow from Department of Assessment data, land use type, population distribution, and other data sources. Although estimates of this type are often used in modeling, when a 10-day period of dry weather occurred during the monitoring period it enabled direct usage of observed dry weather flow data and eliminated the need to base the calibration directly on estimates. Nonetheless, after the calibration steps above were completed, a comparison was made between the observed (ADS flow sensors) and estimated (Department of Assessment, land use type, etc) dry weather flow values. Table 6 in Appendix B shows the area, number of maintenance holes, and dry weather flow in each subbasin under both the ADS observed data and the SPU estimated data.

The two locations that show the greatest difference in dry weather flow values between the SPU estimates and ADS observations are at ADS-1 and ADS-11. Although it is possible that differences in the dry weather flow estimates may be due to errors in the ADS data (e.g., ADS-1 may be over-recording and ADS-11 may be under-recording), it is more likely that the SPU estimates contain incorrect assumptions, so the ADS observed data is used for the dry weather flow calibration process.

Wet Weather Flow Calibration

Wet weather inflows are also often called "Rainfall Derived Inflow and Infiltration" (RDII). These wet weather inflows (or RDII inflows) are computed for a given rainfall record based on a set of triangular unit hydrographs (UH). Each set of unit hydrographs contain three hydrographs, one for a short-term response, one for an intermediate-term response, and one for a long-term response. Each hydrograph shape is controlled by R, T, and K parameters which correspond to:

R: The fraction of rainfall volume that enters the sewer

T: The time from the onset of rainfall to the peak of the UH in hours

K: The ratio of time to recession of the UH to the time to peak

The wet weather calibration procedure includes assigning R, T, and K parameters for the short-, intermediate-, and long-term UH at the subcatchment scale for each month of the calibration period.

The wet weather flow calibration period for the EPA-SWMM 5 includes the entire period of record for the ADS flow monitors (September 19, 2008 – February 20, 2009). The ADS flow monitors were installed in the typically wet winter months to facilitate calibration of the EPA-SWMM 5 model over a range of precipitation magnitudes and groundwater saturation conditions. Also, most large storm events in the Western Washington area also occur during this period, so it was specifically desired that the ADS flow monitors would be in the pipe network during a large precipitation event so as to be able to measure the response of the pipe network to the amount of precipitation that has historically lead to sewer backups.

The project originally included installation of groundwater monitoring wells to assist with I/I analysis. However, during the course of the project, it was determined through discussions with SPU that no accurate correlation could be made between groundwater elevations and infiltration. Therefore, it was agreed to remove groundwater monitoring and use R, T, and K parameters to simulate I/I.

Details on the precipitation events used for wet weather calibration and the wet weather calibration process of assigning R, T, and K values are detailed below. Figures showing the wet weather calibration at each ADS flow sensor for all significant storms during the calibration period are presented in Appendix C. A statistical analysis of the goodness of fit of the modeled data to the observed data for these storms is presented in Appendix C. The final initial abstraction and R, T, and K parameters are also presented in Appendix C.

Data used for Wet Weather

The rainfall records from RG01 and RG07 (Table 2, Figure 2) were obtained from SPU after the ADS sensors collected 5 months of flow data in the basin. The rainfall record obtained included the period of overlap with the ADS sensor data, plus the 4 months preceding ADS sensor installation. This additional 4-month period was used for model spin-up to correctly simulate the antecedent moisture conditions in the area leading up to the calibration period. Data for RG01 and RG07 was applied to each subbasin using the nearest neighbor method (Table 3). Details on precipitation events that occurred during the monitoring period and adjustments to the rainfall data due to snow events are detailed below.

Storm Events used in Wet Weather Calibration

The precipitation events that occurred during the monitoring period are presented in Table 5 and Figures 4 and 5. The “Approximate Return Interval” is based on rainfall statistic for RG01 and RG07 from the report “Analysis of Precipitation-Frequency and Storm Characteristics for the City of Seattle” (MGS 2003). These statistics (i.e., 2-year, 25-year, 100-year precipitation depths) are shown on Figures 4 and 5 for 6-, 12-, 24-, and 48-hour duration storms.

Table 5. Storm events during the ADS flow monitoring period.

		Rainfall (inches)		Duration	Approximate Return
Storm	Date	RG01	RG07	(hours)	Interval (years)
1	10/3/2008	0.66	0.67	24	< 1
2	11/3/2008	0.96	0.89	12	< 1
3	11/6/2008	1.57	1.69	48	< 1
4	12/12/2008	0.56	0.62	24	< 1
5	12/24/2008	1.29	1.09	24	< 1
6	12/26/2008	0.81	0.22	24	< 1
7	1/5/2009	0.94	0.90	24	< 1
8	1/7/2009	1.33	1.33	12	~ 2

Seven storms occurred with return intervals of less than one year, while one 12-hour storm occurred with a return interval of approximately 2-years. The greatest amount of precipitation that fell during a storm was the 1.69 inches that fell over 48 hours on November 6 and 7, 2008, while the largest storm from the perspective of return interval was the 1.33 inches that fell in 12 hours on January 7, 2009. These storms are, unfortunately, quite small relative to the greater than 100-year 24-hour storms that have historically caused sewer backup in Broadview. The 1996 and 2007 storms that are the predominant cause of historical backups in the area were 2.99 and 5.2 inches of precipitation in 24 hours, respectively. Additionally, storms number 5, 6, and 8

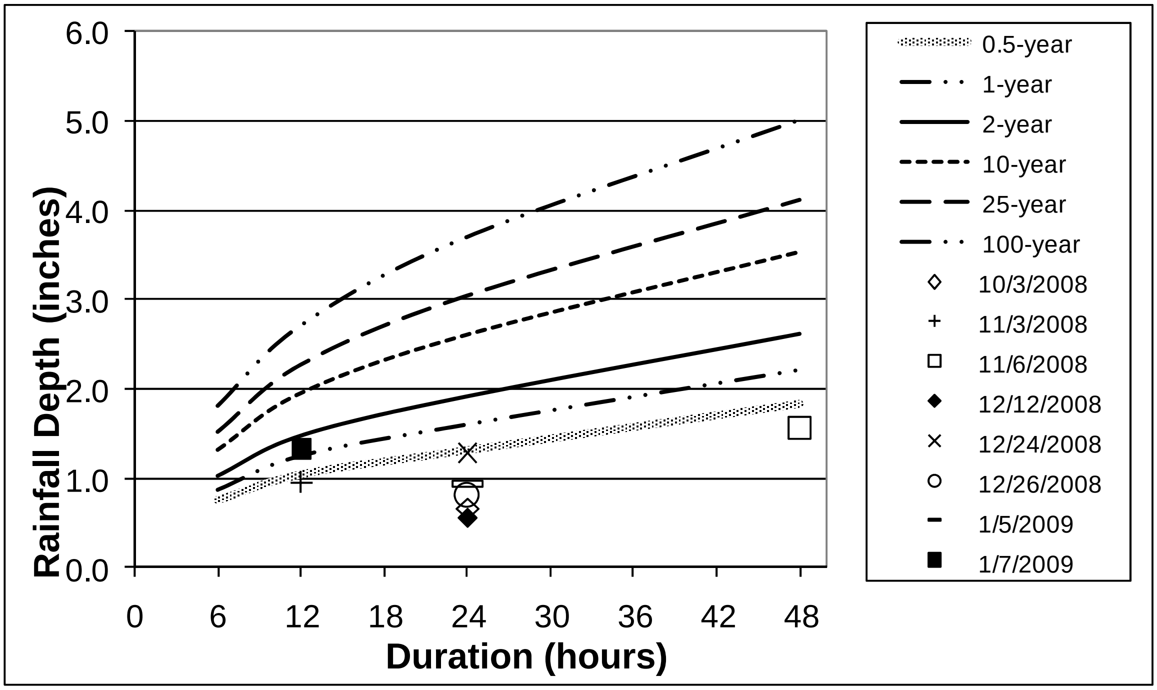


Figure 4. Precipitation depths for the 0.5-, 1-, 2-, 10-, 25-, and 100-year return interval events and storms that occurred during the flow monitoring period for RG01.

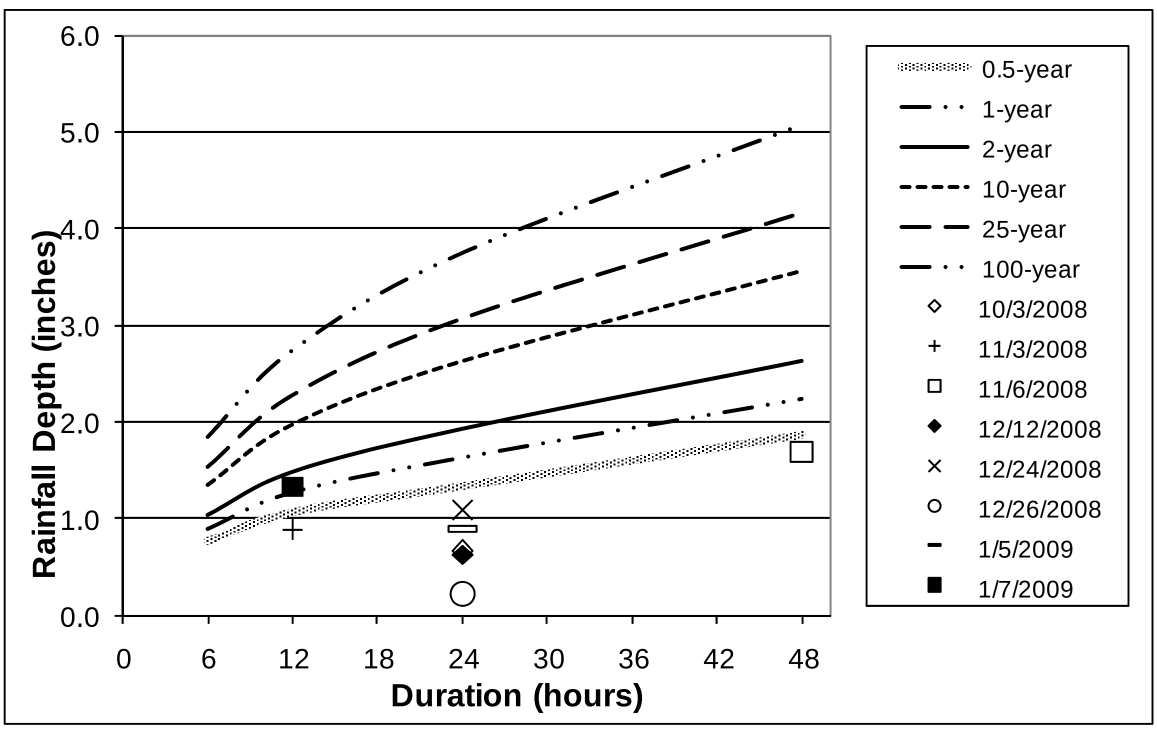


Figure 5. Precipitation depths for the 0.5-, 1-, 2-, 10-, 25-, and 100-year return interval events and storms that occurred during the flow monitoring period for RG07.

that occurred on December 24, December 26, and January 5 are not used in model calibration due the fact they contained snow accumulation and melt that is not well captured in the rain gauge data (see section "Adjustment to Rainfall Data Due to Snow Accumulation and Melt" for further details).

Adjustment of Rainfall Data Due to Snow Accumulation and Melt

Broadview experienced snow accumulation and melt around Christmas 2008 and January 5th, 2009. These snow events are among the eight largest storms during the monitoring period. However, these storms events are not used in model calibration due to likely errors in the precipitation data from the use of tipping buckets rain gauges to measure snowfall amounts. Tipping buckets tend to underestimate the amount of precipitation during snowfall, as well as tend to poorly reflect the timing of when runoff is introduced into the soil or pipe network during snow events (Groisman 1994). For example, an analysis of ADS flow data shows that twice as much runoff occurred during the December 26th event as the December 24th event despite having approximately half as much precipitation. The mechanics of what actually happened during this period is that snow was stored on the ground from the December 24th event, and then melted and ended up in the pipe network during the smaller precipitation on the 26th.

Although these events are not used in model calibration, an adjustment was made to the rainfall data to improve the model's simulation of runoff input into the soil and pipe system and therefore improve the model's antecedent soil moisture for the next storm event. The adjustment made during these snow events was to move the precipitation from the accumulation period to the melt period and to spread the depth of precipitation evenly over when the melt occurred. This redistribution of rainfall was based on a graphical analysis of the ADS flow data. Periods of precipitation during these snow events that were not accompanied by increases in pipe discharge are taken as snow accumulation, while the period preceding the snow events that did not have precipitation but did have increases in discharge are taken as snow melt. For the snowfall on December 24th, this was done by spreading the melt out over 48 hours starting at 11pm on the 26th, while the snowfall from 1am to 7 am on January 5th was spread out evenly from 7am on the 5th to 4pm on the 6th. Only the timing of the melt was altered; the overall volume of precipitation was conserved. Although this adjustment results in a better reflection of actual conditions in the basin during these snow events, the method described above is somewhat subjective and therefore these snow events are not used during model calibration.

Wet Weather Flow Calibration Steps:

1. Evaluate the flow data to verify that all peaks shown in the hydrographs to be used for calibration correspond with observed peaks in rainfall. Disregard all peaks in the hydrographs that cannot be linked to the corresponding rainfall records, as well as disregard all flow data that does not correspond to coincident rainfall data.

2. After verifying the peak flows in the observed flow records to be used in calibration, analyze the RDII data provided by ADS to determine proper

starting R, T, and K values for each slow-, medium-, and fast- hydrograph, for each subcatchment, and for each month of the calibration period. Additionally, based on ADS observed flow data, select values for initial abstraction parameters. Initial abstraction parameters include the maximum depth of abstraction per day and the daily abstraction recovery rate. Once initial values are selected, further evaluate the physical characteristics of the rain hyetographs and flow hydrographs (e.g., fast response versus slow response) to refine R, T, and K values. Analysis of RDII values is contained in Attachment A, Technical Memo- SPU Broadview Collection System Infiltration & Inflow Data Evaluation by ADS Environmental Services

3. Input the R, T, K values determined in step two into the EPA-SWMM 5 model.

4. Run the EPA-SWMM 5 model for the calibration period and plot the simulated flow versus the observed flow at the location of each ADS flow sensor. Evaluate the fit of the observed versus simulated data based upon observed hydrograph shape, volume, peak magnitudes, timing of peaks, and peak flow recession characteristics. In addition to plotting the flow data, generate statistics on how well the model replicates the observed flow.

5. Based on the results from step 4 adjust the R, T, and K parameters to improve the fit between modeled and observed data.

6. Rerun model and reanalyze fit between modeled and observed data.

7. Repeat step 4, 5, and 6 until model calibration has reached desired level. Note: This level is dependent upon perceived quality of the ADS flow data that the model is calibrated to (e.g., observed flow data for ADS-7 is significantly low, so the model was calibrated to over-simulate at this location).

Final R, T, K, and abstraction parameters for each subcatchment and each month are presented in Table 1-7 in appendix C. One example hydrograph figure is also presented in Appendix C to give the reader a graphical depiction of the basin's response to rainfall. The figure presented is for two inches of rainfall evenly distributed over 24 hours for subcatchment 1.

Model Validation

After the EPA-SWMM 5 model was calibrated to reproduce the observed flows during the calibration period, it was run with two historical precipitation events to evaluate how well the model simulates pipe surcharging during the larger storm events that have historically caused sewer backups. This model validation step is especially important since the EPA-SWMM 5 model specifically needs to perform well under the large precipitation events, yet no large precipitation events occurred during the flow observation and calibration period.

Although historical sewer backups appear to be caused by a range of precipitation events, an analysis of the SPU claims database shows that the vast majority of backups have occurred during events that have recurrence intervals of greater than 100 years (Figure 6). The only historic backups that occurred in events smaller than the 100-year return interval were five backups that occurred during events of less than 1-year return interval, and five backups that occurred during periods of no precipitation. With the exception of two backups that occur next to each other in a period of no rain, and two backups that occur on the same date with a small precipitation event, the backups that occur in events of less than the 100-year return interval have no spatial or temporal correlation, indicating they are likely caused by isolated hydraulic conditions (e.g., jet cleaning, debris in pipe, etc) that are not well simulated by the model. Additionally, the SPU claims database lists “broken stub” and “jet cleaning” as the cause of some of the backups that occurred during the periods of no precipitation and small return interval events. Unfortunately, without information on jet cleaning schedule or broken side sewers the EPA-SWMM 5 model cannot simulate these backups, and model validation can only be performed during the larger precipitation events that caused widespread backups in the area. Another option that was considered to increase the pool of validation events was to only calibrate the model to four of the five storms during the flow monitoring period. This approach was ultimately discarded, however, because the number of events for model calibration was small, and because no actual sewer backups occurred during any of the storms in the flow monitoring period.

The precipitation events available for model validation are the two events that caused the majority of the historic backups, namely the December 31, 1996 and December 3, 2007 events. The surcharging that occurred on December 31, 1996 was caused by snowmelt in addition to rainfall, and the EPA-SWMM 5 model was not set up to simulate snowmelt, so an additional amount of rainfall was used to compensate for this. See section “December 31, 1996 / 100-year Event” below for further detail; however, in brief, the 100-year return interval event was used to approximate the runoff present during the December 31, 1996 event. Discussion of model validation under the December 3, 2007 and December 31, 1996 / 100-year event is described below.

It should be noted that on the model validation figures below that historical backups can only be shown for locations where homeowners filed claims with SPU or notified the Broadview Community Council that they had backups. Meetings with Broadview residents over the past year have indicated that there are many locations that experience backups but that were not.

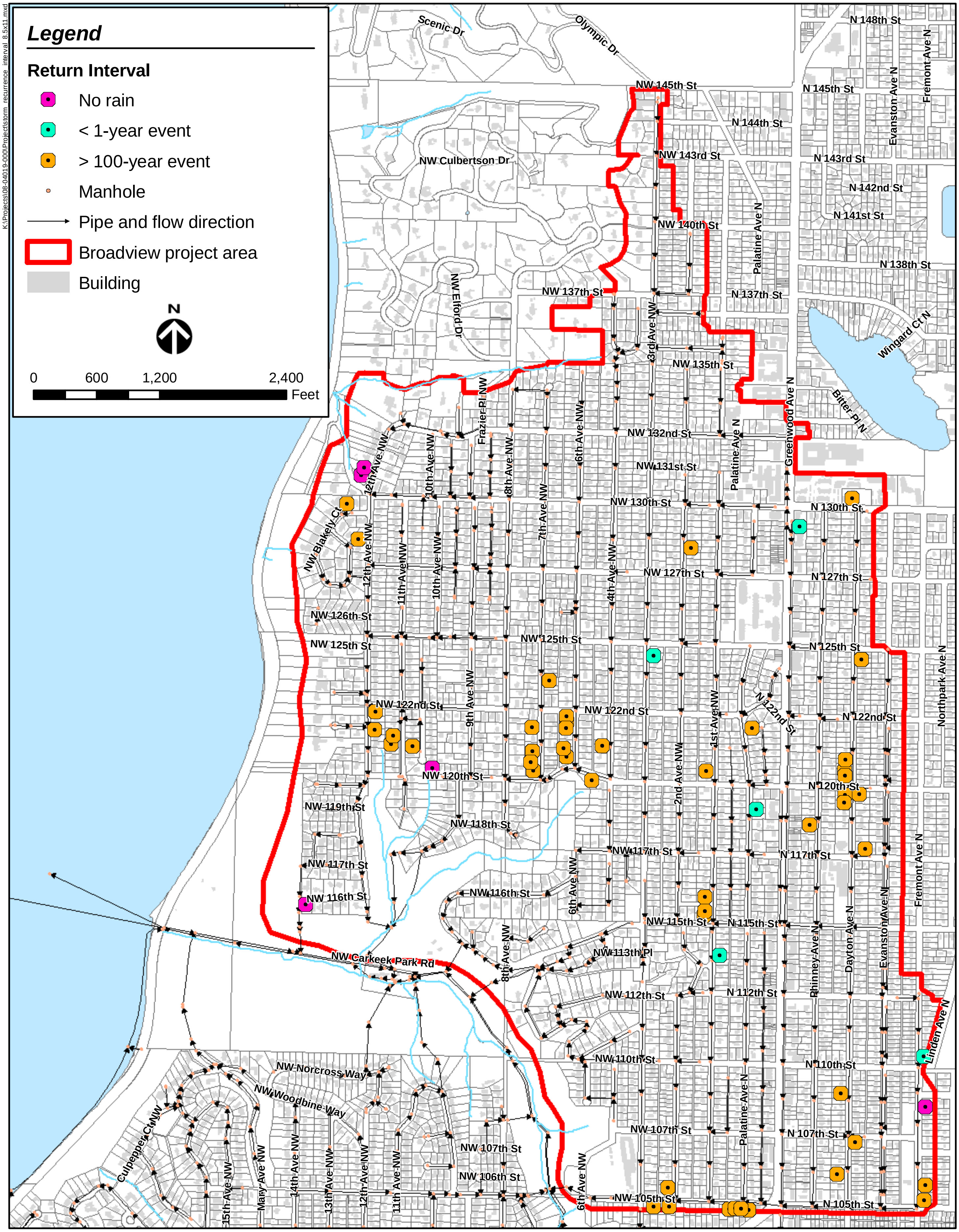


Figure 6. Approximate recurrence interval for storm events causing sewer backups.

This will result in the model correctly showing surcharging at some locations but the model not being confirmed since homeowners have not filed claims. Additionally, "model surcharging" is defined as any place where the depth is greater than the adjacent pipe. Depending upon the elevation difference between the pipe and the basement of the homes that experience surcharging, this surcharging usually needs to reach several feet before it will enter the home. Because of the somewhat inherent mismatched nature of these data sets, the model validation below focuses on the general pattern of backups and the in-depth analysis of each area is carried out under section "Model Analysis".

December 31, 1996 / 100-year Event

The December 31, 1996 precipitation event consisted of 2.99 inches of precipitation in a 24-hour period falling on top of moderate snow cover. According to the Army Corp of Engineers, several meteorological phenomena combined to create an event with an approximate return interval of 130 years. Although it is not ideal to perform model validation with a precipitation timeseries different than what actually occurred in the basin, due to the difficulty of simulating snowmelt but yet having the desire to simulate and event of close to the magnitude of the December 31, 1996 event, the 100-year 24-hour precipitation volume was used to force the model. Based on MGS (2007) this volume is 3.75 inches in a 24-hour period.

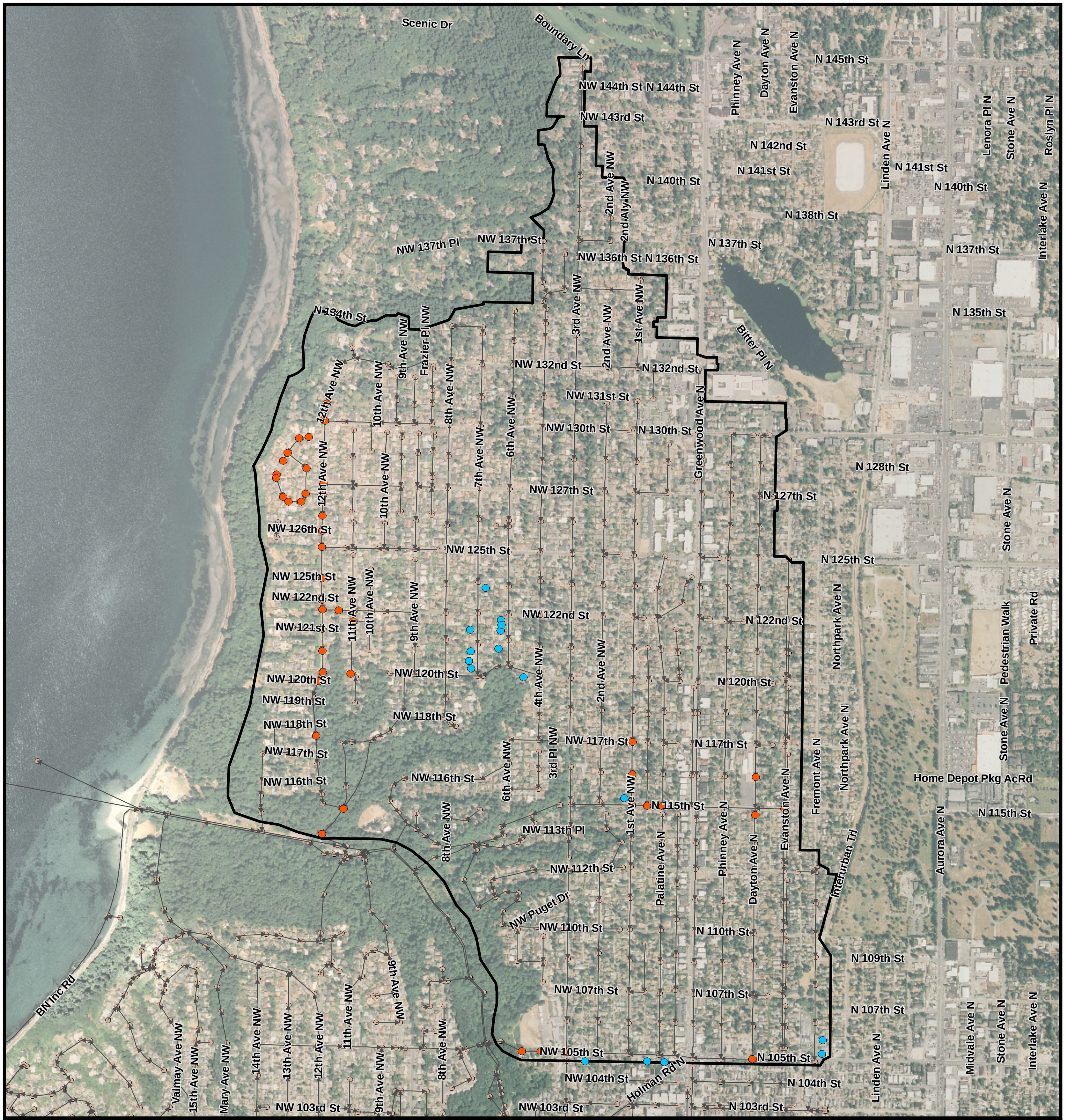
The extent of sewer system surcharging during the hybrid 1996/100-year is shown on Figure 7. The model largely does an accurate job of simulating surcharges at the same locations where actual surcharging occurred during the December 31, 1996 event. A short discussion is provided below for each of the historical backup locations.

1st Avenue NW and NW 115th Street

The location at 1st Avenue NW and NW 115th Street is well simulated. The model shows inadequate capacity out of maintenance hole 224-201 which causes surcharging in the immediate pipes to the north and west. Field investigation showed that this maintenance hole does surcharge as the model shows, and that the homes that have experienced backups are the lowest elevation homes on the upstream side of this maintenance hole.

12th Avenue NW

The model shows pipe surcharging from NW 117th north to NW 130th Street during the December, 31, 1996 / 100-year event but no claims were made to SPU for the December 31, 1996 event. It may be that the model over-simulates discharge or under-simulates capacity in this reach, but meeting with residents has also indicated that this section of pipe surcharges with much greater frequency than what has been reported.



Legend

- Actual backup location
- Modeled surcharging location
- Broadview project area
- Pipe and flow direction
- Manhole

Figure 7. Modeled surcharging and actual backup locations in the December 31, 1996 storm.

N

0 700 1,400 2,800 Feet

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NW 105th Street

The model simulates the historical surcharging around 2nd Avenue NW and NW 105th Street but does not simulate the surcharging that occurred a few blocks to the east around NW 105th Street and Palatine Avenue N. Additionally, the model shows some surcharging to the west of 3rd avenue where surcharging has not been reported in the past.

6th Avenue NW

Although the modeling performed as part of this study uses the calibration parameters obtained from the largest storm during the monitoring period (1/7/2009), it is believed that the EPA-SWMM 5 model does not accurately simulate discharge at this location in large (~100-year) return interval events. Model runs with the 100-year event and December 3, 2007 event do not create surcharging in the pipe network but there were widespread backups in the area in both December of 1996 and December of 2007. The homes that experienced backups during these two events are all situated on the low side of the street on the upstream side of maintenance hole 224-104.

From this, it is believed that this maintenance hole surcharges and increases the hydraulic gradeline to an elevation higher than the basements of these homes. Field investigation by Herrera engineers found evidence of surcharging in this maintenance hole which supports this assessment. Additional model runs were performed using precipitation amounts in excess of December 3, 2007 event to determine the location and extent of surcharge if given enough flow. This additional analysis showed that, as expected, maintenance hole 224-104 was the first location to surcharge. It took a precipitation event approximately three times the 100-year event (11.25 inches in 24 hours) to create the model surcharging.

This poor model calibration for large events may be the byproduct of: 1) not having any events in the flow monitoring period comparable to the events that caused backups in the past, and 2) the percentage of rainfall that turns into discharge in the pipe network increasing with increasing storm size. The percentage of rainfall that becomes direct inflow remains relatively constant regardless of storm size since the area that is directly connected does not change. Infiltration, however, can increase dramatically as storm size increases due to ground saturation. This location is at the head of Venema Creek where the ground may be especially susceptible to saturation during large event. Also, there exists a significant dip or sag in the pipe upstream of maintenance hole 224-104 which could offset pip joints enough to allow a pathway for large amounts of water to enter the system when ground saturation occurs. Although this dip or sag was duplicated in the model in addition to a reduction of the pipe diameter to replicate sedimentation that typically occurs in sags.

Model results for 6th Avenue NW are presented in the “Results” section for both Alternative 2 and 3; however, since the model is not well calibrated at this location these results should be used with caution. The Project Summary Report will provide discussion and recommendations on reducing sewer backups at this location.

Dayton Avenue N

The model does not show any widespread surcharging on Dayton Avenue N during the 1996 / 100-year event, nor were there any claims during the December 1996 event. The model does, however, show slight surcharging where the flow direction turns from south to west at NW 115th Street and NW 105th Street.

December 3, 2007

The December 3, 2007 storm event consisted of 5.2 inches of precipitation in 24 hours and is the largest storm on record for the Seattle area. This event contained three times the maximum 24-hour precipitation seen during the monitoring period, and a 40 percent greater depth than the 100-year event analyzed as part of this project. Modeled surcharging during this event is shown in Figure 8.

1st Avenue NW and NW 115th Street

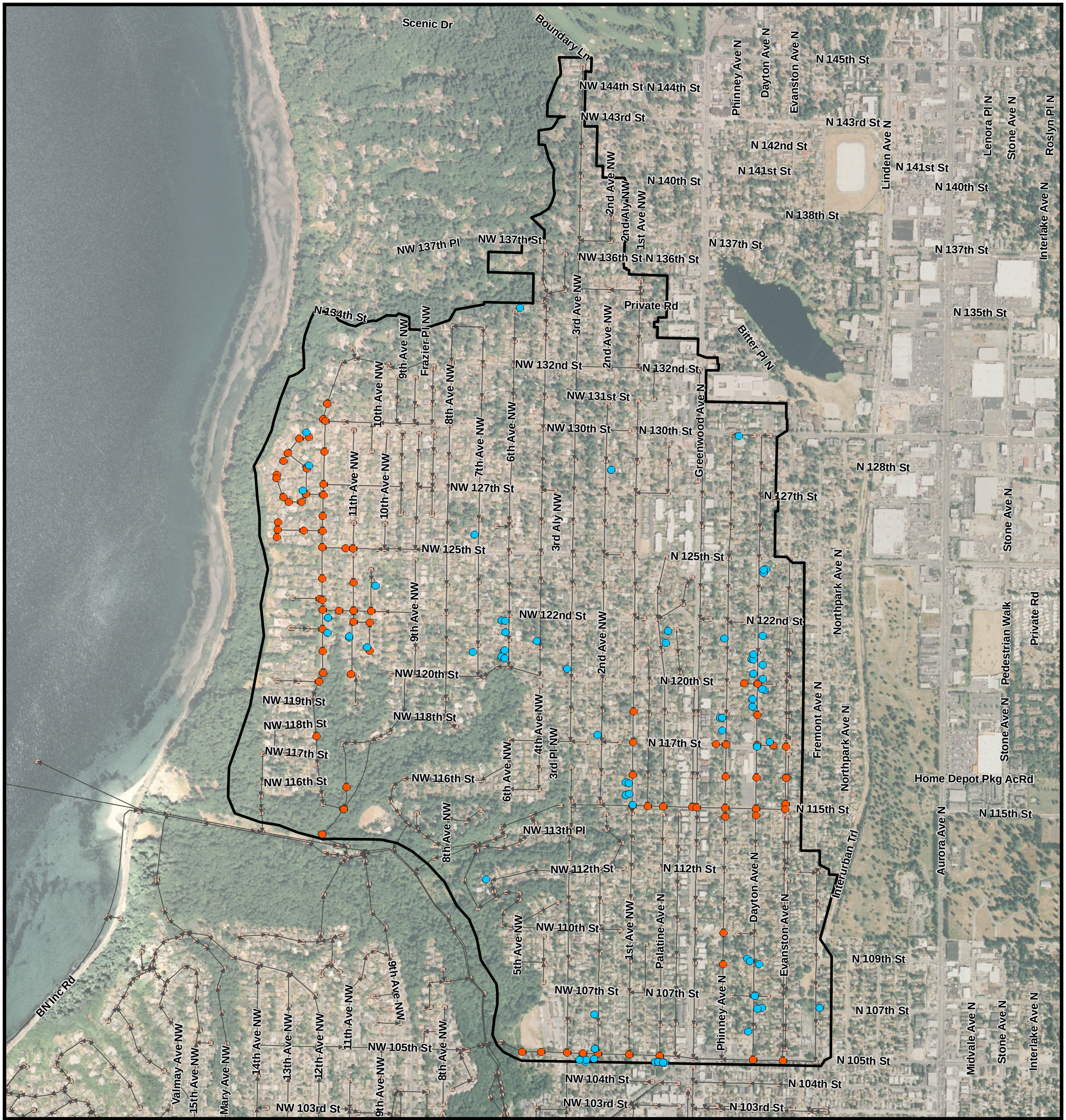
The location at 1st Avenue NW and NW 115th Street is also well simulated under the December 3, 2007 event. The cause of the surcharging is the same as under the 1996 / 100-year event (i.e., inadequate capacity out of maintenance hole 224-201), but under this event the surcharging propagates further upstream. The area of surcharging in the model is likely overestimated somewhat as it does not account for discharge coming out of residential sewer connections just upstream of maintenance hole 224-201.

12th Avenue NW

The model shows pipe surcharging from NW 117th Street all the way north to NW 130th Street during the December 3, 2007 storm while only a handful of claims were made around NW 120th Street to NW 122nd Street and on NW Blakely Court and Blakely Place NW. As with the 1996 / 130-year event, it may be that the model over-simulates discharge or under-simulates capacity in this reach, but meeting with residents has also indicated that this section of pipe surcharges with much greater frequency than what has been reported.

NW 105th Street

The model correctly simulates historical surcharging on NW 105th street between 2nd Avenue NW and Palatine Avenue N for the December 3, 2007 event. As with the December 1996 / 130-year event, it does show pipe surcharging to the west of 3rd Avenue NW where no homes in this area filled claims with SPU.



Legend

- Actual backup location
- Modeled surcharging location
- Broadview project area
- Pipe and flow direction
- Manhole

Figure 8. Modeled surcharging and actual backup locations in the December 3, 2007 storm.

N

0 700 1,400 2,800 Feet

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6th Avenue NW and NW 120th Street

As with the December 1996 / 130-year event, the model does not show any surcharging at this location despite there being a number of homes that experienced backups during the December 3, 2007 event. Further discussion on this location is presented under the alternatives analysis below.

Dayton Avenue N

Although many residents reported surcharging during the December 2007 event, the model does not show surcharging at the locations where the surcharging was reported. Residents along Dayton Avenue N reported to a Herrera engineer that there was an obstruction in the pipe at Christ the King School on December 3, 2007, and that when maintenance crews removed it that all surcharging ceased immediately. The model uses unobstructed pipes in its simulation so this could explain why the model does not replicate surcharge that actually occurred in the basin. It is inconclusive why whether this obstruction existed since the SPU maintenance records show that a field crew responded to a call on the 3rd but does not indicate removal of an obstruction.

Model Analysis

Once the model was calibrated and validated, it was run to simulate sewer pipe flow and sewer backup frequency and extent under current conditions and three alternatives. The model setup and alternatives analyzed are discussed below.

Model Setup

Precipitation Data for Model Analysis

As described above, the precipitation data used in the model analysis is an event-based timeseries containing the 6-month, 2-, 10-, 25-, and 100-year storm events. Use of the event-based timeseries was requested by SPU to facilitate an early analysis of the feasibility and effectiveness of the Alternative 1 pipe replacement solutions. Initially Alternatives 2 and 3 were to be analyzed using the 30-year continuous simulation; however, it was decided that continuing to use the event based analysis would facilitate a more accurate comparison across alternatives.

The synthesized event-based timeseries contains the 24-hour 6-month, 2-, 10-, 25-, and 100-year storm events for RG01 and RG07. The magnitude of the storm events was obtained from the MGS Engineering report titled: Analysis of Historical Extreme Precipitation Events to Support Adaptive Management (MGS 2003) and are provided in Table 6. To facilitate running the EPA-SWMM 5 model with these events a continuous timeseries was developed that contains all of the above events. In the timeseries each event is separated by one month and is preceded by a 0.2-year return interval 24 hour storm followed by 3 dry days. The timestep of this data is 10 minutes.

Table 6. 24-hour precipitation depth in inches by recurrence intervals for RG01 and RG07.

Rain Gauge	24-hour Precipitation Depth (inches) by Recurrence Interval					
	0.2-Year	0.5-Year	2-Year	10-Year	25-Year	100-Year
RG 1	0.93	1.32	1.91	2.61	3.04	3.71
RG 7	0.94	1.33	1.93	2.63	3.07	3.75

Unit Hydrographs

The rain event that occurred on January 7th, 2009 was the largest during the flow monitoring and model calibration period. Based on historical precipitation analysis for the City of Seattle, this storm was a 2-year, 12-hour storm (MGS 2003). Although this storm was smaller than the 2-, 25-, and 100-year rain events used in the model analysis, it was the most comparable storm available, and therefore the unit hydrograph generated for this storm is used for simulating the return interval events used.

Model Time Step and Period

A 10-minute timestep is used for runoff generation and model data output, while the routing timestep is 10 seconds. The short routing timestep is necessary to ensure the highest degree of accuracy and model stability.

Model Scenarios

Existing conditions and three alternatives were analyzed with respect to engineering solutions to reduce the frequency and magnitude of sewer backups. The existing condition scenario consists of the existing pipe network that was in place during the monitoring period, and represents the existing conditions scenario which the alternatives are compared against. Alternative 1 consists of selected pipe replacement, Alternative 2 consists of inflow reduction, while Alternative 3 is aimed at infiltration reduction. "Inflow" is defined as a direct connection of stormwater runoff to the sewer system. Typical examples of this include roof downspouts and area drains. "Infiltration" enters the sewer system where runoff saturates the ground and then seeps in through cracked pipes. Further information on the existing conditions scenario and the three alternatives are described below.

Existing Conditions Scenario

The existing conditions scenario run in the EPA-SWMM 5 model represents current conditions in the basin and is the baseline scenario from which the other scenarios (i.e., Alternatives 1, 2, & 3) can be compared against to evaluate performance. The pipe network in the existing conditions scenario consists of the model network received from SPU plus the QA/QC steps documented in Appendix A. The model results above in the "Model Calibration" and "Model Validation" sections are from the existing conditions model configuration.

Alternative 1, Pipe Replacement

Inclination surveys, CCTV output, locations of historical sewer backups, and model validation results showed locations where increased conveyance within a few segments of pipe could potentially increase overall system performance. These locations focused on areas that have experienced sewer backups. The pipe replacement alternatives are specifically designed to reduce the frequency and magnitude future backups near their locations.

The locations evaluated included the clusters of homes located at 1st Avenue NW Street and 115th Street, 6th Avenue NW and 120th Street NW, 12th Avenue NW, 105th Street NW, and Dayton Avenue NW. The analyses showed that the pipe network near 6th Avenue NW and 120th Street, 12th Avenue NW, and Dayton Avenue NW does not contain pipe reaches that have a significantly lower capacity than the adjoining upstream or downstream pipe reaches. Due to no identification of capacity constrained reaches within the model, these locations were not further evaluated under Alternative 1.

Alternative 2, Inflow Reduction

The location of historical sewer backups, previous inflow reduction studies, and the data from the SvR Smoke Test Report (2008) were used to identify locations where reducing the inflow to the sewer system could reduce the frequency and magnitude of potential future backups. Three different scenarios were modeled under this alternative to develop a better understanding of the "level of disconnection" required to reduce backups. Scenarios 1through 3 include disconnection of 20 percent of connected downspouts, disconnecting 50 percent of connected downspouts, and disconnection of 100 percent of all connections, respectively. The method for modeling these levels of disconnection is presented below.

The smoke testing performed in the Broadview neighborhood in 2008 included an area of 406 acres where 230 connections having a total of 4.38 acres tested positive for some type of connection to the sewer system. Of the 230 connections, 95 were downspout connections from homes. There are 1,464 homes in the area tested, so the 95 downspout connections correspond to a seven percent connection rate. Previous studies (SPU 2009) indicate that smoke testing has a bias towards underreporting the amount of connections present. This is sometimes due to pea traps that block smoke from leaving the sewer pipe. The SPU report presents information on the Lakewood area where smoke testing reported three percent of homes connected while later dye testing reported 34 percent of homes connected. It also presented information on other tests conducted where the undercatch error was less drastic. In conjunction with SPU, a 50 percent scale up factor to the SvR smoke test results was used to better model the downspout connection rate resulting in a 10.5 percent connection rate.

Runoff calculations generated with the EPA-SWMM 5 model are based on percent of total area connected and not as a percent of the total homes connected; therefore the 10.5 percent connection rate must be converted to a value that can be operated on by the unit hydrograph files. The "R" values in the EPA-SMWW 5 unit hydrograph files are the percent of rainfall that becomes runoff. There are three unit hydrographs (fast, medium, and slow) each with their own "R" values. The "fast" unit hydrograph corresponds to direct connections to the sewer system as opposed to infiltration that would be a medium or slow response. The fast "R" is the percentage of rainfall that discharges directly into the sewer system. The fast "R" therefore is the "R" value that must be reduced to reflect the amount of downspouts disconnected under the Alternative 2 scenarios.

As stated above, 4.38 acres out of 406 acres tested positive during smoke testing for a direct connection of 1.1 percent of the area. Of the 230 connections found, 41percent were downspouts (95 connections). Scaling these values up by the 50 percent scaling factor to compensate for smoke test undercatch results in 0.68 percent of the basin area being directly connected to the sewer system through downspout connections (1.1 percent of the area is connected × (multiplied by) 41 percent of connections are downspouts × 1.50 scaling factor = 0.68 percent). Disconnecting all connected downspouts would result in reducing the fast "R" value by this 0.68 percent value.

Scenario 1 assumes that 40 percent of homes that have downspout connections would chose to disconnect their downspouts, and of those that it would be feasible to disconnect 50 percent of them for a total disconnection rate of 20 percent (40 percent participating × percent 50 feasible = 20 percent total). Scenario 2 assumes that 70 percent of homes that have downspout connections would chose to disconnect their downspouts, and of those that it would be feasible to disconnect 70 percent of them for a total disconnection rate of 50 percent (70 percent participating × percent 70 feasible = 50 percent total). Scenario 3 is meant to show the full range of what can only theoretically be achieved in disconnecting all connected area. This scenario models disconnection of all connected area as opposed to disconnecting only the area connected by downspouts. This scenario was developed as a boundary condition for analysis only. This scenario also uses a 200 percent scaling factor to account for smoke test bias as opposed to the 150 percent factor in scenarios 2 and 3. This 200 percent factor is well within the range of the values presented in the SPU 2009 report *Determining Connectivity of Downspouts to the Combined Sewer*.

The fast "R" values used in the existing conditions and Alternatives 2.A, 2.B, and 2.C are presented in Table 7. There are five different unit hydrograph files used in the model to represent the different runoff characteristic within the basin. The unit hydrographs UH2_RG1, UH_3_RG7, UH_4_RG1, and UH_12_RG1 use a 3 percent fast "R" value in the existing conditions model, while UH_1_RG1 uses a 5 percent fast "R" value. The 3 percent and 5 percent values are used as the starting point with the percentage of the basin disconnected in each scenario subtracted from them.

Table 7. Fast "R" values used in the existing conditions and Alternative 2.A, 2.B, and 2,C scenarios.

UH Files	UH2_RG1, UH_3_RG7, UH_4_RG1, UH_12_RG1	UH_1_RG1
Base model fast "R" value	3.00 percent	5.00 percent
Alternative 2.A fast "R" value	2.87 percent	4.87 percent
Alternative 2.B fast "R" value	2.66 percent	4.62 percent
Alternative 2.C fast "R" value	1.35 percent	3.35 percent

Alternative 3, Infiltration Reduction

Locations of historical sewer backups, previous infiltration reduction studies, and observed and modeled discharge in the sewer system were used to identify locations where a reduction in sanitary sewer infiltration would lead directly to a reduction in the frequency and magnitude of potential future backups. As with Alternative 2, three different levels of infiltration reduction are modeled to give a range of the effectiveness of infiltration reduction strategies. Scenarios 1, 2, and 3 include 20 percent, 40 percent, and 80 percent reduction in infiltration respectively. Information related to determining and applying these levels are presented below.

Realistic infiltration reduction levels were obtained from the 2004 King County *Regional Infiltration and Inflow Control Program Study* (King County 2004). The King County report synthesized the finding of 10 regional I & I control pilot programs. The greatest reduction in infiltration achieved was 87 percent in Skyway where the entire pipe system was replaced. Also reporting high infiltration reductions were in Kent and Ronald, and were 76 percent and 74 percent respectively and included replacement of all side sewers. Mercer Island achieved a 37 percent reduction by replacing mainlines, while Northshore obtained a 23 percent reduction through lining the existing maintenance holes. Two locations, Auburn and Redmond, replaced 11 percent and 36 percent of their mainlines and found no measurable reduction in infiltration. From these studies and through discussion with SPU infiltration reduction percentages of 20 percent, 40 percent and 80 percent were used to represent the range of potential infiltration reduction in Broadview.

As stated earlier, the medium and long “R” in the unit hydrograph files are used to represent the infiltration component of discharge in the sewer system. Infiltration needs to make its way through the soil column before reaching cracks in pipes and therefore has a slower response than direct inflow, hence inflow being represented by the fast “R” and infiltration represented by the medium and slow “R”. To model this reduced “R” in the EPA-SWMM 5 model, a 20 percent reduction in the medium and long “R” was applied for scenario 1, a 40 percent reduction in the medium and long “R” was applied for scenario 2, and an 80 percent reduction in the medium and long “R” was applied for scenario 3. The original “R” values used in the base model that were modified can be found in Appendix C, table 2.

Results

Results are presented below for modeling of the existing conditions and the three engineering alternatives. The existing conditions model is used to assess the current capacity of the sewer system and to identify the locations and causes of historic backups, while the modeling of the three alternatives is used to gauge their effectiveness in reducing the frequency and magnitude of potential future sewer backups. All analysis of model output was performed within the EPA-SWMM 5 platform or within an Excel spreadsheet. Figure 9 shows the five main areas of historical sewer backups: these became locations for analysis of peak water surface elevation profiles in the existing conditions and alternatives models. These locations include 1st Avenue NW and NW 115th Street, NW 105th Street to the east of Greenwood Avenue N, 12th Avenue NW between NW 119th Street and NW 132nd Street, 6th Avenue NW and NW 120th Street, and Dayton Avenue N north of NW 115th Street. A summary of model flow routing continuity errors is presented in Appendix D.

Existing Conditions

The existing conditions model simulates pipe surcharging in roughly the same locations that have experienced sewer backups in the past (Figure 10). Modeling shows that a large portion of 12th Avenue NW, 1st Avenue NW at NW 115th Street, Dayton Avenue N near NW 105th Street and NW 115th Street, and portions of NW 105th Street surcharges during the 100-year events. Some of these locations such as 12th Avenue NW and 1st Avenue NW also surcharge in events during 2-year and 25-year return intervals. As discussed in the "Model Validation" section, absent from modeled surcharging is 6th Avenue NW and NW 120th Street. In-depth discussion, including a profile of the peak water surface elevation for the each area during the 2, 25, and 100-year event, is provided below.

1st Avenue NW and NW 115th Street

Field inspection by a Herrera engineer on August 13, 2008 found evidence of past surcharging in maintenance hole 224-201, downstream from the homes that have experienced backups. Maintenance hole 224-201 is located at the corner of 1st Avenue NW and NW 115th Street. Although the basement elevation of these homes has not been surveyed, a rough assessment in the field indicated that the elevations of these basements are roughly the same or below the elevation of the level of surcharging found in the maintenance hole. Surcharge in basements would occur if the elevations of the basements in these homes are below the surcharge elevation in the maintenance hole. Inspections of CCTV in this area also showed that the sewer line into maintenance hole 224-201 from the north has a sag approximately 20' upstream of maintenance hole 224-201.

A Manning's calculation of the free-flow capacity of the existing pipe network shows that the capacity out of the maintenance hole is lower than the capacity into the maintenance hole.

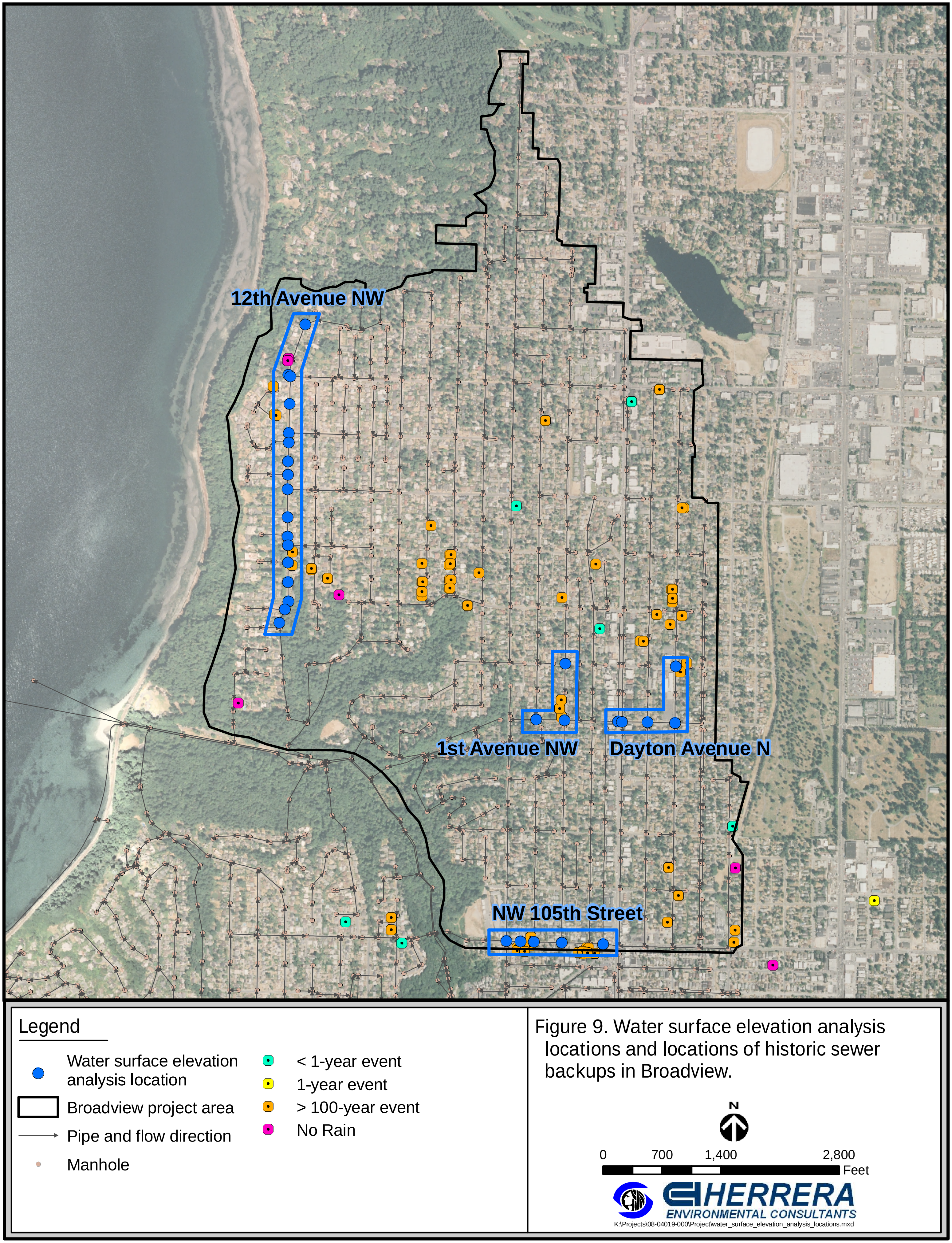


Figure 9. Water surface elevation analysis locations and locations of historic sewer backups in Broadview.

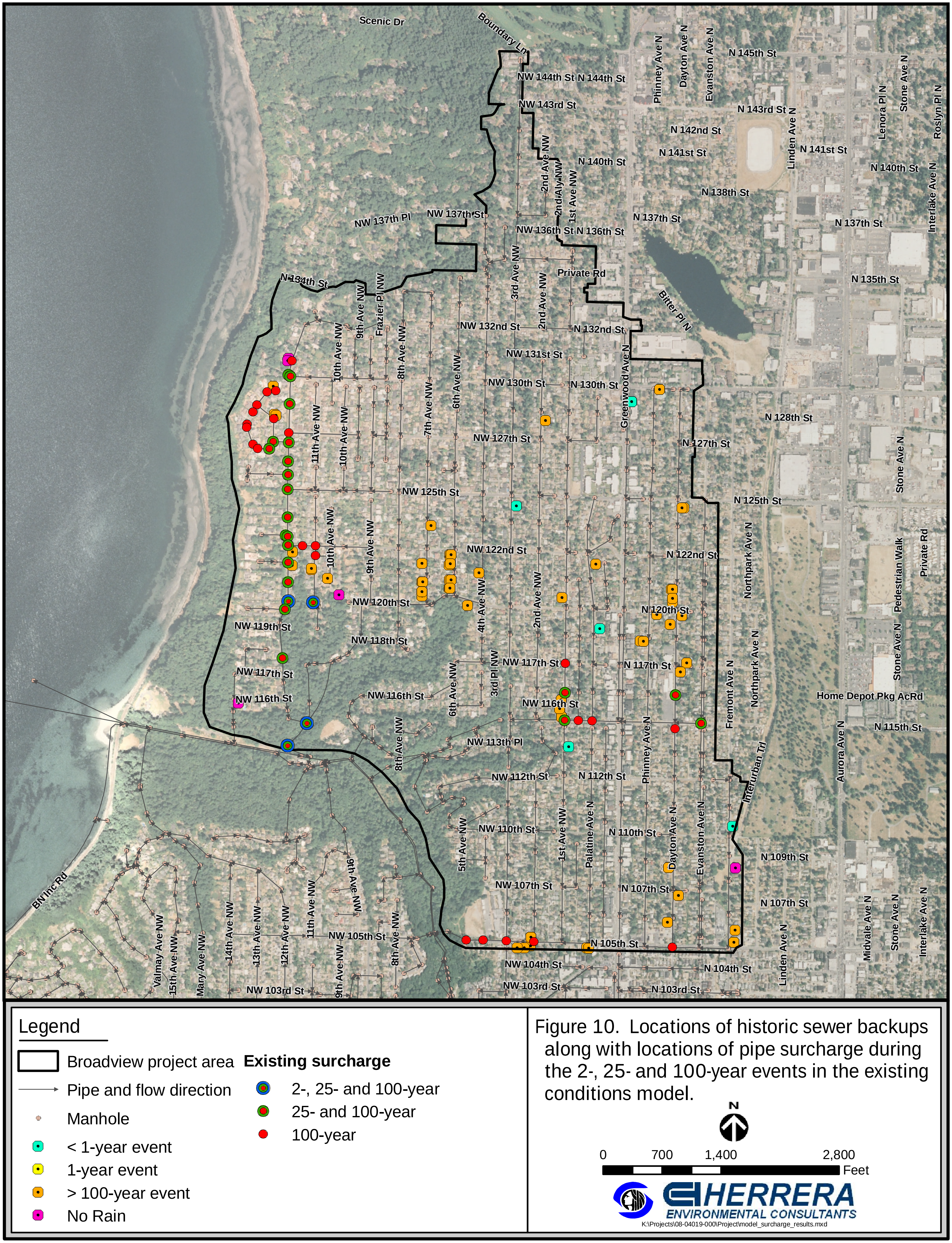


Figure 10. Locations of historic sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the existing conditions model.

Table 8 below shows that the existing capacity of the pipes into the maintenance hole is 5.03 cfs, while the capacity out of the maintenance hole is 3.25 cfs. The lower capacity lower out of the maintenance hole could contribute to surcharge if both pipes into the maintenance hole were flowing full at their capacity.

Table 8. The Manning's capacity, January 7th, 2009 observed discharge, 100-year modeled discharge, and 100-year discharge as a percent of capacity for the pipe segments that connect to the maintenance hole at the corner of NW 115th Street and 1st Avenue NW.

Pipe Segment	Location	Capacity[a] (cfs)	1/7/2009 OBS Discharge (cfs)	100-Year MOD Discharge (cfs)	100-Year MOD Discharge as Percent of Capacity[a] (percent)
224-204 to 224-201 (Inflow to Maintenance hole)	Along NW 115th Street to the west of 1st Avenue NW	3.32	2.45	3.15	95
224-145 to 224-201 (Inflow to maintenance hole)	Along 1st Avenue NW to the north of NW 115th Street	1.71	0.45	0.95	56
224-201 to 224-197 (Outflow from maintenance hole)	Along NW 115th Street to the east of 1st Avenue NW	3.25	2.90	4.12	129

Note:

[a] Capacity calculations presented here are based on Manning's calculations of maximum free flow discharge based on roughness, slope, and pipe diameter. This capacity does not include the effects of pressure head on discharge.

Table 8 also shows the observed discharge in the pipe segments during the 1/7/2009 storm event, the 100-year modeled discharge, and the 100-year modeled discharge as a percent of capacity. The observed discharge during the January 7, 2009 storm, with a return interval of about 2-years, in pipe segment 224-201 to 224-197 (out of the maintenance hole) was 2.9 cfs. The capacity of the pipe is about 0.35 cfs higher than this flow at 3.25 cfs. The 100-year modeled discharge in this segment is 4.12 cfs, which is greater than the capacity. This capacity calculations in the table are based on the free flow Manning's calculation and do not include the effects of pressure head induced during surcharge. Nonetheless, the calculations show that there is insufficient capacity for a storm magnitude between the 2-year and 100-year out of maintenance hole 224-201. Because of the insufficient capacity of the outlet, the maintenance hole and incoming sewer lines surcharge and lead to sewer backups in upstream resident's homes.

Profile plots of the peak water surface elevation during the 2-, 25-, 100-year events are given in Figure 11, and the December 3, 2007 event is plotted in Figure 12. The upstream maintenance hole in these plots is 224-144 located at the corner of 1st Avenue NW and NW 117th Street and

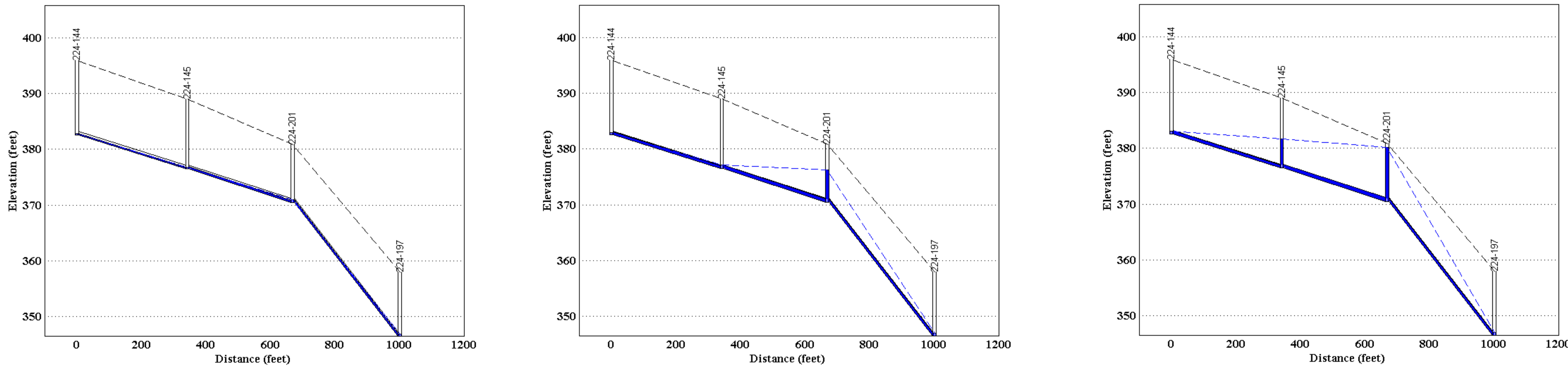


Figure 11. Water surface elevation profiles on 1st Avenue NW and NW 115th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under existing conditions

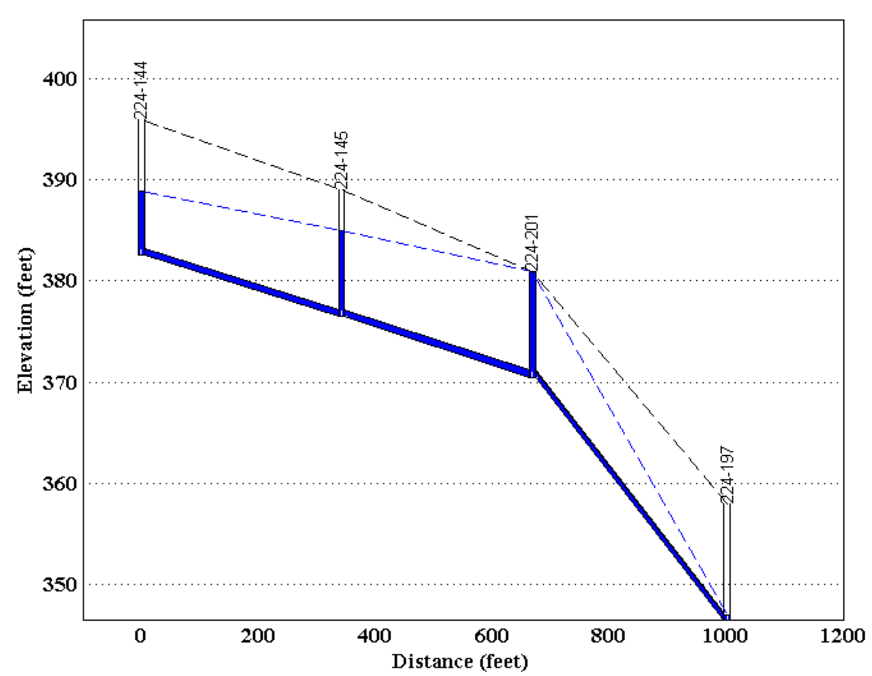


Figure 12. Water surface elevation profile on 1st Avenue NW and NW 115th Street for the December 3, 2007 storm under existing conditions.

the downstream maintenance hole is 224-197 located at the corner of 2nd Avenue NW and NW 115th Street. These plots show that maintenance hole 224-201 does not surcharge during the 2-year event but does surcharge in the 25- and 100-year events. As expected from the capacity calculations above, the under capacity segment from maintenance hole 224-201 to maintenance hole 224-197 seems to cause the maintenance hole and pipe surcharging. The elevation of surcharge shown is close to basement elevations confirming the cause of sewer backups at this location by this segment of pipe.

NW 105th Street

The existing sewer line along NW 105th Street is a 10 inch diameter concrete pipe with 3 foot pipe segments. The capacity of the pipe segments through this area are presented in Table 9. The table illustrates that segment 224-330 to 224-331 has a capacity less than the adjoining pipe. The observed discharge in the pipe segments during the 1/7/2009 storm event, the 100-year modeled discharge, and the 100-year modeled discharge as a percent of capacity are also shown in Table 9. The pipe segment with the lowest capacity is segment 224-331 to 224-330 and has a capacity lower than the 100-year modeled discharge. It serves as a “pinch-point” in the system. The 100-year modeled discharge is 128 percent of the Manning’s capacity in this pipe segment.

Table 9. The Manning’s capacity, January 7th, 2009 observed discharge, 100-year modeled discharge, and 100-year discharge as a percent of capacity for the pipe segments in the area of concern along NW 105th Street.

Pipe Segment	Location	Capacity[a] (cfs)	1/7/2009 OBS Discharge (cfs)	100-Year MOD Discharge (cfs)	100-Year MOD Discharge as Percent of Capacity[a] (percent)
224-341 to 224-337	NW 105th Street between Palatine Avenue and 1st Avenue NW	4.5	1.2	2.99	66
224-337 to 224-331	NW 105th Street between 1st and 2nd Avenue NW	6.2	n/a	3.47	56
224-331 to 224-330	NW 105th Street between 2nd Avenue NW and alley to the west	3.0	1.8	3.84	128
224-330 to 224-326	NW 105th Street between 3rd Avenue NW and alley to the east	5.7	n/a	3.91	69

Note: [a] Capacity calculations presented here are based on Manning’s calculations of maximum free flow discharge based on roughness, slope, and pipe diameter. This capacity does not include the effects of pressure head on discharge.

The location of this pipe segment having the lowest capacity is downstream of the homes at NW 105th Street and 2nd Avenue NW that have experienced sewer backups. Field inspection has confirmed that the upstream maintenance hole in this segment surcharges. Additionally, photographs from the December 3rd, 2007 storm event show overtopping of the maintenance hole. The basement elevations of the homes that have sewer backups have not been surveyed. However, they appear to be at an elevation near the elevation of surcharging for the 100-year event. Eliminating surcharging of these pipe segments would likely eliminate the sewer backing-ups at homes immediately upstream of the surcharged maintenance hole.

The levels of surcharging in the pipe along NW 105th Street during the 2-year, 25-year, and 100-year design storms are shown in Figure 13. The December 3, 2007 event is shown in Figure 14. Surcharging of the pipe system first occurs during the 100-year event (Figure 13) which approximately corresponds to the level of storm that triggered backups in the area in 1996. Surcharging is seen in maintenance hole 224-326 and maintenance hole 224-331 during the 100-year storm. There have not been any reports of backups near maintenance hole 224-326 which may only indicate high basement elevations relative to the level of surcharging or the model is overestimating the extent of surcharge. The surcharge at maintenance hole 224-331 corresponds with the backup locations around 2nd Avenue NW and others west on NW 105th Street. Modeling of the December 3, 2007 event shows that the pipe continues to surcharge east to an alley between Palatine Avenue N and Greenwood Avenue N. This eastern location corresponds to several locations of homes that experienced backups during the December 1996 and December 2007 events.

12th Avenue NW

Modeling performed with the existing conditions indicates that 12th Avenue NW from NW 117th Street to north of NW 130th Street surcharges during large storm events. However, sewer backup claims filed with SPU for 12th Avenue NW include only two homes near NW 122nd Street, two homes near NW Blakely Court, and two homes north of NW 130th Street. The sewer backups at the first four homes occurred during the December 3, 2007 storm while the remaining homes experienced backups during a period of no rain. Discussions with neighbors during Broadview Task Force meetings as well as emails received by SPU indicate that the actual number of homes that experienced backups during the December 3, 2007 event as well as during smaller events is much greater than those reported in the SPU claims record. One resident reported that the maintenance hole 218-098 located at the corner of 12th Avenue NW and NW 130th Street regularly overflows into his yard. This additional information indicates that the surcharging in the existing conditions modeled is likely an accurate representation of what occurs in the basin. Additionally, field investigation has shown that most of the homes that have experienced sewer backups in this area are homes with low basement elevations. Any pipe surcharging above the elevation of these homes will lead directly to sewer backups.

Table 10 below presented the observed discharge in the pipe segments during the 1/7/2009 storm event, the 100-year modeled discharge, and the 100-year modeled discharge as a percent of capacity for pipe reaches along 12th Avenue NW that are near where the ADS flow meter was installed. The capacities of the pipe segments shown are well below the 100-year modeled discharge as well as the observed discharge during the January 7th, 2009 storm. The observed discharges are likely greater than the Manning's capacity in these segment of pipe due to surcharge. Capacity calculations in Table 10 shows that a long stretch of pipe along 12th Avenue NW is under capacity relative to even modest storm events.

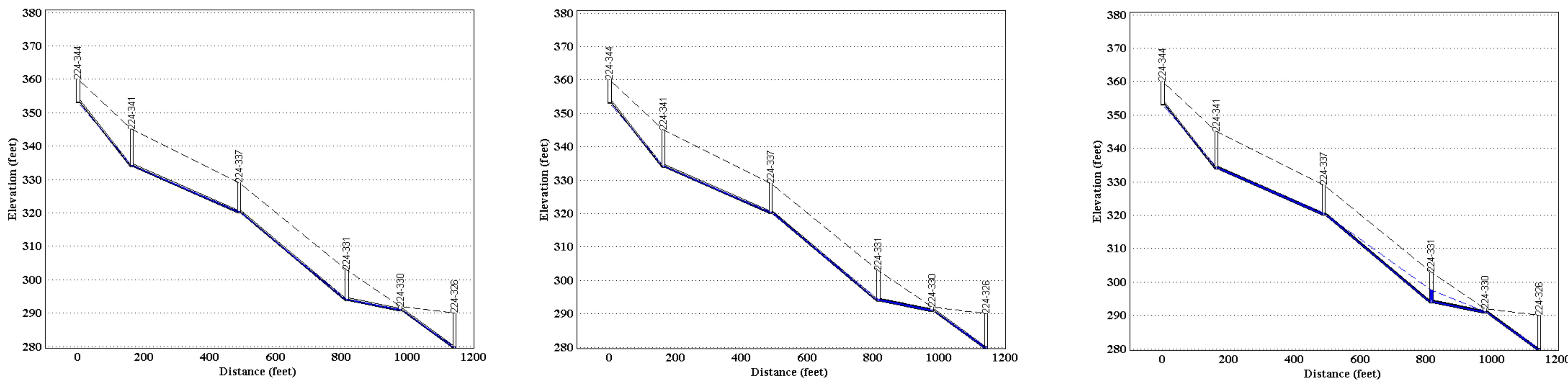


Figure 13. Water surface elevation profiles on NW 105th Street between Greenwood Avenue N and 3rd Avenue NW for the 2-year (left), 25-year (middle), and 100-year (right) storms under existing conditions

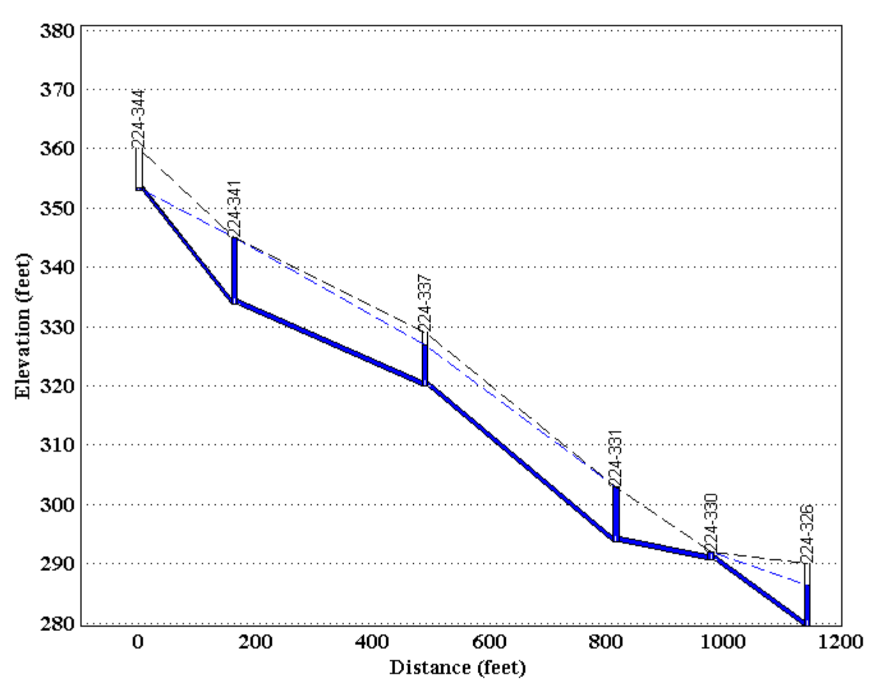


Figure 14. Water surface elevation profile on NW 105th Street between Greenwood Avenue N and 3rd Avenue NW for the December 3, 2007 storm under existing conditions

Table 10. The Manning's capacity, January 7th, 2009 observed discharge, 100-year modeled discharge, and 100-year discharge as a percent of capacity for the pipe segments in the area of concern along NW 12th Avenue.

Pipe Segment	Location	Capacity[a] (cfs)	1/7/2009 OBS Discharge (cfs)	100-Year MOD Discharge (cfs)	100-Year MOD Discharge as Percent of Capacity[a] (percent)
224-019– 224-025	12th Avenue NW south of NW 122nd Street	1.6	1.75	2.74	174
224-025 – 224-067	12th Avenue NW north of NW 120th Street	2.4	1.75	2.74	113
224-067 – 224-070	12th Avenue NW south of NW 120th Street	1.4	1.75	2.74	198
224-070 – 224-071	12th Avenue NW north of NW 119th Street	1.4	1.75	2.74	194

Note: [1] Capacity calculations presented here are based on Manning's calculations of maximum free flow discharge based on roughness, slope, and pipe diameter. This capacity does not include the effects of pressure head on discharge.

Peak water surface elevations for the existing conditions model are shown in Figure 15. Two maintenance holes (224-067 and 224-070) surcharge during the 2-year event, all the maintenance holes between 218-098 and 224-071 surcharge during the 25-year event, and all maintenance holes between 218-070 and 224-071 surcharge during the 100-year event.

6th Avenue NW

Although several homes along 6th Avenue NW between NW 120th Street and NW 122nd Street have experienced sewer backups in the past, the EPA-SWMM 5 model does not show any pipe surcharging at this location. As discussed in the "Model Validation" section, it is believed that increased infiltration during large storm events causes sewer backups at this location. This is likely caused by a under prediction of infiltration due to the short monitoring time period where high infiltration was not observed.

Table 11 below presents the Manning's capacity, observed discharge during the 1/7/2009 storm event, the 100-year modeled discharge, and the 100-year modeled discharge as a percent of capacity for pipe reaches connecting to the maintenance hole at the corner of 6th Avenue NW and NW 120th Street. The calculated capacity at this location far exceeds the 100-year modeled discharge. Since the model likely underestimates infiltration at this location, it is interesting to note that the observed January 7th, 2009 discharge out of maintenance hole 224-104 is only 25 percent of the Manning's capacity. In the area of concern that has the pipe network most similar to 6th Avenue N, the observed discharge out of the corner maintenance hole was over 80 percent of its calculated capacity.

Table 11. The Manning's capacity, January 7th, 2009 observed discharge, 100-year modeled discharge, and 100-year discharge as a percent of capacity for the area of concern near 6th Avenue NW and NW 120th Street..

Pipe Segment	Location	Capacity[a] (cfs)	1/7/2009 OBS Discharge (cfs)	100-Year MOD Discharge (cfs)	100-Year MOD Discharge as Percent of Capacity[a] (percent)
224-042 – 224-104 (IN)	Along 6th Avenue NW to the north of NW 120th Street	1.6	0.26	0.58	36
224-105 – 224-104 (IN)	Along NW 120th Street to the east of 6th Avenue NW	2.7	0.62	0.77	29
224-104 – 224-103 (OUT)	Along NW 120th Street to the west of 6th Avenue NW	3.5	0.88	1.38	39

Note: [a] Capacity calculations presented here are based on Manning's calculations of maximum free flow discharge based on roughness, slope, and pipe diameter. This capacity does not include the effects of pressure head on discharge.

Peak water surface elevation profiles are not shown for 6th Avenue NW since the EPA-SWMM 5 model does not simulate any pipe surcharging at this location.

Dayton Avenue N

A number sewer of backups were reported on Dayton Avenue N during the December 3, 2007 storm event. Most of these homes are clustered upstream of Christ the King School which is on NW 117th Street. Additional locations occurred on Dayton Avenue N between NW 110th Street and NW 105th Street. There have been conflicting reports of a blockage in the sewer pipe at this location during this event but no final determination has been made. Three additional homes reported flooding further south near Dayton Avenue N and NW 107th Street and are discussed at the end of this section.

Five homes upstream of Christ the King School filed claims for sewer backups on the December 3, 2007 storm event. Communications with residents indicate the number of homes that experienced sewer backups may be considerably greater. However, the EPA-SWMM 5 model under existing conditions does not simulate pipe surcharging in this area in either the 100-year or December 3, 2007 event. However, the model does show surcharging to south where the sewer line under Dayton Avenue N turns west. Although the location of the historic backups is near the location of simulated surcharging in the model, the historical backups are not believed to be caused by the same mechanism that creates the modeled surcharging. Modeled surcharge is caused by inadequate capacity along NW 115th Street to the west of Dayton Avenue N. If surcharge occurring here were to impact the upstream locations where sewer backups were reported on December 3, 2007, many additional homes would likely have experienced sewer backups.

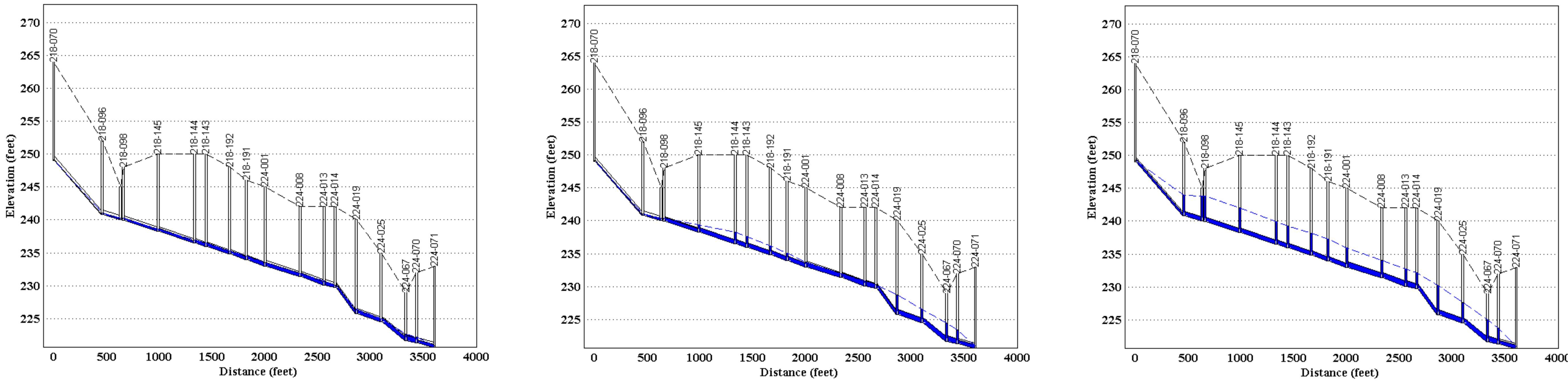


Figure 15. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under existing conditions

Table 12 below presents the Manning's capacity, observed discharge during the 1/7/2009 storm event, 100-year modeled discharge, and the 100-year modeled discharge as a percent of capacity for the sewer line on Dayton Avenue N just south of NW 120th Street and for the sewer line on NW 115th Street just to the east of Greenwood Avenue N. The Manning's capacity of the pipe segment on Dayton Avenue N exceeds the 100-year modeled discharge which would confirm the claim that there was a pipe blockage during the December 3, 2007 event. The downstream pipe segment on NW 120th Street, however, has a capacity under the 100-year modeled discharge.

Table 12. The Manning's capacity, January 7th, 2009 observed discharge, 100-year modeled discharge, and 100-year discharge as a percent of capacity for Dayton Avenue N south of NW 120th Street and for NW 120th Street to the east of Greenwood Avenue N.

Pipe Segment	Location	Capacity[a] (cfs)	1/7/2009 OBS Discharge (cfs)	100-Year MOD Discharge (cfs)	100-Year MOD Discharge as Percent of Capacity[a] (percent)
225-036–225-045	Dayton Avenue N south of NW 120th Street	1.6	n/a	0.7	44
225-071 – 22-070	NW 115th Street east of Greenwood Avenue N	1.1	1.7	2.0	182

Note: [a] Capacity calculations presented here are based on Manning's calculations of maximum free flow discharge based on roughness, slope, and pipe diameter. This capacity does not include the effects of pressure head on discharge.

Peak water surface profiles of the pipe segments from Dayton Avenue N and NW 117th (maintenance hole 225-054) to Greenwood Avenue N and NW 115th Street (maintenance hole 225-070) are shown in Figure 16 for the 2-, 25- and 100-year events in the existing conditions model. A small amount of surcharging is present in the 2-year simulation at maintenance holes 225-071 and 225-072. This surcharging becomes progressively worse for the 25- and 100-year events and extends to maintenance hole 225-064.

The southern portion of Dayton Avenue N by NW 105th Street shows surcharge in the existing condition model under the 100-year event to a depth of 1.5 feet. Although Dayton Avenue to the north of NW 115th Street appears to be hydraulically disconnected from Dayton Avenue N to the south of NW 115th Street, an overflow outlet exists at six feet elevation in the maintenance hole at Dayton Avenue N and NW 115th Street allowing excessive surcharge in maintenance hole 225-072 to discharge to the south. Reducing surcharge on Dayton Avenue N north of NW 115th Street may also reduce surcharge on Dayton Avenue N south of NW 115th Street if the overflow at maintenance hole 225-072 were not activated.

Alternative 1

Output from the EPA-SWMM 5 model indicates that the backup locations near 1st Avenue NW and NW 115th Street and NW 105th Street between Greenwood Avenue N and 3rd Avenue NW occur at locations where segments of pipe have a capacity lower than the 100-year modeled discharge. Upsizing a limited amount of pipe at these locations can reduce the potential of sewer backups in the future as is modeled under Alternative 1. Figure 17 shows Alternative 1 and indicates elimination of surcharging up to the 100-year event at the area of concern at 1st Avenue NW and NW 115th Street and at NW 105th Street to the east of Greenwood Avenue N (this figure should be compared against Figure 10 – Existing Conditions). Additionally, the figures show surcharging that occurs on 12th Avenue NW and Dayton Avenue N are not affected by Alternative 1. As a result, these areas must be addressed under Alternatives 1 and 2. Information on the proposed pipe network and model simulation under Alternative 1 is presented below.

1st Avenue NW and NW 115th Street

The most cost-effective solution to reducing surcharging in maintenance hole 224-201 was obtained from increasing the diameter of the pipe segment 224-201 to 224-197 which conveys discharge out of the maintenance hole. The existing pipe is 8 inches in diameter and has a capacity of 3.25 cfs. The proposed alternative replaces the pipe with a 12-inch pipe which increases the capacity to 9.6 cfs. Since segment 224-145 to 224-201 has sag, it also was replaced as part of the alternative. Although Manning's calculations and modeling show segment 224-145 to 224-201 has sufficient capacity, a 12 inch pipe is proposed to replace the 8 inch pipe due to the pipe sag and since the area includes historical sewer backups. This will result in an increase of capacity in this segment to 4.84 cfs. The effectiveness of this alternative in reducing surcharging is discussed below.

Analysis with the EPA-SWMM 5 model shows that maintenance hole 224-201 does not surcharge under the proposed alternative during the 2-year through 100-year events (Figure 18) and during the December 3, 2007 event (Figure 19). This is compared against Figures 8 and 9 which show pipe surcharging in the existing conditions model. Historical sewer backups at this location have been caused directly by the surcharging of this maintenance hole, hence eliminating surcharging at this maintenance hole will reduce the likelihood of future backups at this location.

Upsizing pipe segment 224-201 to 224-197 from 8-inch to 12-inch diameter causes a maximum downstream peak flow increase of 0.48 cfs in the 100-year event (4.28 cfs for the existing conditions versus 4.6 cfs for Alternative 1). Additionally, the alternative does not create any new areas of surcharging in the downstream pipe network in events up to and including the 100-year event. However, it causes surcharging that would have occurred in the existing pipe network at maintenance hole 224-201 during the December 3, 2007 event to occur at the next maintenance hole downstream (Figure 19).

NW 105th Street

Upsizing pipe segment 224-331 to 224-330 from a 10 inch diameter pipe to a 15 inch diameter pipe will reduce the frequency and magnitude of surcharging in this section of pipe. The existing

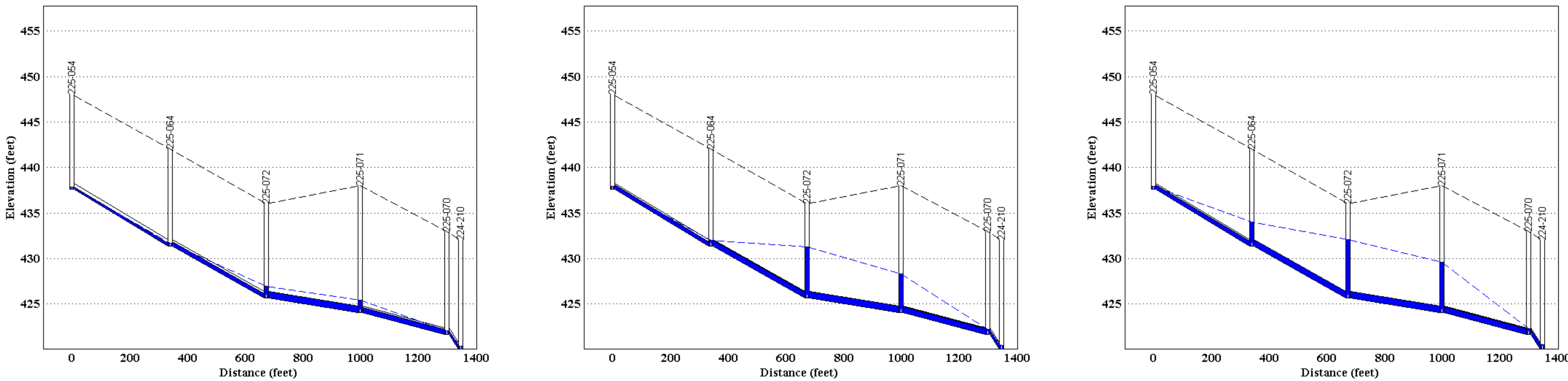
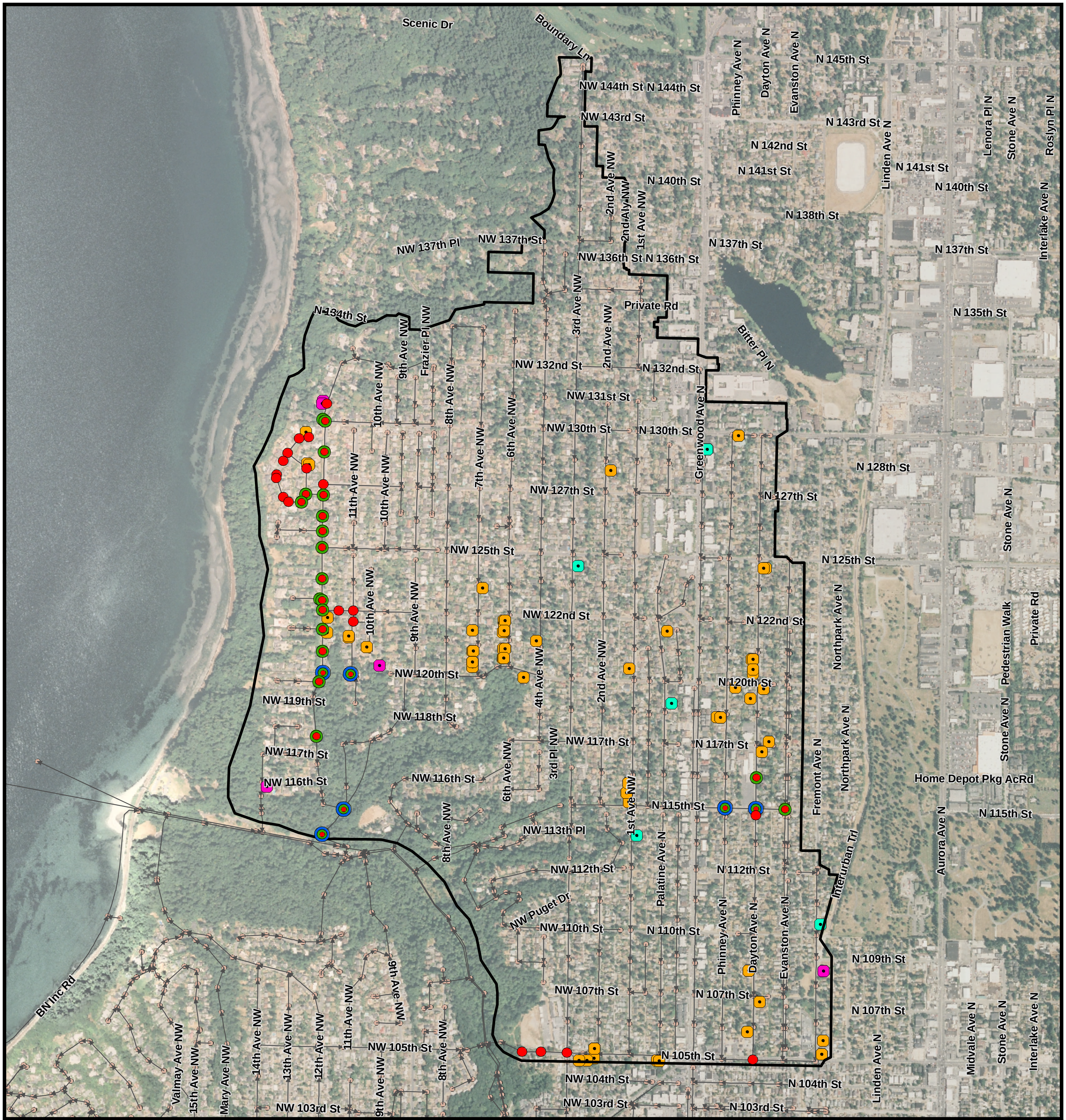


Figure 16. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under existing conditions



Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 1 surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 17. Locations of historic sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 1 model.

N

0 700 1,400 2,800 Feet

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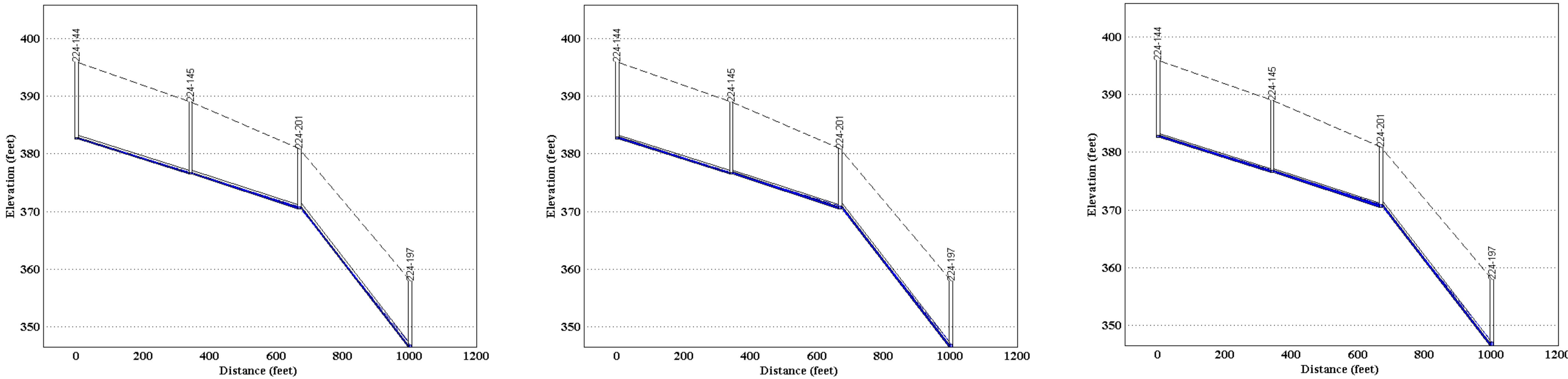


Figure 18. Water surface elevation profiles on 1st Avenue NW and NW 115th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

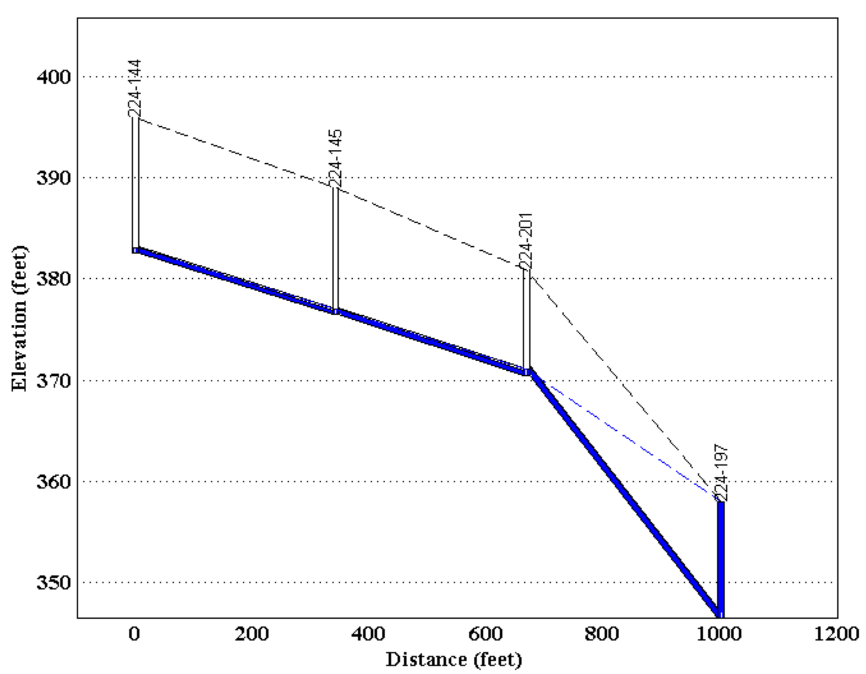


Figure 19. Water surface elevation profiles on 1st Avenue NW and NW 115th Street for the December 3, 2007 storm under Alternative 1

capacity of this pipe segment is 3.0 cfs. Upsizing the pipe increases the capacity to 8.8 cfs. Table 9 above shows that pipe segment 224-341 to 224-337 has adequate capacity for the modeled 100-year event. However, its capacity is lower than the adjoining pipes and it is located where sewer backups have occurred on multiple occasions. Because of this proximity to historical backups and having a lower capacity than surrounding pipes, the modeling done under this alternative also includes upsizing this segment from 10 inch to 15 inch.

The figures below show the peak hydraulic grade line along NW 105th Street for the 2-year, 25-year, and 100-year design events (Figure 20) and the December 3, 2007 event (Figure 21) for the proposed pipe replacement alternative. Modeling of existing conditions shows no surcharging in the 2- and 25-year events but does show surcharging in the 100-year and December 3, 2007 event. The proposed alternative (Figures 17 and 18) eliminates surcharging to the west of 3rd Avenue N for events up to and including the December 3, 2007 event. Specifically, the proposed alternative eliminates surcharging between maintenance hole 224-330 and maintenance hole 224-337 during the 100-year event (Figure 20), and between maintenance hole 224-330 and maintenance hole 224-344 up to the December 3, 2007 event (Figure 21). This reach of pipe is where historical backups have occurred.

The downstream impacts associated with upsizing these two segment of pipe include a maximum increase in downstream water surface elevation of 0.03 feet during the 100 year event. Additionally, the peak flow increase in the downstream pipe is 0.02 cfs (4.04 in existing conditions versus 4.06 in the alternative 1 model) during the 100-year event.

Alternative 2, Inflow Reduction

The modeling done under Alternative 2 applies the inflow reductions across the entire Broadview Basin, enabling review of the flow reductions anywhere in the study area. However, if one of these scenarios were implemented, it would likely be targeted to the specific drainage areas upstream of historical sewer backup locations. Nonetheless, basin wide results are presented in Figures 22, 23, and 24 for scenarios 2.A, 2.B, and 2.C., respectively. Modeling done under Alternative 2 assumes that the Alternative 1 pipe replacement options will be implemented. Therefore, Figure 22, 23, and 24 should be compared against Figure 17 (Surcharging Locations – Alternative 1) to gauge the effectiveness of the Alternative 2 scenarios.

The problem areas that still exist after the Alternative 1 solution are 12th Avenue NW, 6th Avenue NW between NW 120th Street and NW 122nd Street, Dayton Avenue NW north of NW 105th Street and Dayton Avenue NW north of NW 115th Street. The Alternative 2 scenarios (Figures 22, 23, and 24) show an overall decreasing trend in the amount of surcharging at these locations. Along 12th Avenue NW, each increasing level of inflow reduction results in fewer surcharging maintenance holes. Along NW 105th Street, the surcharging remaining in the Alternative 1 model west of 3rd Avenue N is reduced in Alternative 2.A and eliminated in Scenarios 2.B and 2.C. The modeled surcharging at the corner of Dayton Avenue N and NW 105th Street is eliminated in Scenario 2.A, while the surcharging at Dayton Avenue N and NW 115th Street is progressively reduced in Scenarios 2.A through 2.C. More detailed information for each of the problem locations is presented in the sections below.

12th Avenue NW

Peak discharges from the 100 year event are presented below in Table 13 for the existing conditions and Alternative 2 scenarios. The discharges given are for discharge into maintenance hole 224-071 (located on 12th Avenue NW just north of NW 122nd Street). This segment of pipe is 10 inch concrete with a Manning's capacity is 1.4 cfs. The Manning's capacity is the highest discharge that can flow through the pipe without any pressure head behind it. Surcharging of upstream pipe can force more water through and allow discharge in excess of the Manning's free flow capacity. As can be seen from column "Peak Discharge", all discharges are in excess of the free flow capacity. Alternative 2.C which is the most aggressive inflow reduction scenario still has a peak 100-year discharge 0.85 cfs greater than the Manning's pipe capacity. The percentage reductions in peak flow are 2 percent, 4 percent, and 14 percent in Alternative 2.A through 2.C. A 46 percent reduction in peak flow is required to limit discharge to the Manning's capacity of the pipe. However, any reduction in inflow and peak flow will reduce the probability and/or extent of backups in the future. Further discussion on this location is provided in the "Conclusions" section.

Table 13. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 224-071 for the existing conditions and Alternative 2 scenarios during the 100-year event.

Model Run	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	2.61	n/a
Alt 2.A	2.56	2
Alt 2.B	2.51	4
Alt 2.C	2.25	14

Alternative 1 peak water surface elevations along 12th Avenue NW are shown in Figure 25 for comparison with Figures 26, 27, and 28, which show the peak water surface elevation at the same location in Alternative 2.A through 2.C models for the 2-, 25-, and 100-year events. The small amount of surcharging in maintenance hole 224-067 in the existing conditions 2-year event model still exists in the Alternative 2.A and 2.B scenarios but is eliminated by the Alternative 2-C scenario. During the 25-year event the existing conditions model simulates approximately 3,000 feet of pipe surcharging from maintenance hole 218-098 to maintenance hole 224-071. In alternatives 2.A, 2.B, and 2.C the surcharging is progressively reduced. In alternative 2.C only a small depth of surcharging exists in maintenance holes 224-067 and 224-070. The surcharge associated with the 100-year event exists from maintenance holes 218-070 to 224-071 (~3,600 feet) in the existing conditions model. The surcharge in the Alternative 2.A and 2.B scenarios begins 500 feet further downstream. For Alternative 2.C, the extent of surcharging has decreased considerably, and is at a depth of less than 1 feet.

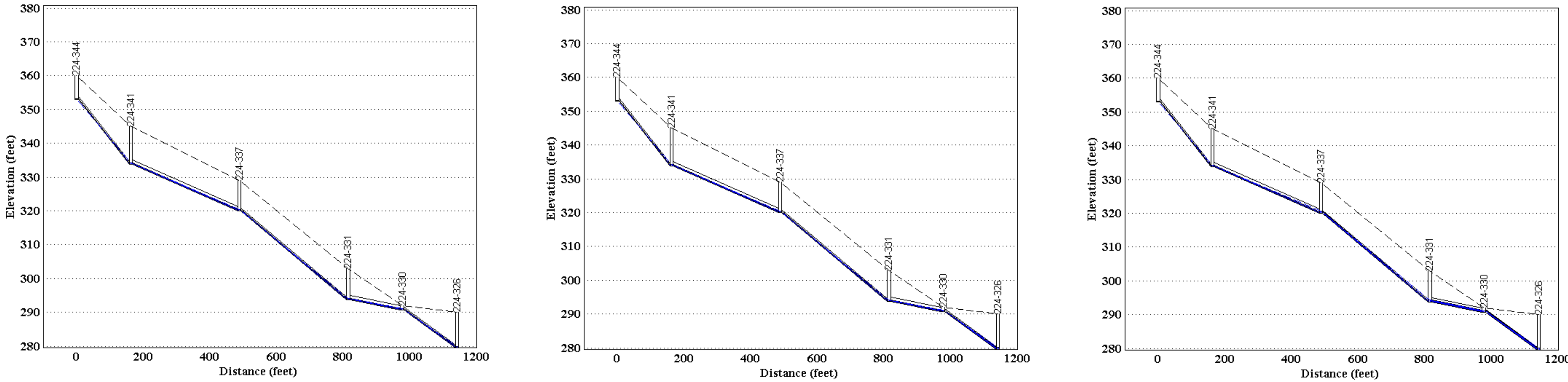


Figure 20. Water surface elevation profiles on NW 105th Street between Greenwood Avenue N and 3rd Avenue NW for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

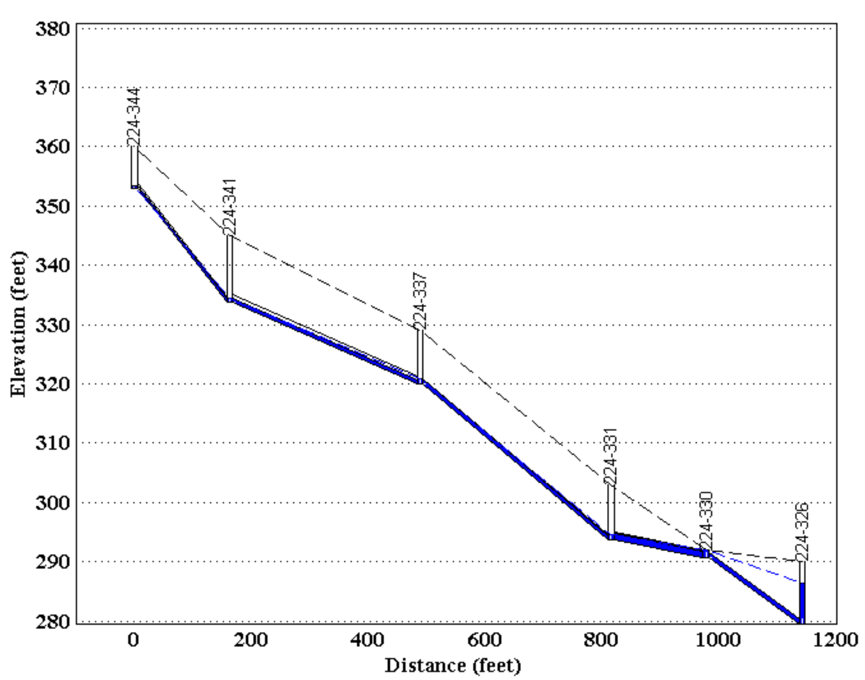
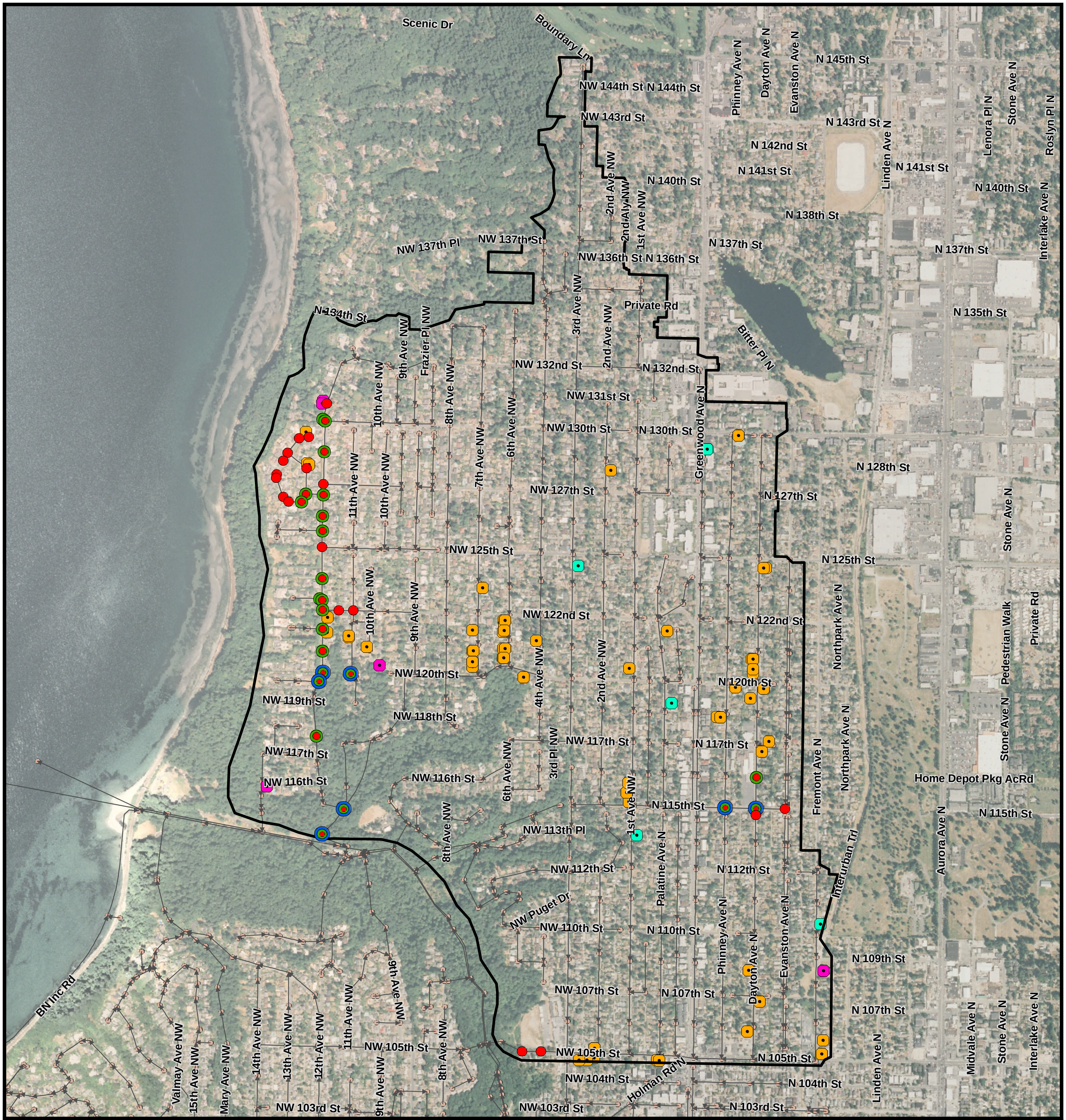


Figure 21. Water surface elevation profile on NW 105th Street between Greenwood Avenue N and 3rd Avenue NW for the December 3, 2007 storm under Alternative 1



Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 2.A surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 22. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 2.A model.

N

0 700 1,400 2,800 Feet

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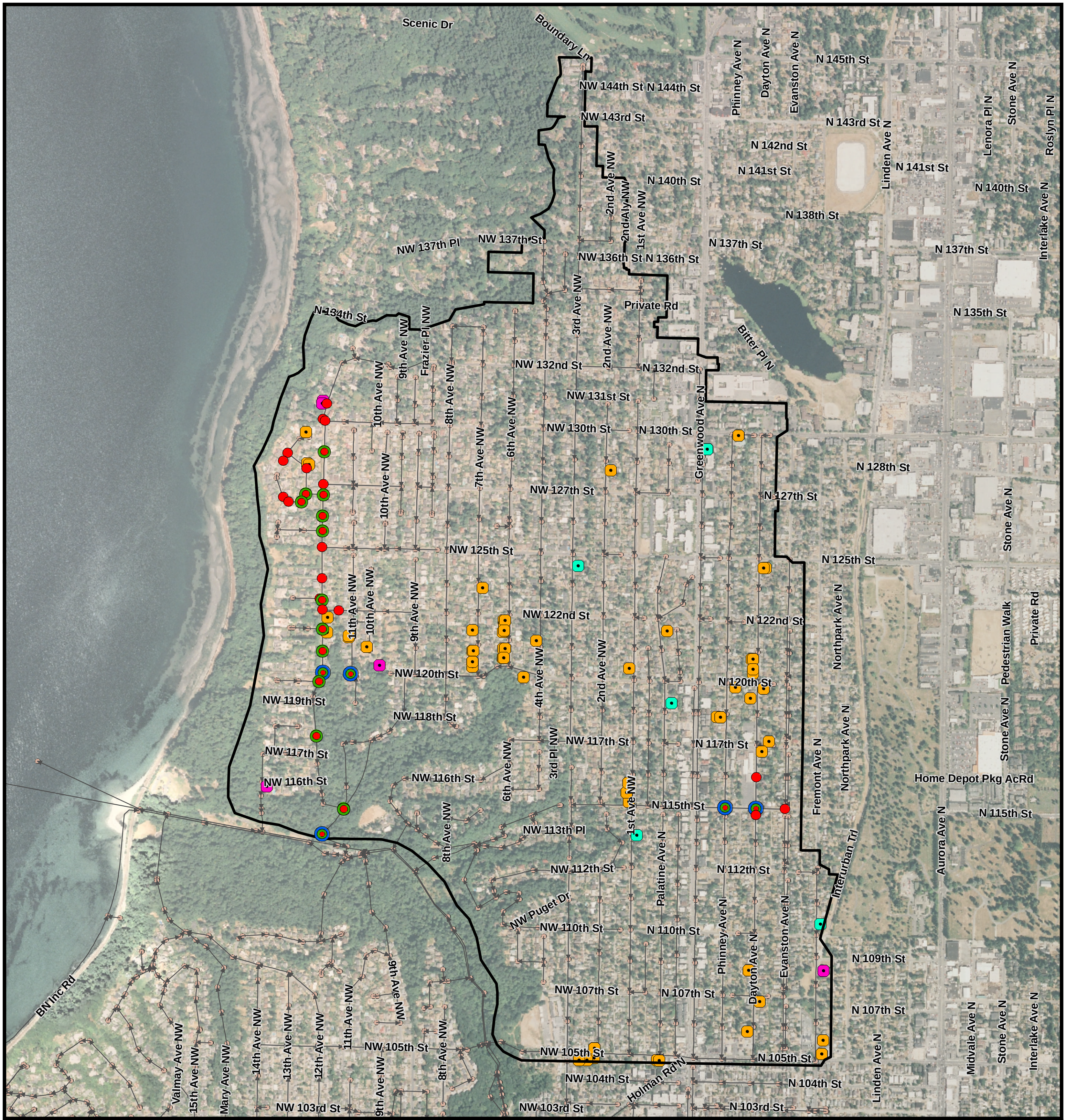

Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 2.B surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 23. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 2.B model.

N

0 700 1,400 2,800 Feet

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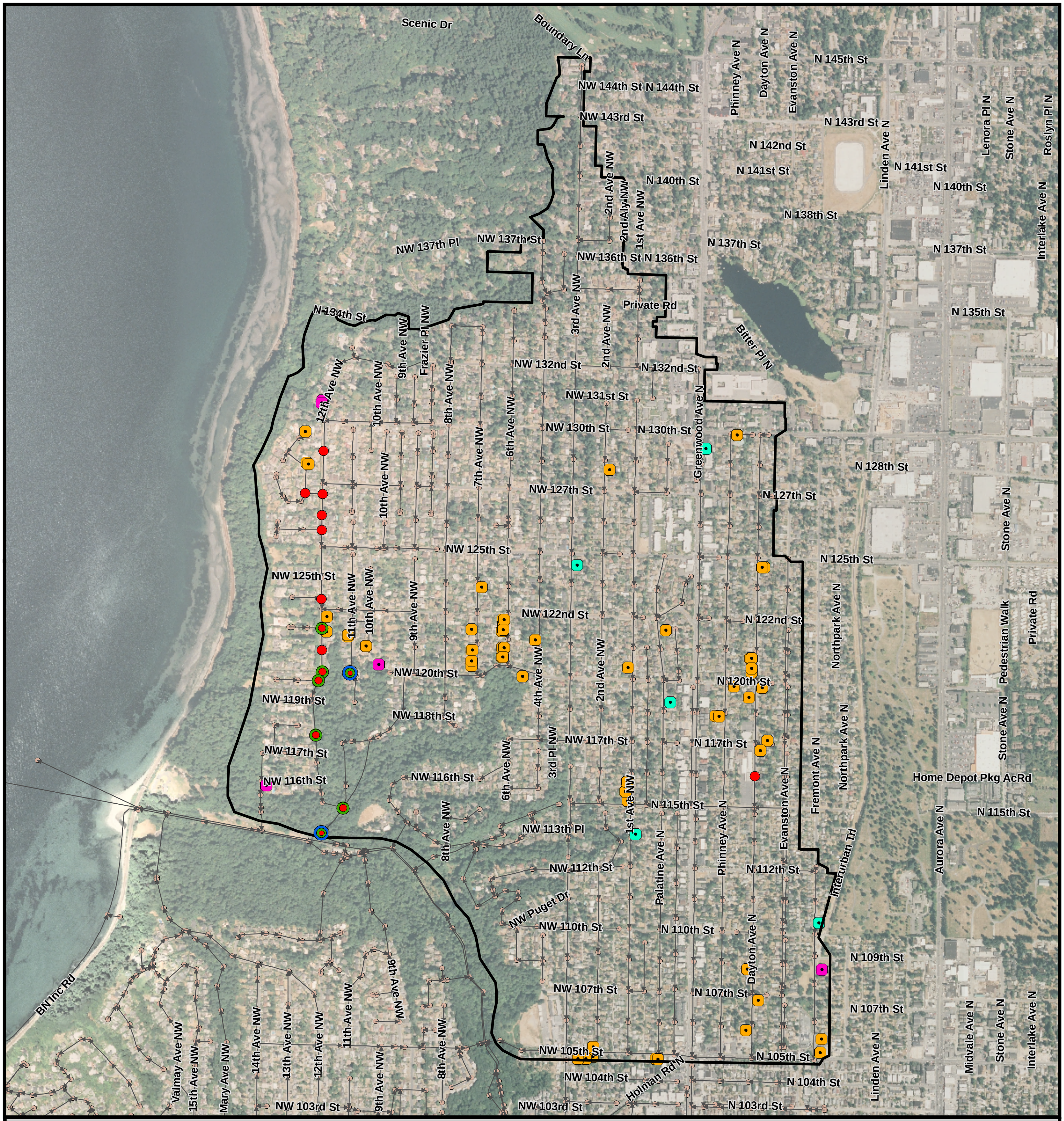

Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 2.C surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 24. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 2.C model.

N

0 700 1,400 2,800 Feet

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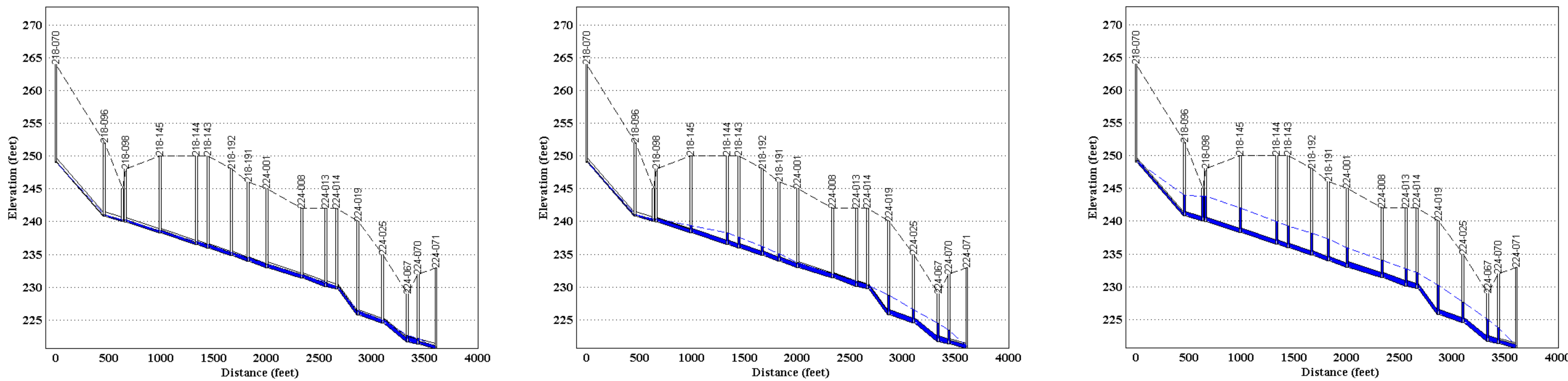


Figure 25. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

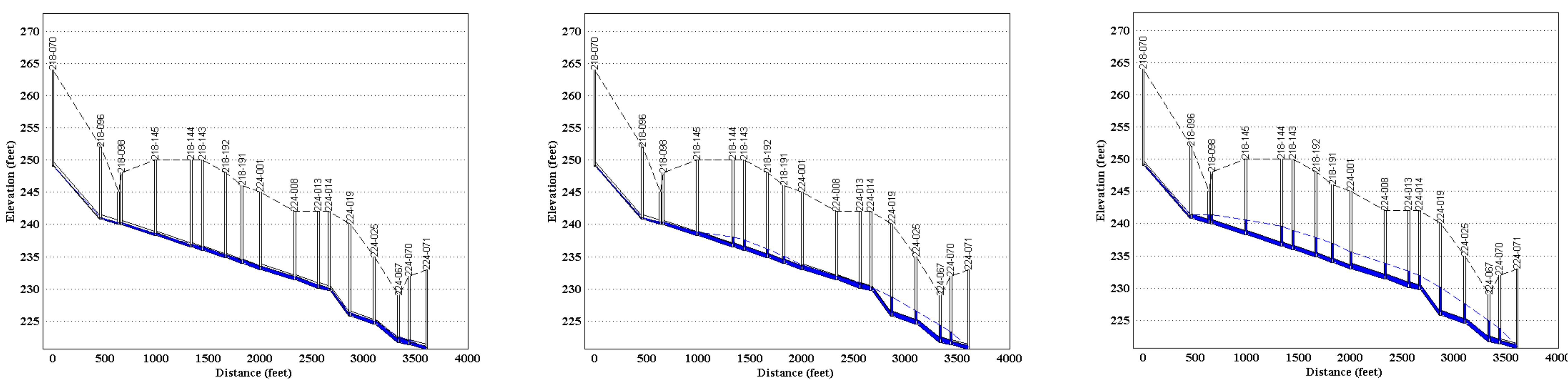


Figure 26. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.A

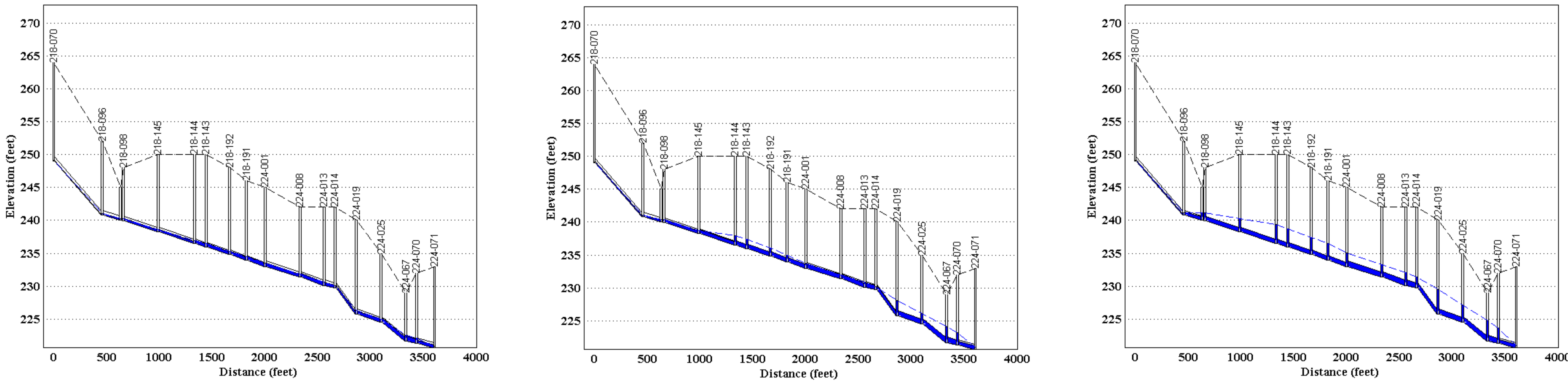


Figure 27. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.B

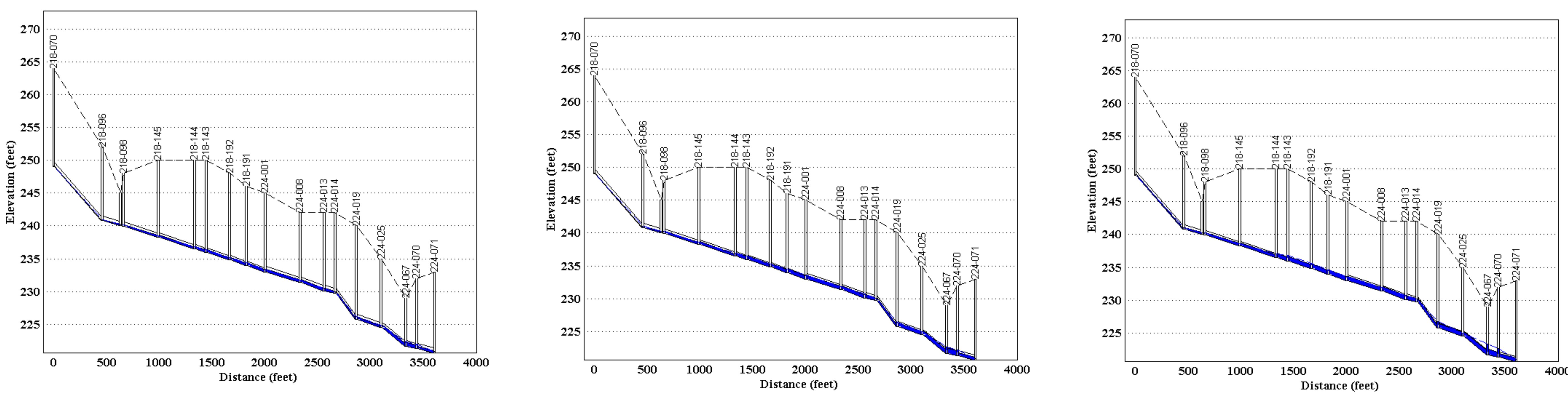


Figure 28. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.C

6th Avenue NW

As discussed in the “Model Validation” and “Results / Existing Conditions“ sections, the EPA-SWMM 5 model does not accurately simulate discharge during large return interval events. Nonetheless, Table 14 below shows the reduction in peak discharge that is achieved with the Alternative 2 scenarios. The discharges shown are for maintenance hole 224-104 which is at the corner of 6th Avenue NW and NW 120th Street. A detailed discussion is not provided for this table because the discharge numbers presented are not representative.

Table 14. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 224-104 for the existing conditions and Alternative 2 scenarios during the 100-year event.

Model Run	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	1.38	n/a
Alt 2.A	1.33	3
Alt 2.B	1.26	8
Alt 2.C	0.81	41

Dayton Avenue N

Although the existing conditions model does not simulate pipe surcharge in historic locations on Dayton Avenue N north of NW 120th during either the 100-year or December 3, 2007 events, it does show surcharge two blocks south where the sewer line under Dayton Avenue N heads west. Although the location of the historic backups is near the location of simulated surcharging in the model, the historical backups are not believed to be caused by the same mechanism. Figure 29 plots Alternative 1’s hydraulic grade line between the intersection of Dayton Avenue N and NW 117th (maintenance hole 225-054) and the intersection of Greenwood Avenue N and NW 115th Street (maintenance hole 225-070). Figure 29 is provided as reference for Figures 30, 31, and 32 which show water surface elevation profiles associated with the 2-, 25- and 100-year events under the Alternative 2 scenario models. Although the peak water surface elevation figures presented for this location do not include the location near NW 120th Street where backups occurred during the December 3, 2007 event (because the model does not simulate any surcharging at this location), the reductions in peak discharges at this location are presented in Table 15.

In the existing conditions model, a small amount of surcharging is present in the 2-year simulation at maintenance holes 225-071 and 225-072. The same maintenance holes surcharge during the 2-year event in Scenarios 2.A and 2.B but at slightly lower depths. Surcharging at both these maintenance holes is eliminated in the 2-year event in Scenario 2.C. Under the existing conditions model in the 25-year event the same two maintenance holes surcharge with maintenance hole 225-072 surcharging approximately 5 feet. Scenario 2.A shows a negligible decrease in water surface elevation, while in scenario 2.B the water surface elevation is reduced by approximately one foot in both maintenance holes that surcharge. During the 100-year event, the existing conditions model now surcharges at maintenance hole 225-064 and surcharges in maintenance hole 225-072 to the elevation of the overflow outlet at 6 feet above the bottom of the maintenance hole. The scenario 2.A model under the 100-year event has peak surcharging to essentially the same depth as the existing conditions model. The surcharging depth in the scenario 2.B model is only slightly less than in the 2.A model; however, by scenario 2.C there is a marked decrease in peak water surface elevation.

Table 15. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 225-036 for the existing conditions and Alternative 2 scenarios during the 100-year event.

	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	0.73	n/a
Alt 2.A	0.72	2
Alt 2.B	0.68	7
Alt 2.C	0.50	31

Table 16 below shows the peak discharge at maintenance hole 225-070 at the intersection of NW 115th Street and Greenwood Avenue N for the existing conditions and Alternative 2.A, 2.B, and 2.C scenarios. For comparison, the Manning's capacity for the 8 inch pipe is 1.1 cfs which is lower than the modeled peak discharge associated with the 100-year event. This peak discharge above the Manning's capacity shows the effects of pipe surcharging and pressure head on the discharge. The reduction in peak discharge associated with scenarios 2.A, 2.B, and 2.C are 0 percent, 0 percent, and 12 percent, respectively. Although these reductions in peak discharge may seem erroneous, the existing conditions, scenario 2.A, and scenario 2.B all have the same discharge because the upstream surcharging (pressure head) is to the 6 foot overflow elevation. Only by scenario 2.C does is the flow reduced because of the drop in water surface elevation seen in the profile plots.

Table 16. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 225-070 for the existing conditions and Alternative 2 scenarios during the 100-year event.

	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	1.99	n/a
Alt 2.A	1.98	0
Alt 2.B	2.00	0
Alt 2.C	1.74	12.6

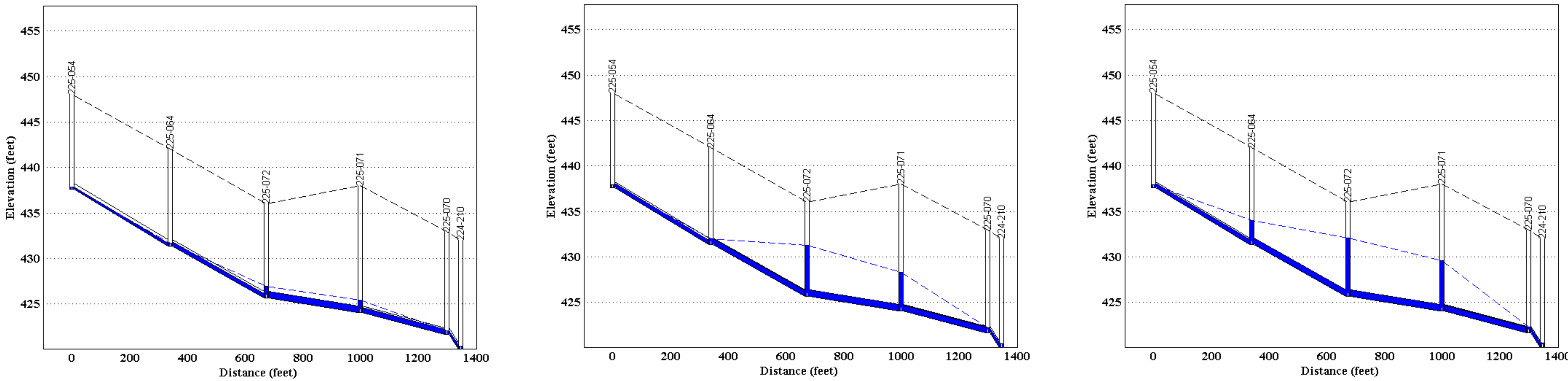


Figure 29. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

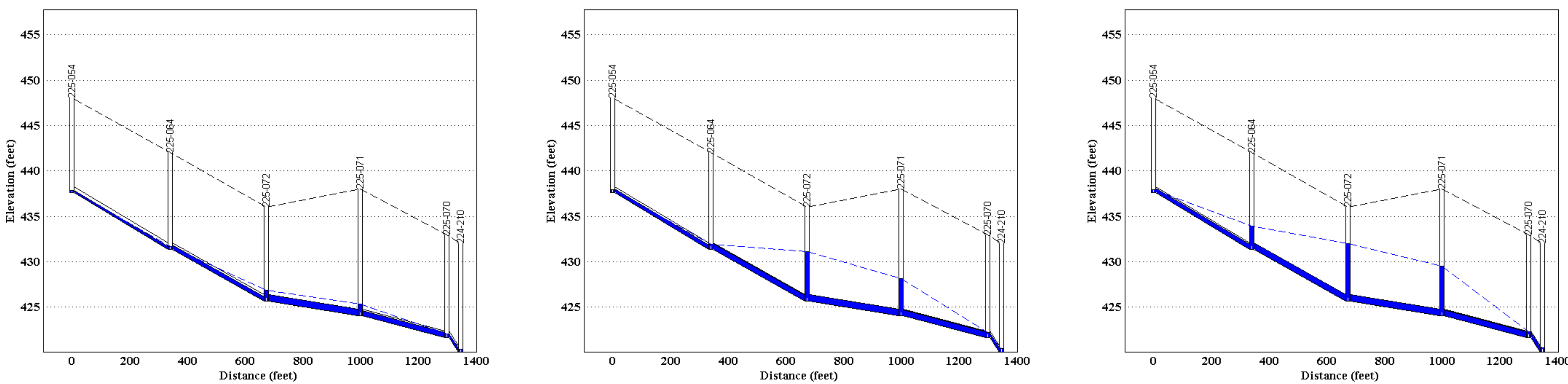


Figure 30. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.A

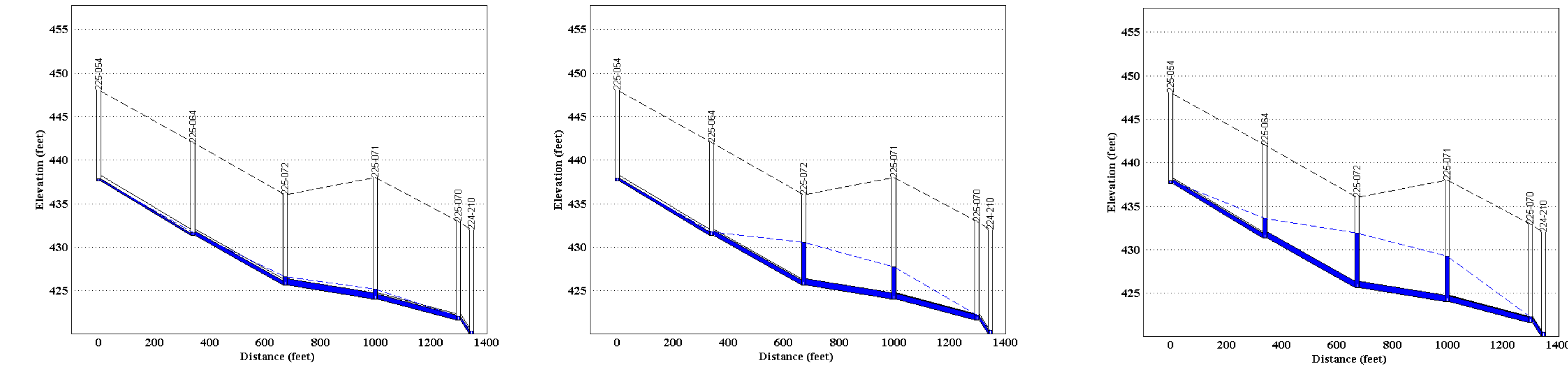


Figure 31. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.B

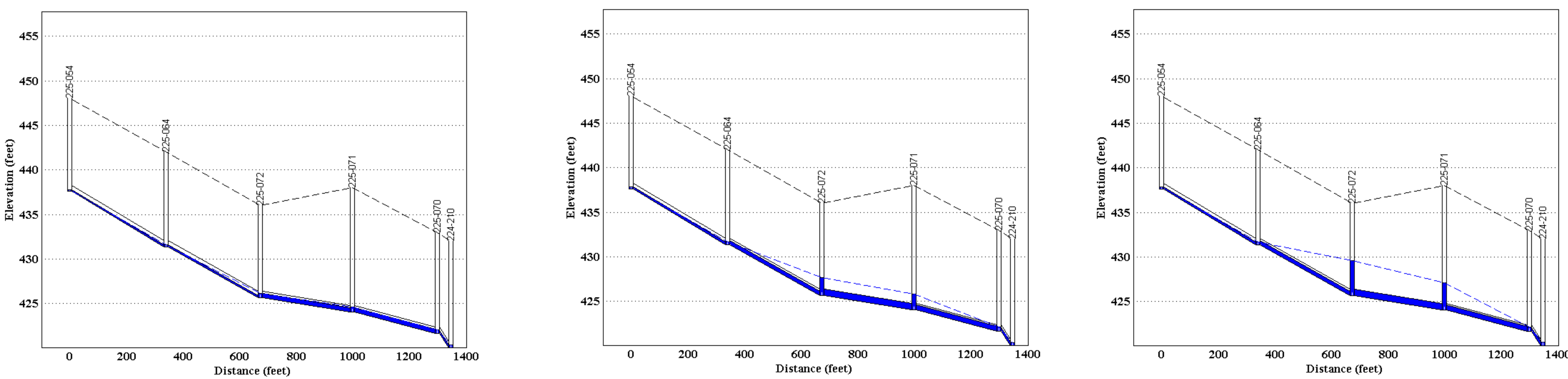


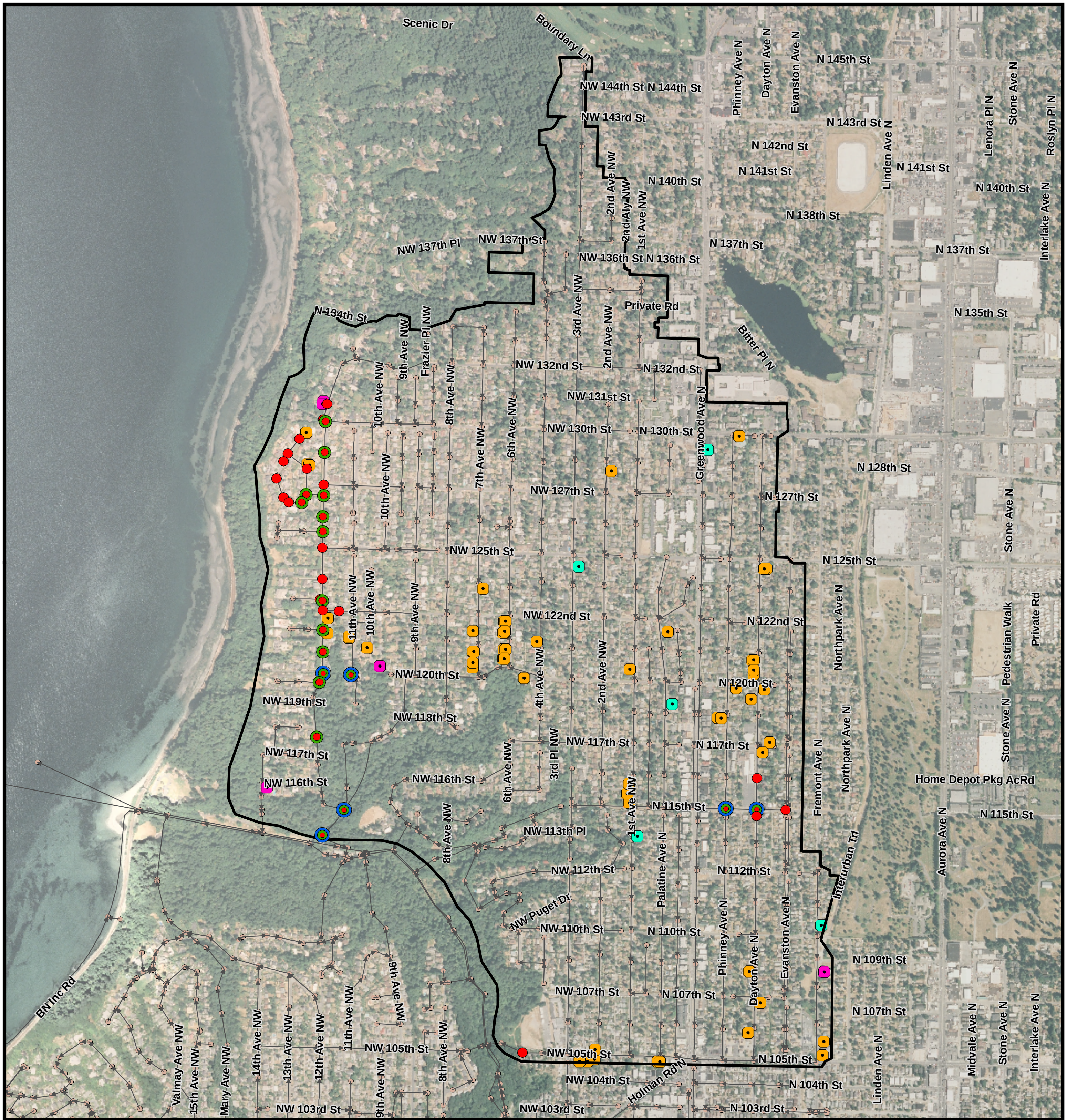
Figure 32. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 2.C

Although water surface profiles are not shown for this location (due to absence of modeled surcharging), Table 13 presents the peak discharge at maintenance hole 225-036 at the intersection of NW 120th Street and Dayton Avenue N for the existing conditions and Alternative 2.A, 2.B, and 2.C scenarios. For comparison, the Manning's capacity for the 8 inch pipe is 1.6 cfs which is greater than the peak modeled discharge associated with the 100-year event. This peak discharge below the Manning's capacity supports the claim of a blockage existing in the pipe network during the December 3, 2007 event (although it may also indicate an under-simulation of I/I in the model). The reduction in peak discharge associated with scenarios 2.A, 2.B, and 2.C are 2 percent, 7 percent, and 31 percent, respectively. Although these reductions in peak discharge are not required here since they are already under the pipe capacity, they do have the benefit of taking discharge out of the system to help reduce the likelihood of sewer backups at downstream locations where the pipe may be closer to its maximum capacity

Alternative 3, Infiltration Reduction

The modeling done under Alternative 3 applies the infiltration reductions across the entire Broadview Basin, enabling review of the flow reductions anywhere in the study area. However, if one of these scenarios were implemented, it would likely be targeted to the specific drainage areas upstream of historical sewer backup locations. Although it is beneficial to reduce infiltration into the sewer system as much as possible (reduces the volume of rainwater that goes to a treatment plant, reduces the likelihood of CSO events, etc), reducing infiltration at a point downstream of backup locations will not help reduce the likelihood of those backups in the future (with the exception of backups caused by downstream controls). Regardless, basin wide results are presented, as well as in-depth results for the locations where infiltration reduction can potentially reduce backups at historic backup locations.

The Alternative 1 pipe replacement eliminates surcharge up to the 100-year event at both 1st Avenue NW and NW 115th as well as on NW 105th Street between 3rd Avenue NW and Greenwood Avenue N. The problem areas that still exist after the Alternative 1 solution are 12th Avenue NW, 6th Avenue NW between NW 120th Street and NW 122nd Street, Dayton Avenue NW north of NW 105th Street and Dayton Avenue NW north of 115th Street. The Alternative 3 scenarios (Figures 33, 34, and 35) show a progressive decrease in the amount of locations that are susceptible to surcharging. Along 12th Avenue NW, each increasing level of infiltration reduction results in fewer maintenance holes surcharging for a given event. Further discussion is provided below, but in general on 12th Avenue NW the Alternative 3 infiltration reduction scenarios prove more effective at reducing pipe surcharging than the Alternative 2 inflow reduction scenarios. Along NW 105th Street, the surcharging remaining in the Alternative 1 model west of 3rd Avenue N is reduced in the Alternative 3, Scenario 1 and eliminated in Scenarios 2 and 3. The modeled surcharging at the corner of Dayton Avenue N and NW 105th Street is eliminated in Scenario 1, while the surcharging at Dayton Avenue N and NW 115th Street remains in Scenarios 1 and 2 but is eliminated in scenario 3. More detailed information for each of the problem locations is presented in the sections below.



Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 3.A surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 33. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 3.A model.

N

0 700 1,400 2,800
Feet

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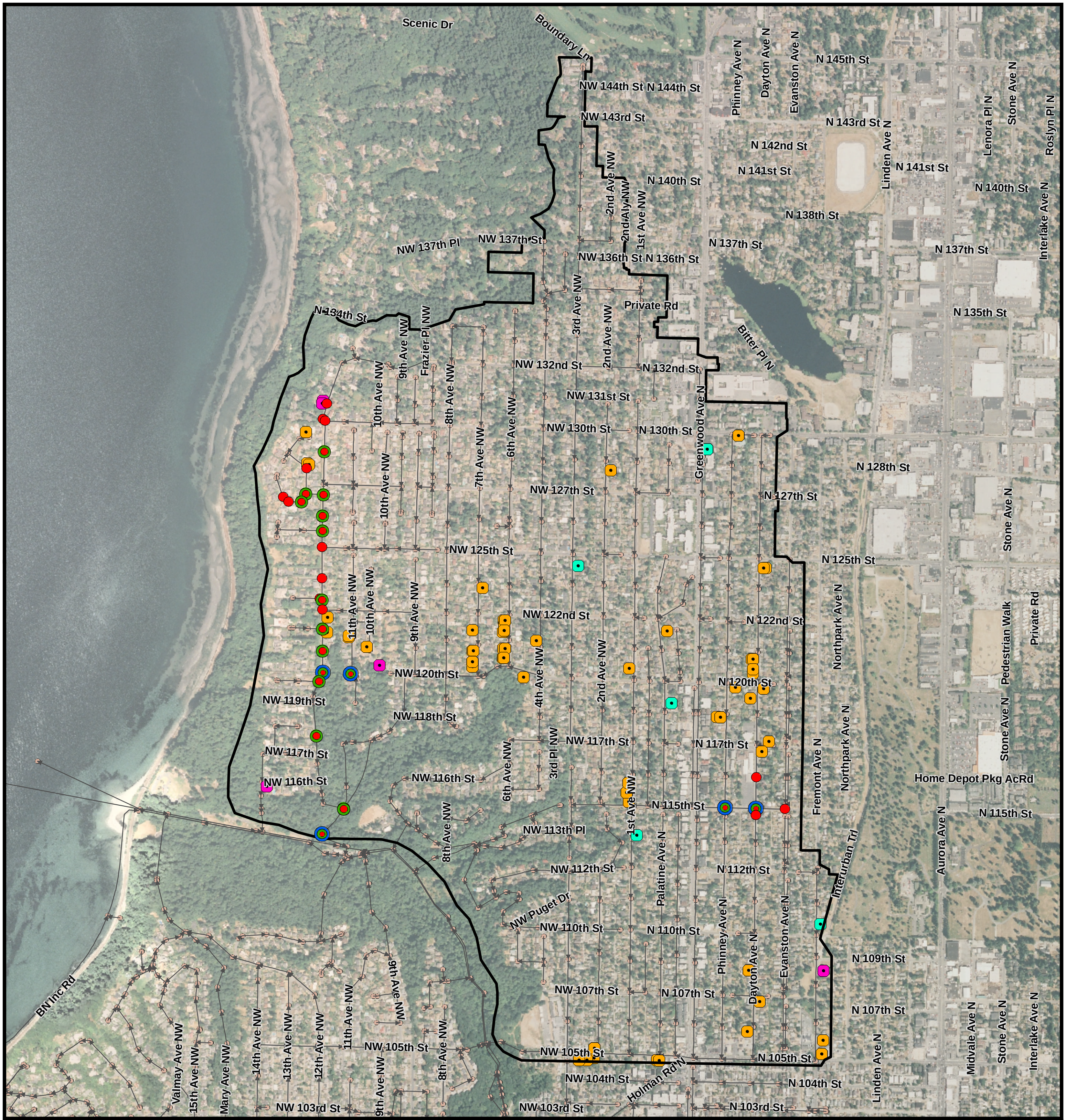

Legend

Broadview project area

Pipe and flow direction

Manhole

< 1-year event

1-year event

> 100-year event

No Rain

Alternative 3.B surcharge

2-, 25- and 100-year

25- and 100-year

100-year

Figure 34. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 3.B model.

N

0 700 1,400 2,800 Feet

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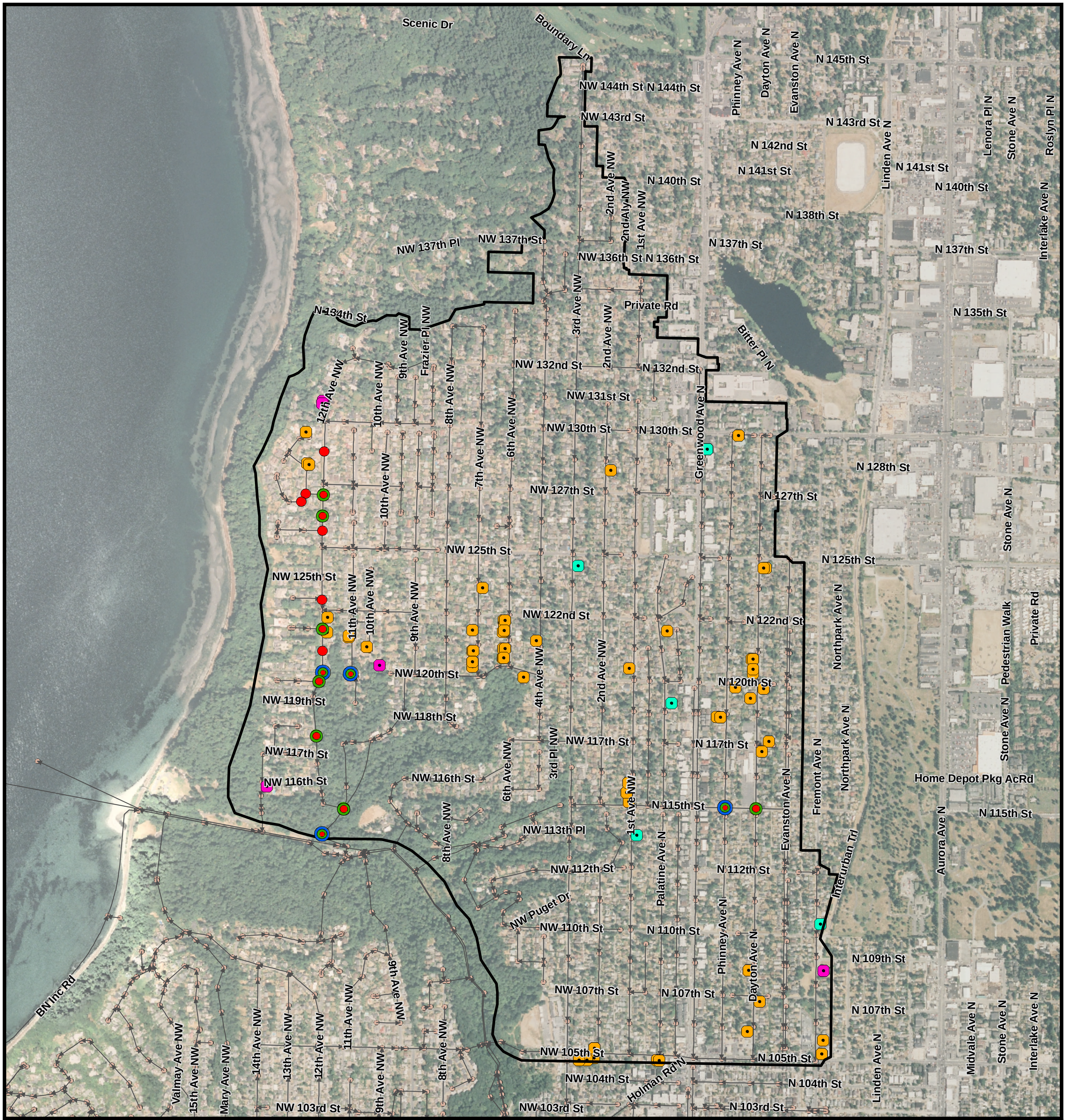

Legend

- Broadview project area
- Pipe and flow direction
- Manhole
- < 1-year event
- 1-year event
- > 100-year event
- No Rain

Alternative 3.C surcharge

- 2-, 25- and 100-year
- 25- and 100-year
- 100-year

Figure 35. Location of historical sewer backups along with locations of pipe surcharge during the 2-, 25- and 100-year events in the Alternative 3.C model.

N

0 700 1,400 2,800 Feet

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12th Avenue NW

Figure 36 plots Alternative 1's water surface elevation profile on 12th Avenue NW for comparison with Figures 37, 38, and 39, which show the peak water surface elevation on 12th Avenue NW under the Alternative 3 scenarios during the 2-, 25-, and 100-year. During the 2-year event, maintenance holes 224-067 and 224-070 have a small amount of surcharging in scenario 3.A and 3.B, but none by scenario 3.C. Modeling done for the 25-year event shows approximately 3,000 feet of pipe (maintenance hole 218-098 to maintenance hole 224-071) surcharging in the existing conditions scenario. Scenarios 3.A and 3.B have the same spatial extent of surcharging but to a slightly lower depth, while in scenario 3.C the surcharging is reduced to only near the outlet of NW Blakely Court in maintenance holes 218-143 and 218-192 and between NW 122nd Street and NW 119th Street. During the 100-year event the existing conditions model shows pipe surcharging from NW 132nd Street down to NW 119th Street. In the scenario 3.A model the surcharging is one foot less deep and only goes as far north as NW 130th Street. The spatial extent is the same in the scenario 3.B model but the water surface elevation drops again by up to one foot. In the scenario 3.C model the pipe flows full on 12th Avenue NW with localized surcharging around NW Blakely Court in maintenance holes 218-143 and 218-144 and between NW 122nd Street and NW 119th Street in maintenance holes 224-019 to 224-071.

Peak discharges from the 100-year event are presented below in Table 17 for the existing conditions and Alternative 3 scenarios. The discharges given are for discharge into maintenance hole 224-071 (located on 12th Avenue NW just north of NW 122nd Street). This segment of pipe is 10 inch concrete with a Manning's capacity of 1.4 cfs. The Manning's capacity is the highest discharge that can flow through the pipe without any pressure head behind it. Surcharging of upstream pipe can force more water through and allow discharge in excess of the Manning's free flow capacity.

Table 17. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 224-071 for the existing conditions and Alternative 3 scenarios during the 100-year event.

Model Run	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	2.61	n/a
Alt 3.A	2.54	2
Alt 3.B	2.43	7
Alt 3.C	2.33	11

As can be seen from column "Peak Discharge", all discharges are in excess of the free flow capacity. The existing conditions scenario has a peak discharge 1.2 cfs in excess of the Manning's capacity. Scenario 3.C, which has the greatest amount of infiltration reduction, still has a peak 100-year discharge 0.93 cfs greater than the Manning's pipe capacity. The percentage reductions in peak flow are 2 percent, 7 percent, and 11 percent in scenarios A through C respectively. Although a 46 percent reduction in peak flow is required to limit discharge to the Manning's capacity of the pipe, any reduction in infiltration and peak flow will reduce the probability and/or extent of backups in the future.

6th Avenue NW

Although several homes along 6th Avenue NW between NW 120th Street and NW 122nd Street have experienced sewer backups in the past, the EPA-SWMM 5 model does not show any pipe surcharging at this location. As discussed in the "Model Validation" and "Model Results / Existing Conditions" sections, it is believed that excessive infiltration in large storm events is the cause of backups at this location, and that this infiltration is not well simulated in the model. Table 18 below shows the reduction in peak flows that are achieved with the Alternative 3 scenarios. The discharges shown are for maintenance hole 224-104 which is at the corner of 6th Avenue NW and NW 120th Street. A detailed discussion is not provided for this table because it is believed the discharge numbers presented are not representative of what occurs in the pipe system.

Table 18. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 224-104 for the existing conditions and Alternative 3 scenarios during the 100-year event.

Model Run	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	1.38	n/a
Alt 3.A	1.32	4
Alt 3.B	1.25	9
Alt 3.C	1.13	18

Dayton Avenue N

Alternative 1's water surface profile between the intersection of Dayton Avenue N and NW 117th (maintenance hole 225-054) and the intersection of Greenwood Avenue N and NW 115th Street (maintenance hole 225-070) is given in Figure 40. This figure is provided for comparison with peak water surface profiles at the same location shown in Figures 41, 42, and 43 for the three different Alternative 3 scenarios.

In the existing conditions model a small amount of surcharging is present in the 2-year simulation at maintenance holes 225-071 and 225-072. The same maintenance holes surcharge during the 2-year event in Scenarios 3.A, 3.B, and 3.C but to a slightly lower depth. Under the existing conditions model in the 25-year event the same two maintenance holes surcharge with maintenance hole 225-072 surcharging to approximately five feet. Scenario 3.A and scenario 3.B show progressive 1 foot reductions in the water surface elevation in both maintenance holes that surcharge. During the 100-year event, the existing conditions model now surcharges at

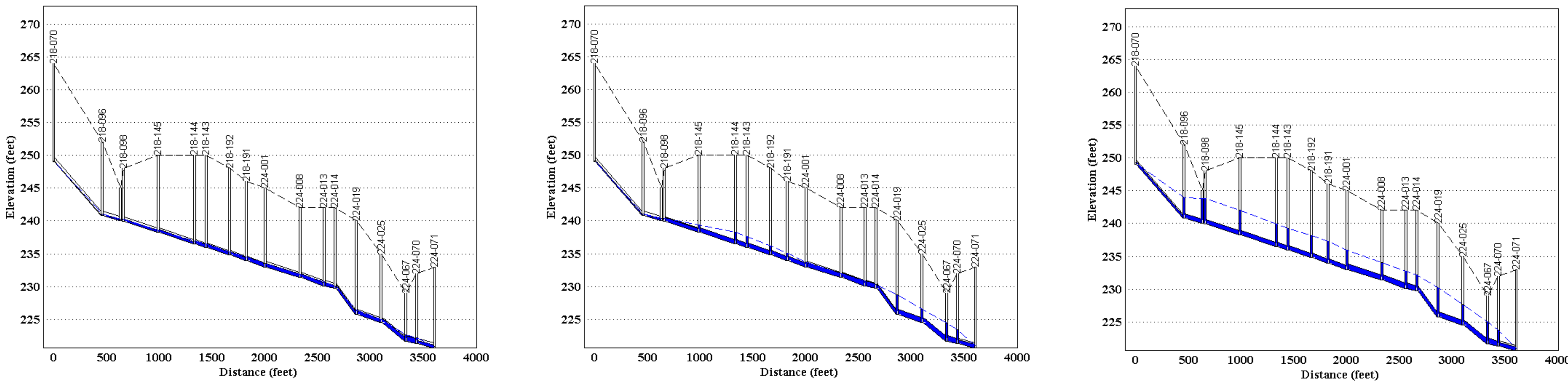

Figure 36. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

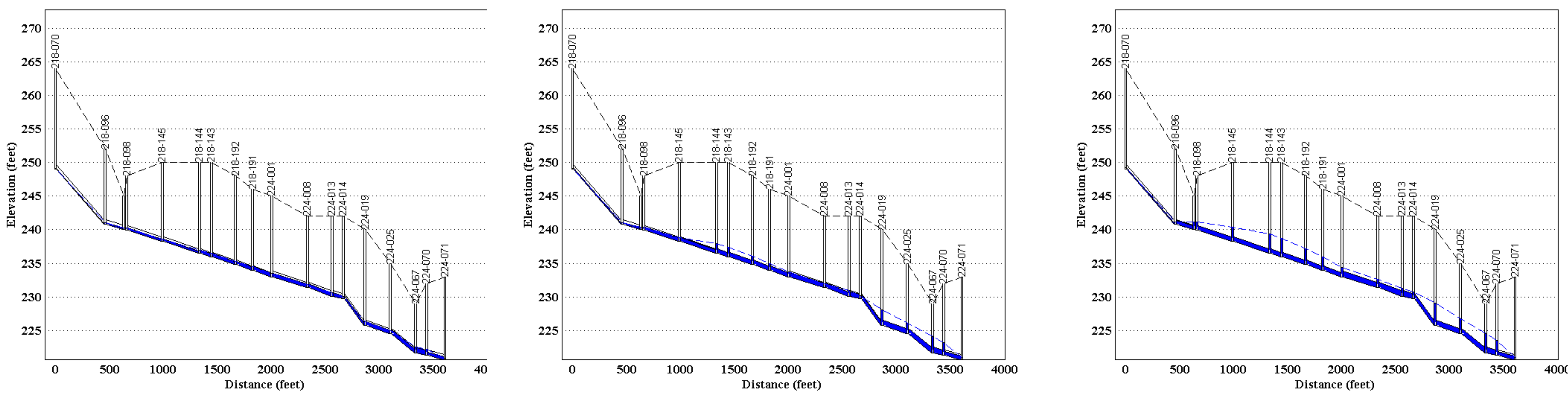

Figure 37. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.A

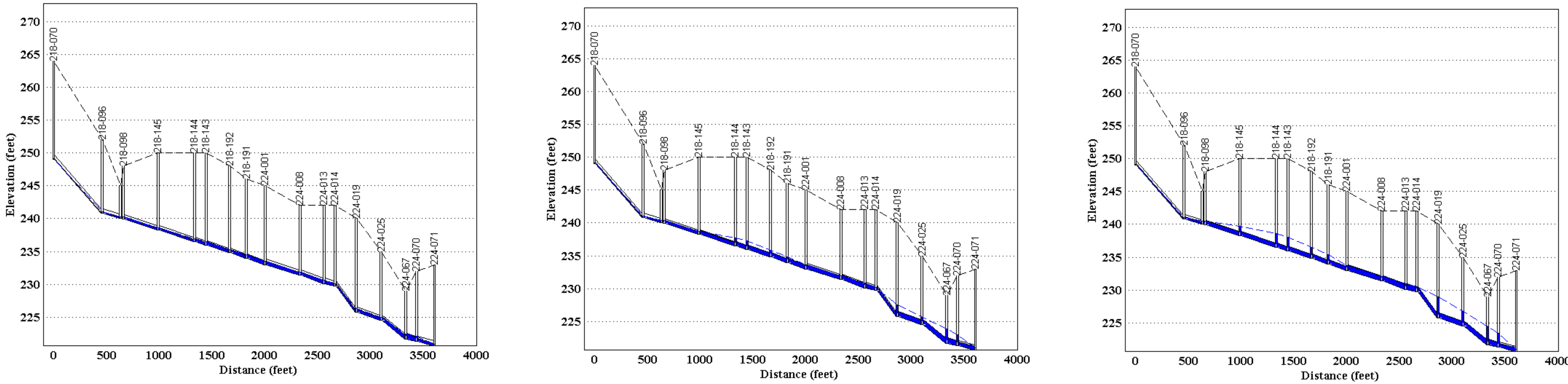

Figure 38. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.B

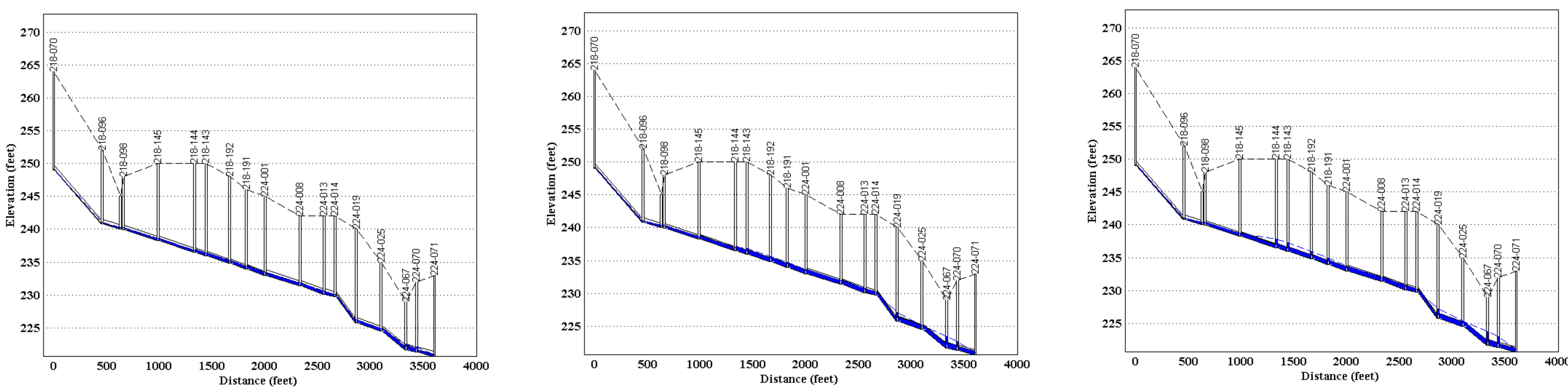

Figure 39. Water surface elevation profiles on 12th Avenue NW between NW 132nd Street and NW 119th Street for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.C

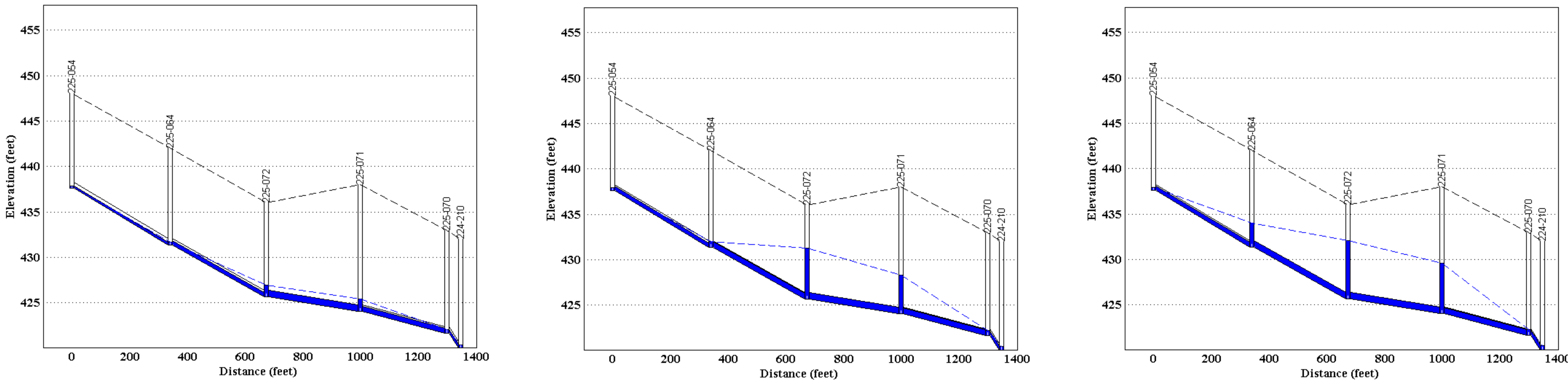

Figure 40. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 1

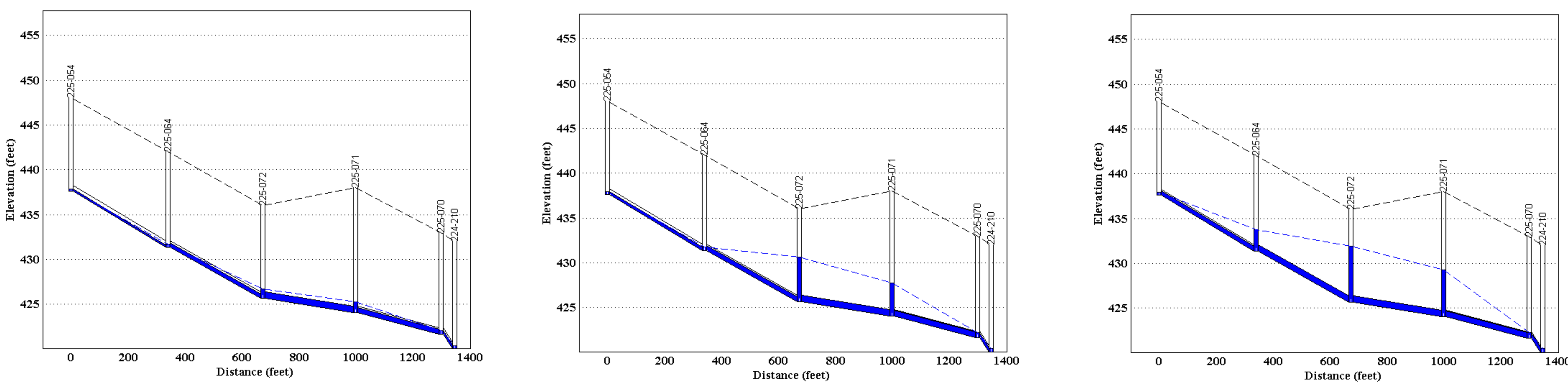

Figure 41. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.a

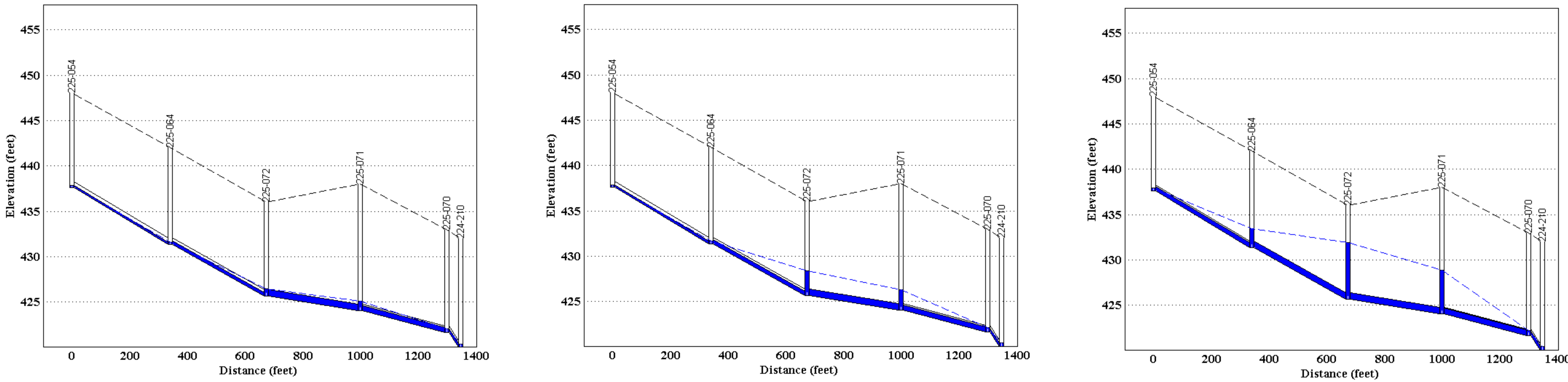

Figure 42. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.b

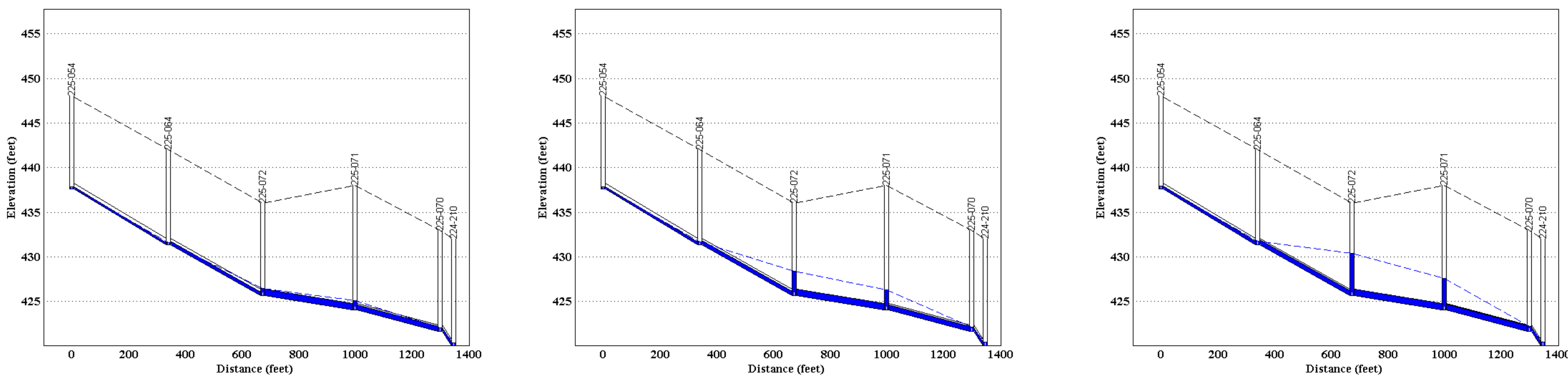

Figure 43. Water surface elevation profiles on Dayton Avenue N for the 2-year (left), 25-year (middle), and 100-year (right) storms under Alternative 3.c

maintenance hole 225-064 and surcharges in maintenance hole 225-072 to the elevation of the overflow outlet at 6 feet. The scenario 3.A model under the 100-year event has a similar elevation of peak surcharging as the existing conditions model. The surcharging depth in the scenario 2.B model is only slightly less than in the 2.A model, while the peak water surface elevation in the 2.C model decreases about 1 foot to an elevation of 5 feet in maintenance hole 225-072 and three feet in maintenance hole 225-071.

Table 19 below shows the peak discharge at maintenance hole 225-070 at the intersection of NW 115th Street and Greenwood Avenue N for the existing conditions and Alternative 3.A, 3.B, and 3.C scenarios. For comparison, the Manning's capacity for the 8 inch pipe is 1.1 cfs which is lower than the modeled peak discharge associated with the 100-year event. This peak discharge above the Manning's capacity shows the effects of pipe surcharging and pressure head on the discharge. The reduction in peak discharge associated with scenarios 3.A, 3.B, and 3.C are 0 percent, 0 percent, and 7 percent, respectively. The reduction in peak discharge is first seen in scenario 3.C when surcharging drops below the elevation of the overflow in maintenance hole 224-071.

Table 19. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 225-070 for the existing conditions and Alternative 3 scenarios during the 100-year event.

	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	1.99	n/a
Alt 3.A	2.01	-1.1
Alt 3.B	1.99	0.1
Alt 3.C	1.85	7.1

Table 20 below shows the peak discharge at maintenance hole 225-035 at the intersection of NW 120th Street and Dayton Avenue N for the existing conditions and Alternative 3.A, 3.B, and 3.C scenarios for the 100-year event. For comparison, the Manning's capacity for the 8 inch pipe is 1.6 cfs, which is greater than the peak modeled discharge associated with the 100-year event. Profiles of the hydraulic grade line are not shown for this area because the model does not simulate any pipe surcharging.

Table 20. Peak discharge (cfs) and reduction in peak discharge (percent) at maintenance hole 225-036 for the existing conditions and Alternative 3 scenarios during the 100-year event.

	Peak Discharge (cfs)	Reduction in Peak Discharge (percent)
Existing Conditions	0.73	n/a
Alt 3.A	0.69	5
Alt 3.B	0.66	10
Alt 3.C	0.58	20

Conclusions & Recommendations

Flow monitoring and EPA-SWMM 5 modeling were performed in Broadview to identify the causes of sewer backups and to evaluate potential engineering alternatives to reducing the likelihood and magnitude of backups in the future. The flow monitoring was performed by ADS Environmental and consisted of 12 monitors installed in the basin from September 19, 2008 through February 20, 2009. The EPA-SWMM 5 model was calibrated from the flow monitoring data and then used to simulate discharge in the pipe network over a range of storm events.

Three alternatives were analyzed in the EPA-SWMM 5 model with respect to their effectiveness in reducing the likelihood and magnitude of future sewer backups. Alternative 1 is a pipe replacement solution targeted to 1st Avenue NW and NW 115th Street and NW 105th Street between Greenwood Avenue N and NW 3rd Street. Other locations were also analyzed under Alternative 1 but were dismissed because they were not considered good candidates for this solution. Alternative 2 consists of three different levels of inflow reduction. Scenario 2.A is a 20 percent reduction in connected downspouts, scenario 2.B is a 50 percent reduction in connected downspouts, and scenario 2.C is reduction in 100 percent of the total connected area. Alternative 3 consists of three different levels of infiltration reduction. Scenario 3.A is a 20 percent reduction in infiltration, scenario 3.B is a 40 percent reduction in infiltration, and scenario 3.C is an 80 percent reduction in infiltration. SPU has indicated that Alternative 1 will be constructed so alternative 2 and 3 focus on areas where the Alternative 1 pipe replacement solution is not applicable. These locations include the remaining problem areas at 12th Avenue NW, 6th Avenue NW, and Dayton Avenue N. A summary of the number of nodes surcharging in the base and alternative runs for the 2-, 25-, and 100-year events are presented in Table 21. A summary of results and recommended actions is also provided for each area of concern.

1st Avenue NW and NW 115th Street

Pipe replacement analyzed under Alternative 1 provides an effective solution at 1st Avenue NW and NW 115th Street for reducing the likelihood of sewer backups in the future. The existing conditions model simulates pipe surcharging at the corner of 1st Avenue NW and NW 115th Street in events as small as the 25-year return interval event which corresponds well with reported historic sewer backups at this location. Analysis of the Alternative 1 simulation shows no surcharging at this location in up to and including the 100-year event. It should be noted that the surcharging simulated at 1st Avenue NW and NW 115th Street during the December 3, 2007 event in the existing conditions model is moved downstream to 2nd Avenue NW and NW 115th Street in the Alternative 1 simulation.

NW 105th Street between Greenwood Avenue N and NW 3rd Avenue

For NW 105th Street the existing conditions model first simulates pipe surcharging during the 100-year event which corresponds well with reported historic backups at this location. The existing conditions model simulates an additional reach of pipe surcharging under the

December 3, 2007 event (also corresponding well with sewer backups during this storm). The alternative 1 pipe replacement solution eliminates surcharging in these segments for events up to and including the December 3, 2007 event. No additional downstream locations surcharge along NW 105th Street due to the pipe replacement option being implemented here.

Table 21. Summary of the number of nodes surcharging in the existing conditions and alternative runs during the 2-, 25-, and 100-year events.

	Entire Study Area	NW 105th Street	12th Avenue NW	6th Avenue NW	1st Avenue NW	Dayton Avenue N
2-year						
Existing Conditions	8	0	1	0	0	2
Alt. 1	7	0	1	0	0	2
Alt. 2 (a,b,c)	8,6,4	0,0,0	2[a],1,0	0,0,0	0,0,0	2,2,0
Alt. 3 (a,b,c)	7,6,5	0,0,0	1,1,1	0,0,0	0,0,0	2,1,1
25-year						
Existing Conditions	30	1	14	0	2	2
Alt. 1	27	0	14	0	0	2
Alt. 2 (a,b,c)	25,19,10	0,0,0	13,9,3	0,0,0	0,0,0	2,2,2
Alt. 3 (a,b,c)	20,19,13	0,0,0	10,9,5	0,0,0	0,0,0	2,2,2
100-year						
Existing Conditions	53	2	16	0	3	3
Alt. 1	46	0	16	0	0	3
Alt. 2 (a,b,c)	43,36,19	0,0,0	16,16,9	0,0,0	0,0,0	3,3,2
Alt. 3 (a,b,c)	39,32,19	0,0,0	16,15,9	0,0,0	0,0,0	3,3,2

[a] One node (224-070) surcharged by up to 0.1 feet for 12 minutes in the alternative 2.A 2-year model but not in the other 2-year models.

12th Avenue NW between NW 119th Street and NW 132nd Street

The existing conditions model simulates pipe surcharging along 12th Avenue NW from NW 119th Street to NW 132nd Street (~3,500 feet). Because multiple segments of pipe have a Manning's capacity below the modeled 100-year discharge it is more appropriate to target this area for inflow and infiltration reduction than for large scale pipe replacement. Scenarios A and B in both Alternative 2 and 3 reduce the length of pipe that surcharges by approximately 500 feet. Although Alternative 3.C is slightly more effective than Alternative 2.C, it still does not eliminate surcharging in the pipe completely. Because of this it is recommended that the area upstream of maintenance hole 224-074 (12th Avenue NW and NW 119th Street) be targeted for both inflow and infiltration reduction to the maximum extent feasible. Additional monitoring and site investigation will likely indicate areas within this subbasin that have high inflow and infiltration and that should be targeted first.

6th Avenue NW and NW 120th Street

Although the modeling performed as part of this study uses the calibration parameters obtained from the largest storm during the monitoring period (1/7/2009), it is believed that the EPA-SWMM 5 model does not accurately simulate discharge at this location in large (~100-year) return interval events. It is believed that the additional source of discharge seen during large storm events that is not simulated by the EPA–SWMM 5 model is infiltration due to rising groundwater. The percentage of rainfall that becomes direct inflow remains relatively constant regardless of storm size since the area that is directly connected does not change. Infiltration, however, can increase dramatically as storm size increases due to ground saturation. This location is at the head of Venema Creek where the ground is believed to be especially susceptible to saturation during large event. Also, there exists a significant sag in the pipe upstream of maintenance hole 224-104 which could allow a pathway for infiltration to enter the system when ground saturation occurs. It is recommended that SPU continue to monitor discharge in the pipe network at this location and to initiate a pilot program aimed at locating and reducing infiltration.

Dayton Avenue N and NW 105th Street

Modeling using the existing pipe network shows two locations on Dayton Avenue N that surcharge. The locations furthest to the south, NW 105th Street and Dayton Avenue N, surcharges only during the 100-year event. All of the Alternative 2 and 3 scenarios eliminate this surcharging in events up to and including the 100-year event. Although this area appears hydraulically disconnected from Dayton Avenue N north of 115th, there is an overflow that allows surcharging in the northern part of the basin to head south to NW 105th Street during surcharging of the maintenance hole at NW 115th Street. The south part of Dayton Avenue N only experiences surcharging when the northern part of the basin surcharges and sends extra flow south, therefore it is recommended to reduce inflow and infiltration in the northern part of the basin since this reduce the likelihood of backups at both locations.

Dayton Avenue N and NW 115th Street

The area near NW 115th Street and Dayton Avenue N surcharges in the existing conditions model, however, the location of modeled surcharging is two blocks downstream of where sewer backups were experienced in the past. The location of reported sewer backup during the December 3, 2007 event was just north of Christ the King school on NW 117th Street where there has been conflicting reports of a blockage in the pipe during the December 3, 2007 storm. The model shows sufficient capacity at the area near NW 117th Street but simulates surcharging a few blocks downstream near NW 115th Street. The modeled surcharging near NW 115th Street is progressively reduced in the alternative 2 scenarios but not entirely eliminated. Surcharging is also progressively reduced in the alternative 3 scenarios to the point where it is eliminated in scenario 3-C. Although there is a few block discrepancy between the location of the observed sewer backups and the location of the modeled pipe surcharging, it is recommended to implement inflow and/or infiltration reduction here to the maximum extent feasible. Reducing inflow and infiltration in the area upstream of NW 115th Street and Dayton Avenue N has the added benefit that it will also reduce the likelihood of sewer backups at NW 105th Street and Dayton Avenue N as well as at NW 115th Street and 1st Avenue N.

Venema GreenGrid Project

The approach used for the Alternative 2 Inflow Reduction Alternative has some similarities to the proposed Venema GreenGrid Project. The objective of the Venema GreenGrid Project is to reduce the peak flow and total volume of stormwater discharging to the Venema Creek subbasin. This will be accomplished primarily through the installation of Natural Drainage System (NDS) swales, but also in part by installing cisterns and rain gardens in the basin to handle runoff from roof area. Roof area that is currently connected to the sewer system and is disconnected to a cistern or rain garden as part of the Venema GreenGrid Project will effectively be a reduction of inflow into the sewer system. Roof downspouts that are not currently connected to the sewer system and are directed to cisterns and raingardens as part of the Venema GreenGrid project are not similar to the inflow reduction modeled under Alternative 2 because these downspouts do not currently discharge to the sewer system. Additionally, roof runoff that is currently connected to a stormwater conveyance system (e.g., ditch) and will be infiltrated as part of the Venema GreenGrid project has the potential to increase infiltration into the sewer system. However, open ditches can also serve to infiltrate storm water. Stormwater that was conveyed off the site before may now be more intensely infiltrated locally in either a raingarden or NDS swale, and could increase the likelihood of entering the sewer system as infiltration through cracked pipes or pipe joints that are not sealed properly. The extent to which infiltration into the sewer system will increase is highly dependent upon the location of the rain gardens and NDS swales relative to side sewers and mainlines, soil conditions, as well as the condition of the pipes below the rain gardens and NDS swales.

The percentage of roof downspouts connected to the sewer system in the Venema GreenGrid project area is approximately equal to the assumptions used for modeling Alternative 2, making the analysis presented under Alternative 2 directly applicable to the Venema GreenGrid project. The sewer backup problem areas that have the greatest potential to be affected by the Venema GreenGrid project are Dayton Avenue N near 120th Street (75% of the contributing drainage area is within the Venema GreenGrid project area) and 1st Avenue NW and NW 115th Street (50% of the contributing area is within the Venema GreenGrid project area). The sewer backup areas on NW 105th Street as well as on the southern portion of Dayton Avenue N are disconnected hydrolocally from the Venema GreenGrid with the exception of overflow outlets in two manholes on NW 115th Street (sewer lines drain west on NW 115th street with the exception of two outlets at 6 feet off the bottom of the manhole that continue south). These two locations in the southern part of the Broadview study area are will only be affected by the Venema GreenGrid project if it changes the frequency or magnitude with which these overflows are activated (i.e., if the project reduces these overflows being activated then it will reduce the likelihood of backups at the southern locations in the study area). For the sewer backup locations near 6th Avenue N and NW 120th Street, only one block out of the 13 block contributing area is within the Venema GreenGrid project area, so the affect on this location will likely be minimal. This location should, however, have a more in-depth analysis of how the stormwater drainage along NW 120th Street N into Venema Creek will affect local groundwater in this area. The sewer backup locations on 12th Avenue NW are hydrolocally disconnected from the Venema GreenGrid project area and will not be affected by it.

It should be noted that the modeling results presented in this report are based on an EPA–SWMM 5 model that was calibrated from a period that did not contain any major storm events. The largest storm during the flow monitoring and calibration period was the 12-hour 2-year storm on January 7, 2009. Although the EPA-SWMM 5 model is well calibrated to this event, there remains some uncertainty as to how well the model simulates storms that have return intervals of greater than those seen during the monitoring period. Model validation does, however, show that the calibrated model simulates pipe surcharging at largely the same locations that have experienced sewer backups in the past.

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APPENDIX A

Pipe Network Quality Assurance / Quality Control Performed upon the EPA-SWMM 5 Model

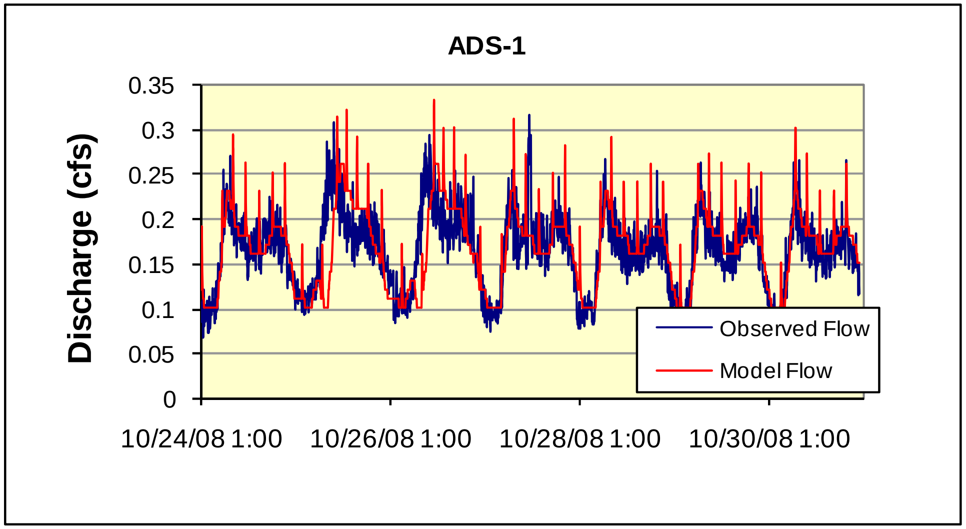
Appendix A. Pipe network quality assurance / quality control performed upon the EPA-SWMM 5 model.

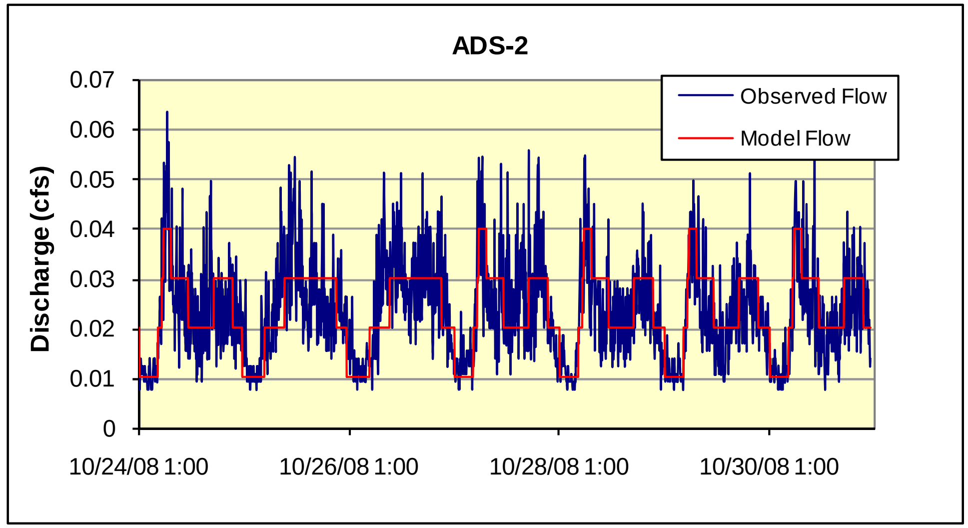
Location (MH #)	QA/QC Issue	Action
219-246	Outlet elevation is 6.2 feet below invert elevation	Fixed per As-Built profile
224-117	Conduit 224-117 to 224-146 has negative slope	Changed invert elevation to 408, image not on SPU's Virtual Vault
225-070	Conduit 225-070 to 225-147 has negative slope	Visual inspection showed this conduit does not exist, other two conduits are at invert elevation of MH. Model adjusted accordingly.
225-071	Conduit 225-071 to 225-072 has inlet and outlet elevation 6' & 4' higher than bordering nodes.	Changed 225-071 to 225-151 to 6.1' invert elevation per visual inspection
225-072	Inlet elevation on conduit 225-072_225-157 is at same elevation as main outlet from structure. Field investigation showed this inlet elevation is at 6'.	Changed 225-072 to 225-157 to 6.1' invert elevation per visual inspection
225-158	Inlet to node 225-158 is lower than outlet	Changed per As-Built profiles
225-183	Inlet to node 225-183 has a .6' drop.	No As-Built, not changed, could have visual inspection
225-196	Inlet to 225-196 has a 6' drop.	No As-Built, not changed, could have visual inspection
224-201	Node 224-201 has 2 outlets at same elevation	As-Built 777-104-14 shows no conduit running S from MH 224-201, conduit deleted
224-236	Node 224-236 has a 2.9' inlet drop	No As-Built, but changed to 0 offset based on all other As-Builts not having significant dropoffs
232-003	Inlet to node 232-003 is 1' lower than outlet	As-Builts show no "sump", model changed to reflect this
232-004	Inlet to node 232-003 is .1' lower than outlet	As-Builts show no "sump", model changed to reflect this
224-331	Inlet to node 224-331 has 6' drop	Visual inspection showed no outlet drop, model changed to reflect this
218-112	Inlet to conduit is 6' from MH invert elevation	No As-Built, inlet to conduit set at ivert elevation to be consistnent with existing As-Built
224-302	Inlet to node 224-302 has a 2' drop	Not on As-Built, away from flooding areas so left as is
224-179	Inlet to node 224-179 has 3.9' drop	Not on As-Built, away from flooding areas so left as is
224-222	One inlet to node 224-222 has 2' drop	As-Built of Puget Drive shows no sumps or drops, offset changed to 0
224-348	Outlet from 224-348 is 3' higher than inlet, 2 outlets at same elevation	Not on As-Built, away from flooding areas, but inlet offsets changed to zero to be consistent with As-Builts
224-356	One inlet to 224-356 is lower than outlet	Not on As-Built but inlet offsets changed to zero to be consistent with As-Builts for other locations
224-142	Pipe makes a 180 degree turn at node 224-142	fixed per As-Built
224-204	Both inlets to 224-204 have a 5.9' drop	As-Built shows no inlet drops, changed accordingly
224-181 - 224-182	Manhole inlet has 8' drop off	No As-Built, model not changed
219-245 - 219-246	Pipe has negative slope, and 6' drop at outlet	Fixed per As-Built

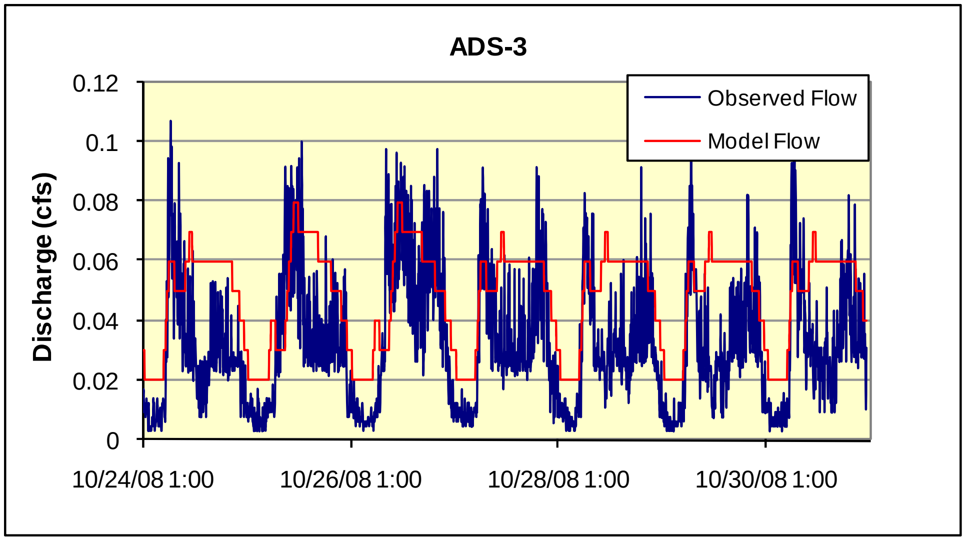
Location (MH #)	QA/QC Issue	Action
218-200	Upstream pipe has negative slope, inlet has 9' drop into MH	No As-Built, linearly interpolated to match upstream and downstream profiles
218-228 - 218-229	Top upstream node has two outlets at same elevation. One goes down street, other goes through back yard to 8th street	No As-Built, but conduit 218-228 - 218-229 deleted to leave conduit in street, as opposed to back yard
218-169	Inlet has 7' drop	Confirmed drop on As-Built, model not changed
224-415	Confirm upstream of 224-415 replaced by 1.25' pipe	HEC 1998 report confirms, model not changed
224-021	One inlet to 224-021 has .4' drop	No As-Built, model not changed
218-112	Inlet is 6' below outlet	No As-Built, not near flooding, but changed to be consistent with other As-Builts (no outlets above inlets)
218-140	Manhole 218-141 inlet is .3' higher than outlet	No As-Built to west of 12th, left as is
218-146	Inlet to MH has 6' drop	Confirmed drop on As-Built, model not changed
218-146	Inlet to MH 218-144 has 3' drop	Confirmed drop on As-Built, model not changed
218-150	One inlet to MH has 7' drop	Confirmed drop on As-Built, model not changed
224-006	Manhole 224-006 has 1 inlet lower than outlet	No As-Built, model changed to be consistent with other As-Built to have no sump. Away from flooding areas
218-163	Manhole 218-163 has 8' drop	Confirmed drop on As-Built, model not changed
224-019	Inlet to MH 224-019 has 2' drop	Visual inspection showed no outlet drop, model changed to reflect this
224-188	Segment 224-188_224-020 pipe is only .25' diameter	No As-Built on SPU's Virtual Vault, model not changed
224-003	Conduit upstream had negative slope.	As-Built show continuous slope, model changed accordingly
224-412	Manhole 224-412 has 2 outlets	No As-Built to west of 12th, model not changed

APPENDIX B

Dry Weather Flow Calibration Parameters and Figures


ADS-1
Discharge (cfs)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00
Observed Flow
Model Flow


ADS-2
Discharge (cfs)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00
Observed Flow
Model Flow


ADS-3
Discharge (cfs)
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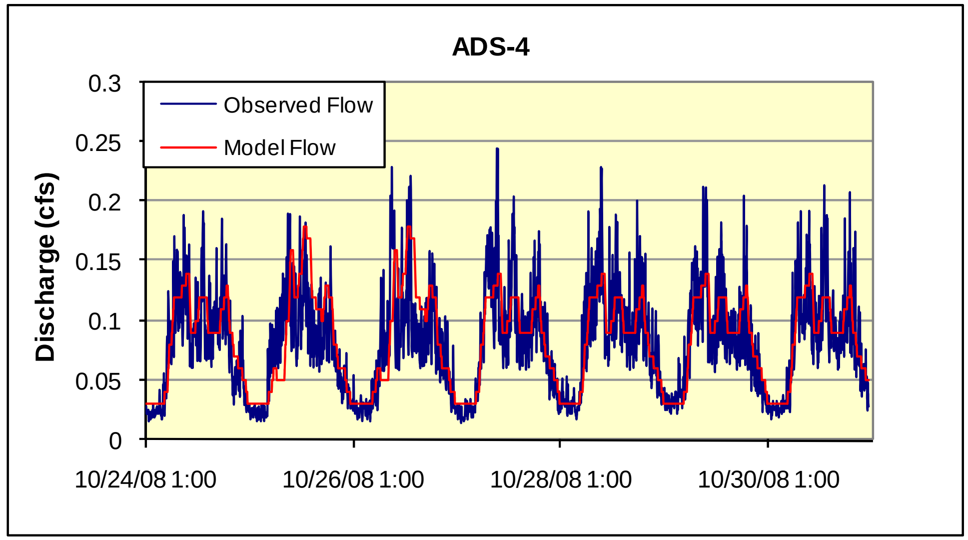
0.1
0.08
0.06
0.04
0.02
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00
Observed Flow
Model Flow


ADS-4
Discharge (cfs)
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0.25
0.2
0.15
0.1
0.05
0
10/24/08 1:00
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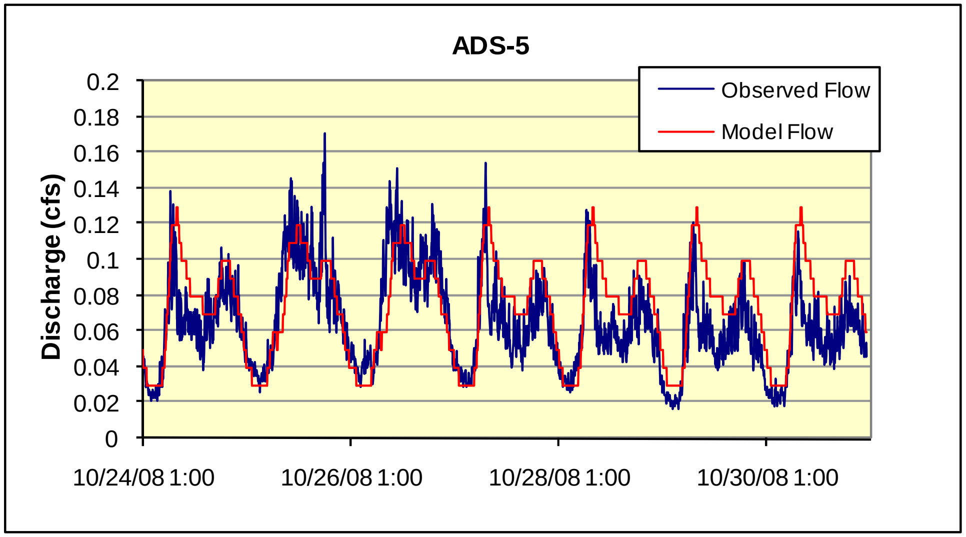
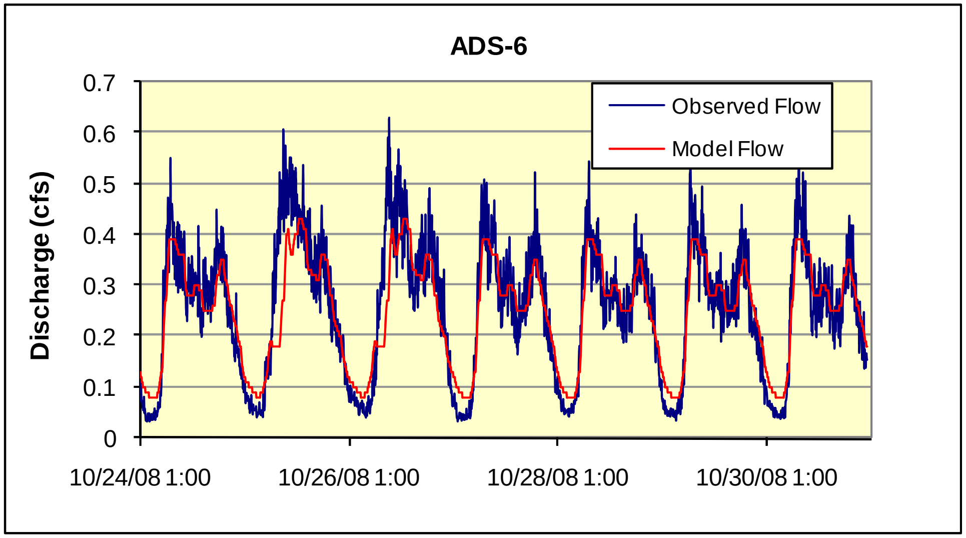
10/30/08 1:00
Observed Flow
Model Flow


ADS-5
Observed Flow
Model Flow
Discharge (cfs)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00


ADS-6
Observed Flow
Model Flow
Discharge (cfs)
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0.6
0.5
0.4
0.3
0.2
0.1
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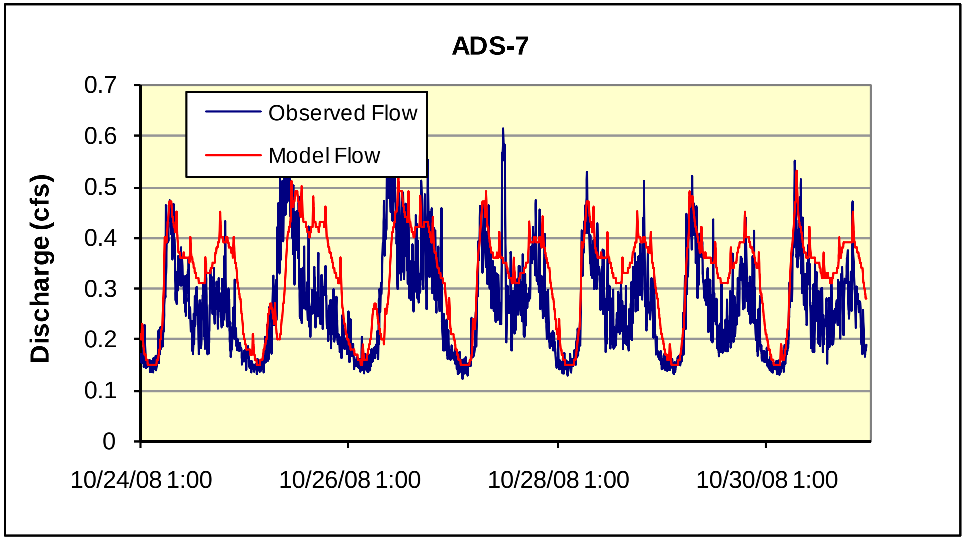
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00


ADS-7
Observed Flow
Model Flow
Discharge (cfs)
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0.6
0.5
0.4
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0.1
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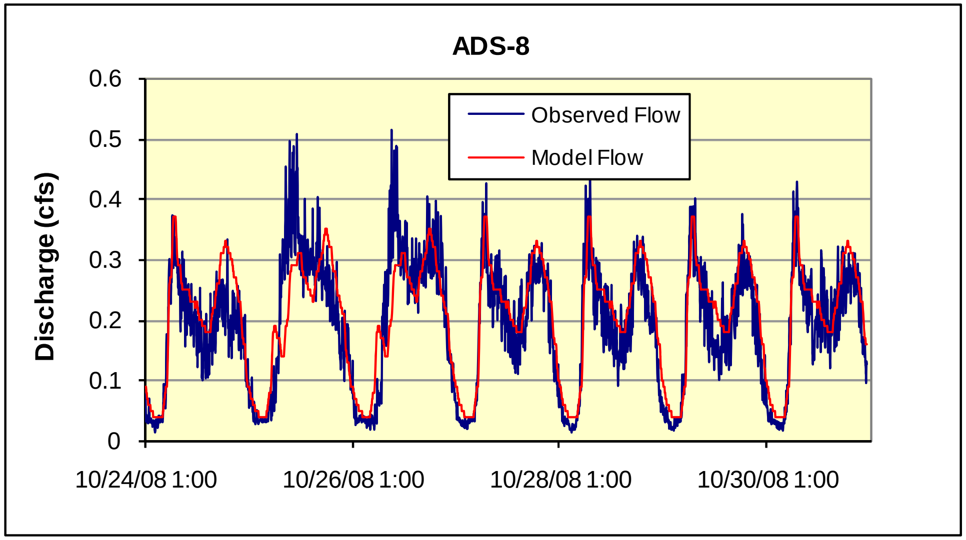
10/28/08 1:00
10/30/08 1:00


ADS-8
Observed Flow
Model Flow
Discharge (cfs)
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0.5
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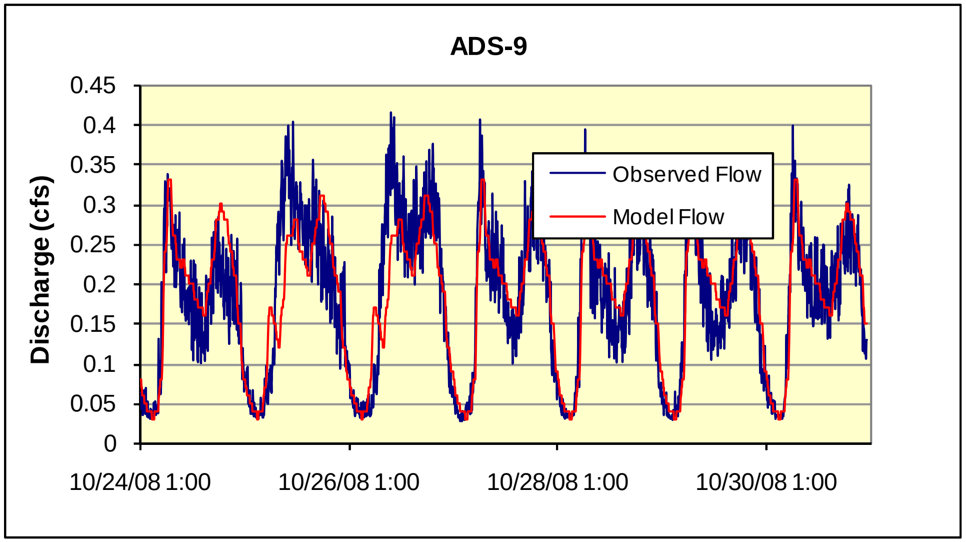
10/30/08 1:00


ADS-9
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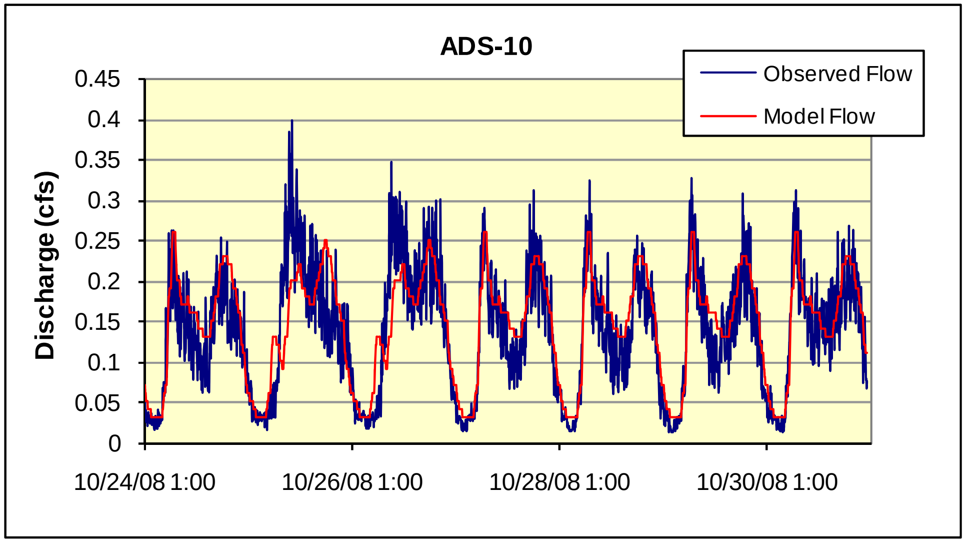
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00
Observed Flow
Model Flow


ADS-10
Discharge (cfs)
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0.35
0.3
0.25
0.2
0.15
0.1
0.05
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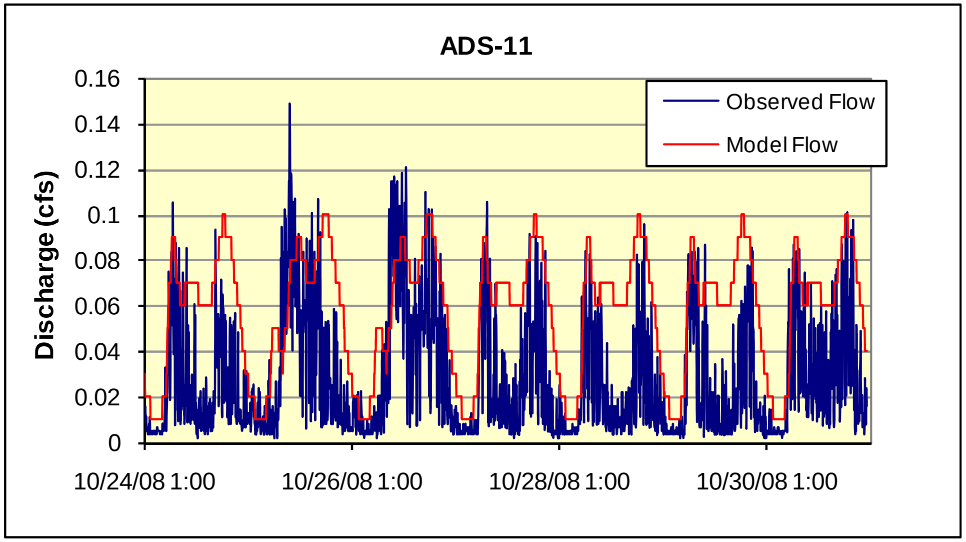
10/30/08 1:00
Observed Flow
Model Flow


ADS-11
Discharge (cfs)
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0.14
0.12
0.1
0.08
0.06
0.04
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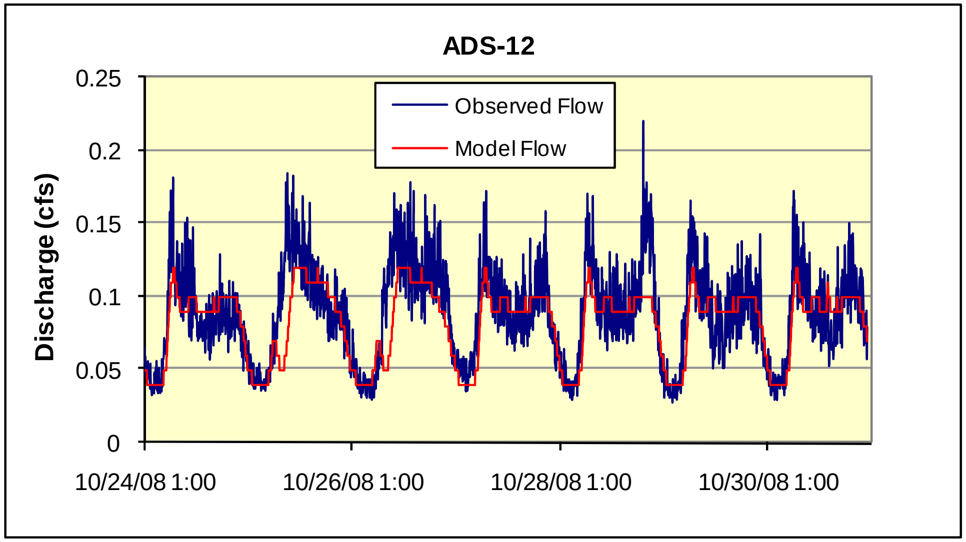
10/30/08 1:00
Observed Flow
Model Flow


ADS-12
Discharge (cfs)
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0.2
0.15
0.1
0.05
0
10/24/08 1:00
10/26/08 1:00
10/28/08 1:00
10/30/08 1:00
Observed Flow
Model Flow

APPENDIX C

Wet Weather Flow Calibration Parameters and Figures

Table C-1. Unit hydrograph files used in each subcatchment for the EPA-SWMM 5 model.

Subcatchment	UH File
ADS-1	UH_3 – RG7
ADS-2	UH_4 – RG1
ADS-3	UH_2 – RG1
ADS-4	UH_2 – RG1
ADS-5	UH_1 – RG1
ADS-6	UH_2 – RG1
ADS-7	UH_3 – RG7
ADS-8	UH_3 – RG7
ADS-9	UH_3 – RG7
ADS-10	UH_2 – RG1
ADS-11	UH_4 – RG1
ADS-12	UH_12 – RG1
Upper Basin	UH_2 – RG1
Lower Basin	UH_3 – RG7

Table C-2. Unit hydrograph file for UH_1 – RG1.

Month	UH-term	R (%)	T (hours)	K (fraction)
January	Short	0.05	0.15	2
	Medium	0.1	2	12
	Long	0.25	24	12
February – March	Short	0.02	0.15	0
	Medium	0.06	2	8
	Long	0.06	24	3
April – November	Short	0.02	0.15	2
	Medium	0.03	2	8
	Long	0.03	6	8
December	Short	0.02	0.15	2
	Medium	0.03	2	12
	Long	0.06	24	6

Table C-3. Unit hydrograph file for UH_2 – RG1.

Month	UH-term	R (%)	T (hours)	K (fraction)
January	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.12	24	8
February – March	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.05	24	3
April – November	Short	0.02	0.15	2
	Medium	0.02	2	8
	Long	0.02	6	8
December	Short	0.03	0.15	2
	Medium	0.03	2	8
	Long	0.05	24	3

Table C-4. Unit hydrograph file for UH_3 – RG7.

Month	UH-term	R (%)	T (hours)	K (fraction)
January	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.13	24	7
February – March	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.05	24	3
April – November	Short	0.02	0.15	2
	Medium	0.02	2	8
	Long	0.02	24	3
December	Short	0.03	0.15	2
	Medium	0.03	2	8
	Long	0.05	24	3

Table C-5. Unit hydrograph file for UH_4 – RG1.

Month	UH-term	R (%)	T (hours)	K (fraction)
January	Short	0.03	0.15	2
	Medium	0.04	2	8
	Long	0.09	24	4
February – March	Short	0.03	0.15	2
	Medium	0.04	2	8
	Long	0.05	24	3
April – November	Short	0.01	0.15	2
	Medium	0.015	2	8
	Long	0.02	6	8
December	Short	0.015	0.15	2
	Medium	0.03	2	8
	Long	0.05	24	3

Table C-6. Unit hydrograph file for UH_12 – RG1.

Month	UH-term	R (%)	T (hours)	K (fraction)
January	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.15	24	8
February – March	Short	0.03	0.15	2
	Medium	0.05	2	8
	Long	0.05	24	3
April – November	Short	0.02	0.15	2
	Medium	0.02	2	8
	Long	0.02	6	8
December	Short	0.03	0.15	2
	Medium	0.03	2	8
	Long	0.07	24	3

Table C-7. Initial abstraction parameters used in the EPA-SWMM 5 model.

Parameter	Units	Value
Maximum depth	inches	0.2
Recovery rate	inches/day	0.1
Initial depth	inches	0

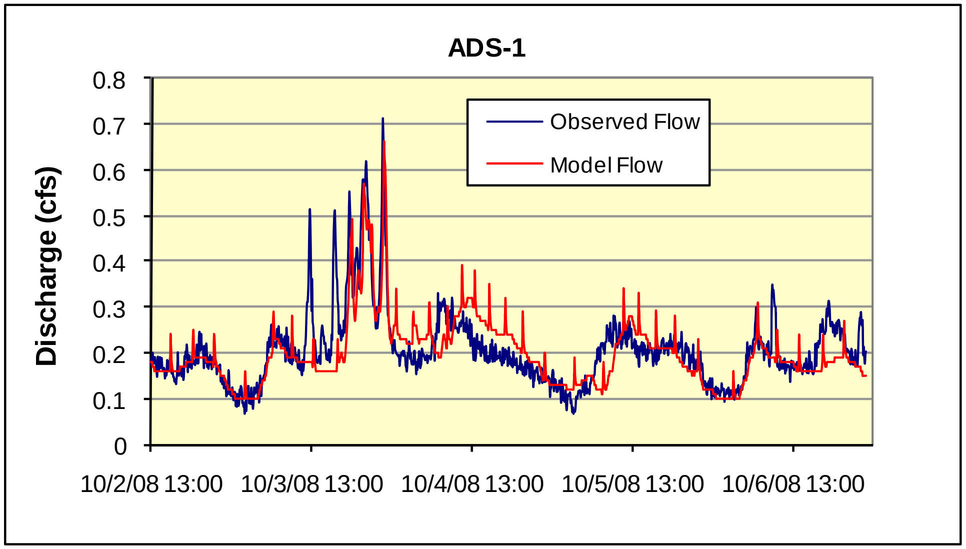
Table C-8. Goodness of fit between modeled and observed peak flows

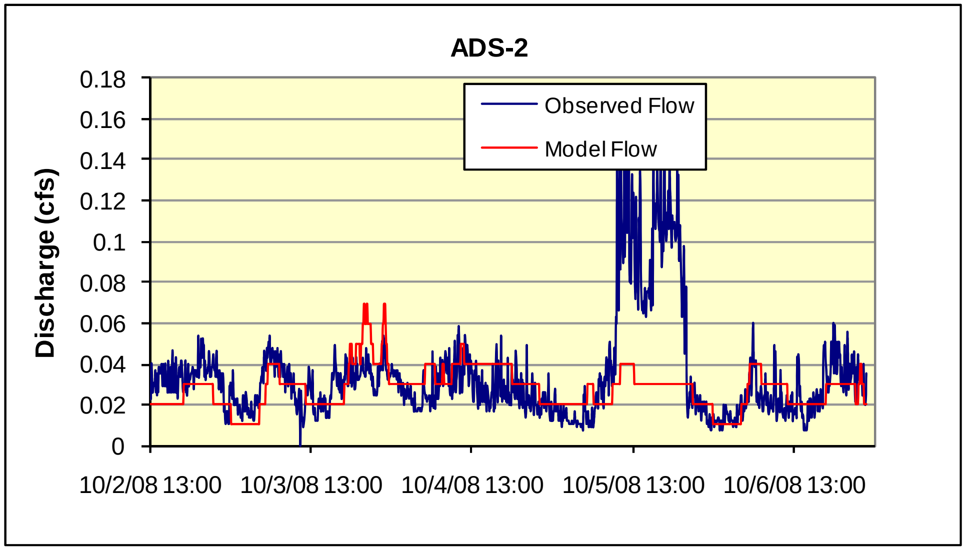
Dry Weather Flow: 10/24/08 01:00 - 10/30/08 00:00 (0 inches of precipitation)												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	0.314	0.0634	0.1067	0.2429	0.1702	0.6281	0.6111	0.5136	0.4146	0.396	0.1485	0.2197
Modeled Maximum Flow (cfs)	0.33	0.04	0.08	0.18	0.13	0.43	0.53	0.37	0.33	0.26	0.10	0.12
Absolute Error (cfs)	0.02	-0.02	-0.03	-0.06	-0.04	-0.20	-0.08	-0.14	-0.08	-0.14	-0.05	-0.10
Percent Error	5%	-37%	-25%	-26%	-24%	-32%	-13%	-28%	-20%	-34%	-33%	-45%
Average of Percent Error	-26%											
Storm 2: 10/3/08 13:00 - 10/6/08 00:00 (0.59 inches of precipitation												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	0.7116	0.1655	0.2862	0.2599	0	0.8509	1.1417	0.5538	0.4641	0.4254	0.1176	0.4393
Modeled Maximum Flow (cfs)	0.66	0.07	0.21	0.19	0.41	0.84	1.27	0.65	0.58	0.42	0.18	0.44
Absolute Error (cfs)	-0.05	-0.10	-0.08	-0.07	0.41	-0.01	0.13	0.10	0.12	-0.01	0.06	0.00
Percent Error	-7%	-58%	-27%	-27%		-1%	11%	17%	25%	-1%	53%	0%
Average of Percent Error	-1%											
Storm 3: 11/3/08 12:00 - 11/8/08 00:00 (2.57 inches of precipitation)												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	1.168	0.1191	0.4347	0.3543	0.5121	1.7203	1.7156	0.9375	0.7286	0.6482	0.2738	0.6281
Modeled Maximum Flow (cfs)	0.83	0.10	0.32	0.24	0.62	1.23	1.61	0.89	0.79	0.55	0.25	0.65
Absolute Error (cfs)	-0.34	-0.02	-0.11	-0.11	0.11	-0.49	-0.11	-0.05	0.06	-0.10	-0.02	0.02
Percent Error	-29%	-16%	-26%	-32%	21%	-29%	-6%	-5%	8%	-15%	-9%	3%
Average of Percent Error	-11%											
Storm 4: 11/6/08 00:00 - 11/9/08 00:00 (1.86 inches of precipitation)												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	0.9947	0.1299	0.4254	0.3543	0.5121	1.7203	1.4697	0.9375	0.7317	0.6528	0.2738	0.6791
Modeled Maximum Flow (cfs)	0.82	0.10	0.27	0.27	0.53	1.17	1.61	0.89	0.79	0.55	0.25	0.54
Absolute Error (cfs)	-0.17	-0.03	-0.16	-0.08	0.02	-0.55	0.14	-0.05	0.06	-0.10	-0.02	-0.14
Percent Error	-18%	-23%	-37%	-24%	3%	-32%	10%	-5%	8%	-16%	-9%	-20%
Average of Percent Error	-13%											

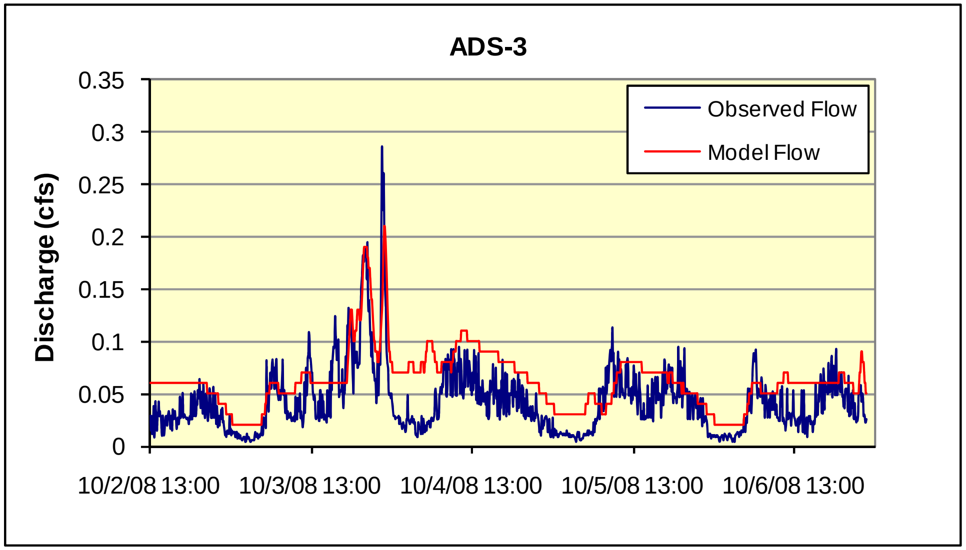
Table C-8 (continued). Goodness of fit between modeled and observed peak flows

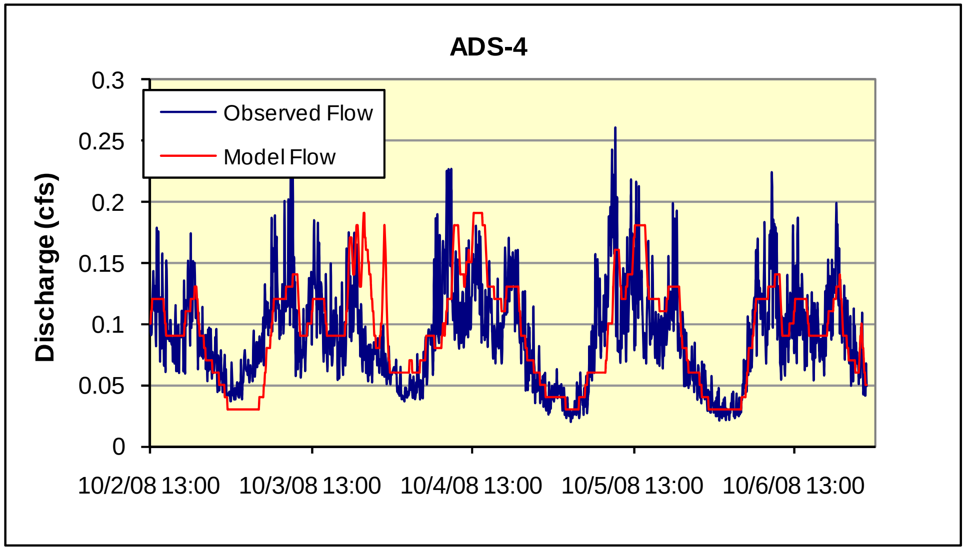
Storm 5: 12/12/08 00:00 - 12/14/08 00:00 (0.57 inches of precipitation)												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	0.8493	0.0696	0.2723	0.2568	0.28	0.6683	1.1432	0.6142	0.4084	0.5244	0.1686	0.4749
Modeled Maximum Flow (cfs)	0.74	0.10	0.30	0.26	0.38	0.98	1.58	0.84	0.75	0.53	0.27	0.59
Absolute Error (cfs)	-0.11	0.03	0.03	0.00	0.10	0.31	0.44	0.23	0.34	0.01	0.10	0.12
Percent Error	-13%	44%	10%	1%	36%	47%	38%	37%	84%	1%	60%	24%
Average of Percent Error	31%											
Storm 6: 1/6/09 21:00 - 1/13/09 03:00 (1.75 inches of precipitation)												
	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10	BV11	BV12
Observed Maximum Flow (cfs)	1.892	0.2769	0.8725	0.4517	1.7419	2.831	2.5572	2.1875	1.5161	1.2453	1.038	1.3892
Modeled Maximum Flow (cfs)	2.03	0.35	0.85	0.52	1.79	3.13	4.30	2.34	2.11	1.51	0.87	1.63
Absolute Error (cfs)	0.14	0.07	-0.02	0.07	0.05	0.30	1.74	0.15	0.59	0.26	-0.17	0.24
Percent Error	7%	26%	-3%	15%	3%	11%	68%	7%	39%	21%	-16%	17%
Average of Percent Error	16%											

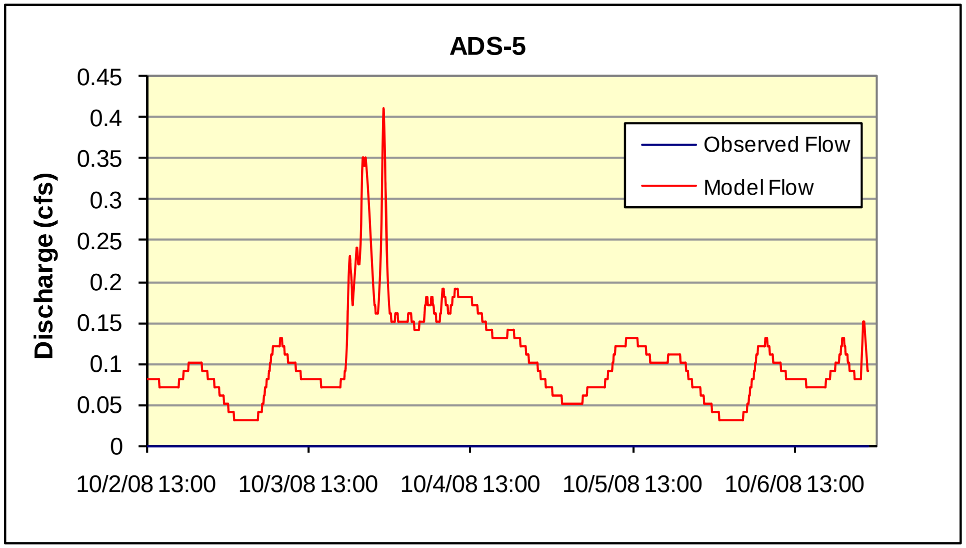
Storm 1

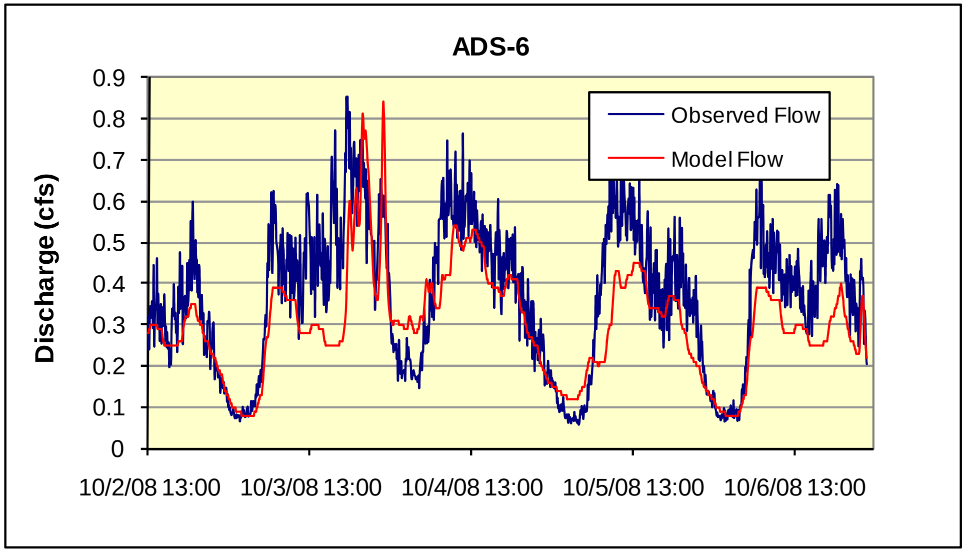

ADS-1
Observed Flow
Model Flow
Discharge (cfs)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

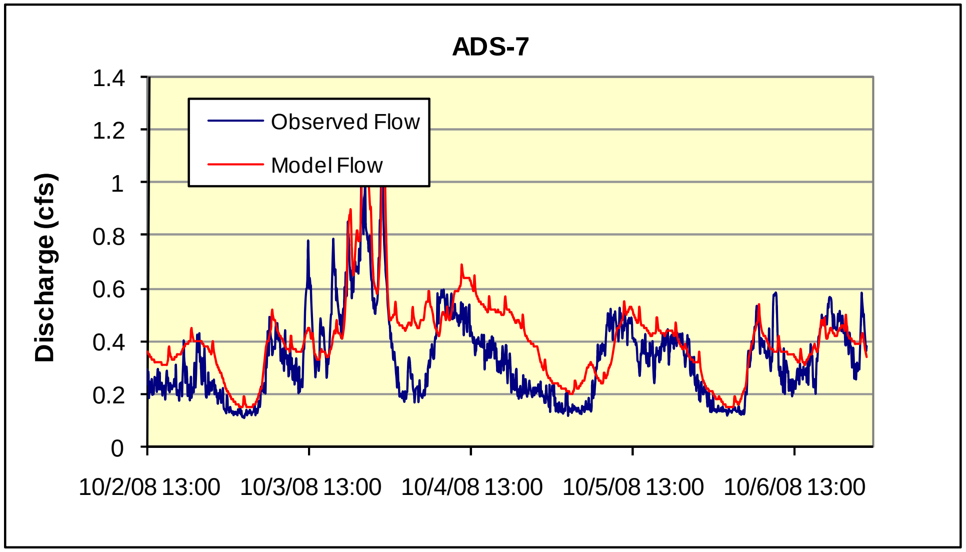

ADS-2
Observed Flow
Model Flow
Discharge (cfs)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

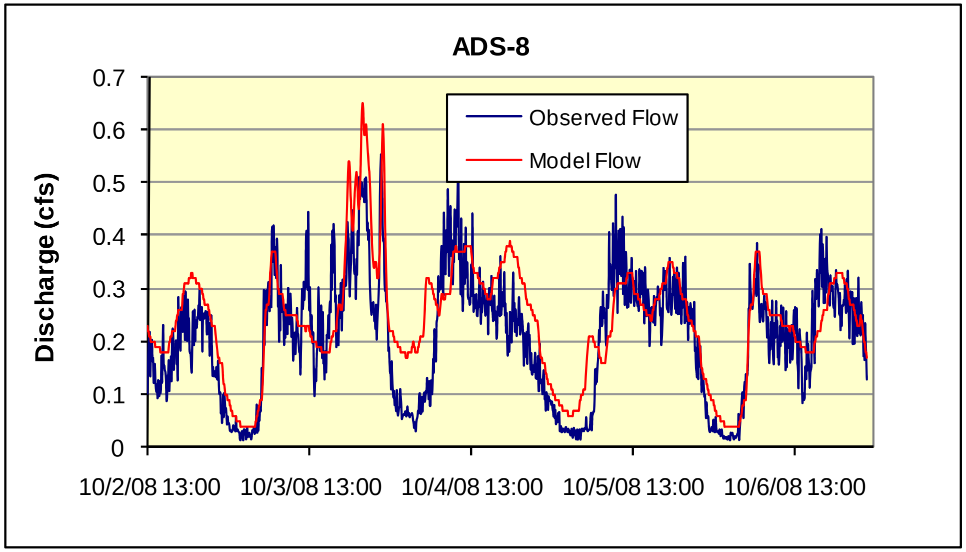

ADS-3
Observed Flow
Model Flow
Discharge (cfs)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

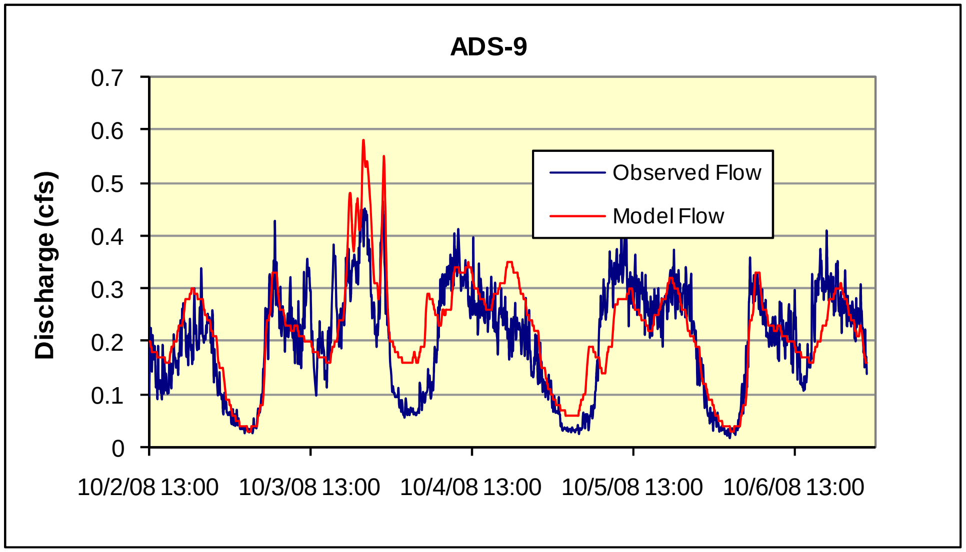

ADS-4
Observed Flow
Model Flow
Discharge (cfs)
0.3
0.25
0.2
0.15
0.1
0.05
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

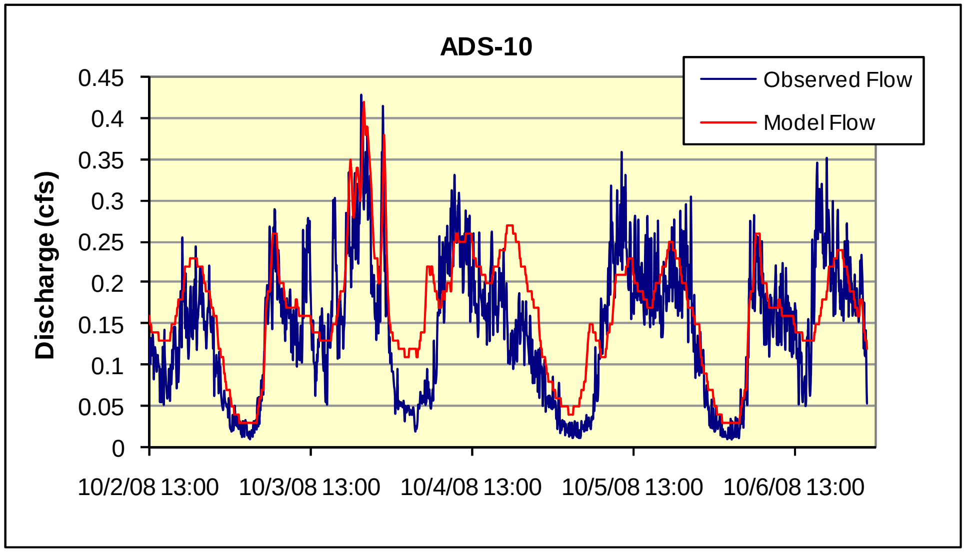

ADS-5
Discharge (cfs)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00
Observed Flow
Model Flow

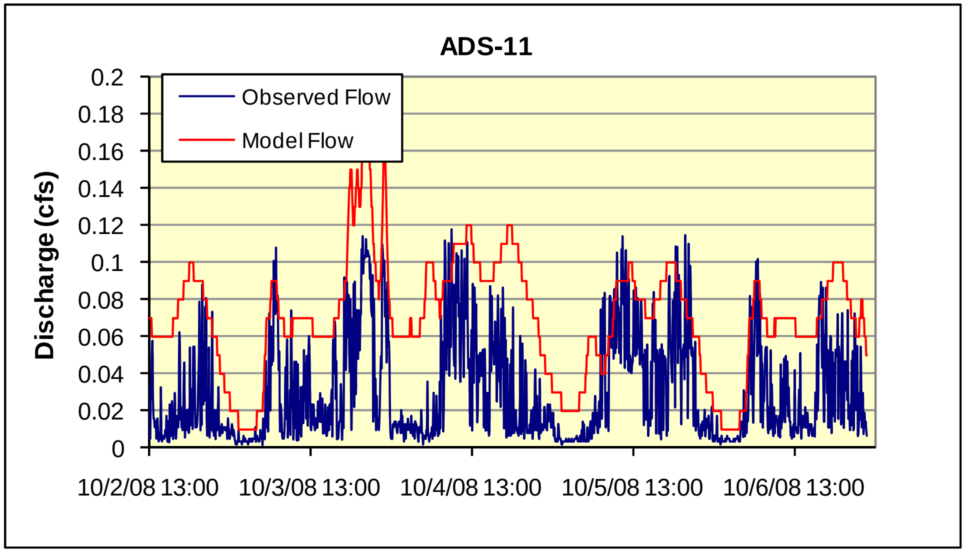

ADS-6
Discharge (cfs)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00
Observed Flow
Model Flow

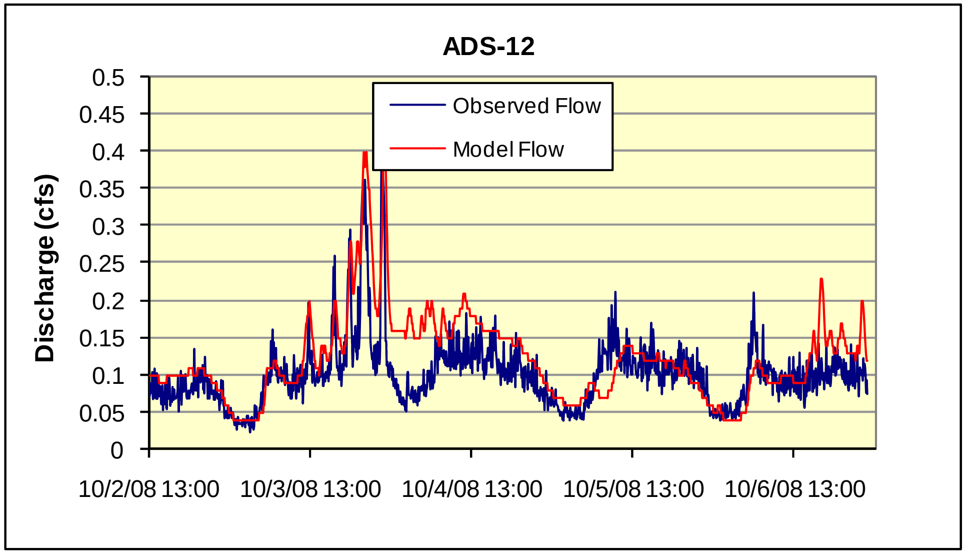

ADS-7
Discharge (cfs)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00
Observed Flow
Model Flow


ADS-8
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00
Observed Flow
Model Flow

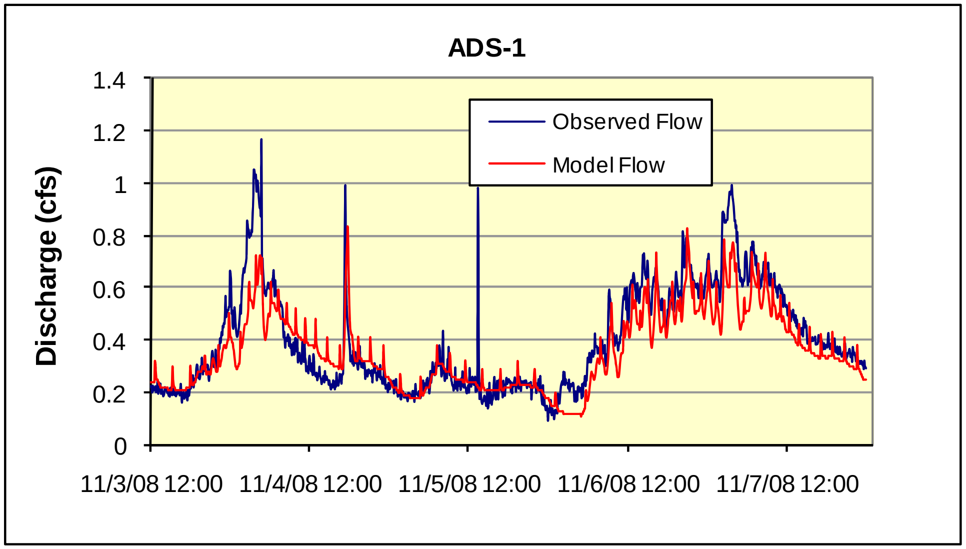

ADS-9
Observed Flow
Model Flow
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

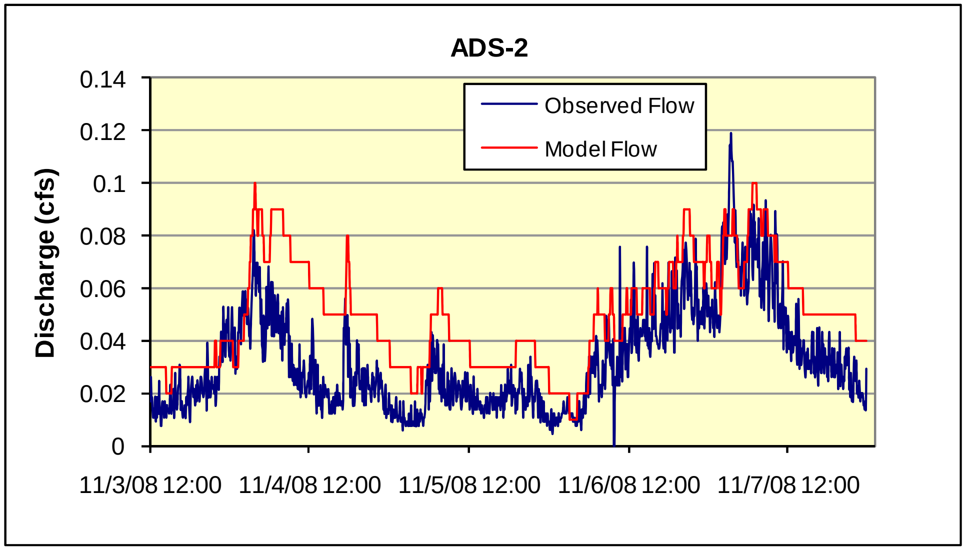

ADS-10
Observed Flow
Model Flow
Discharge (cfs)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

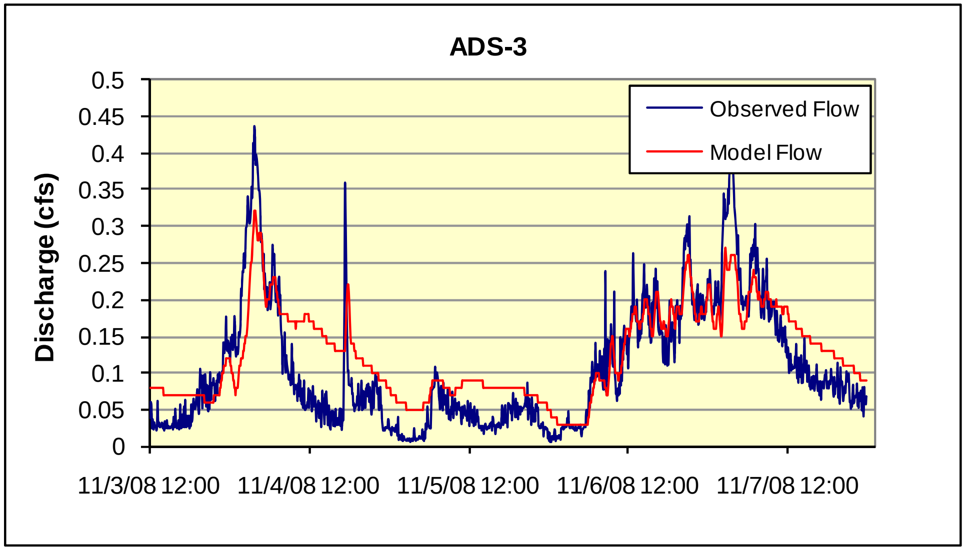

ADS-11
Observed Flow
Model Flow
Discharge (cfs)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

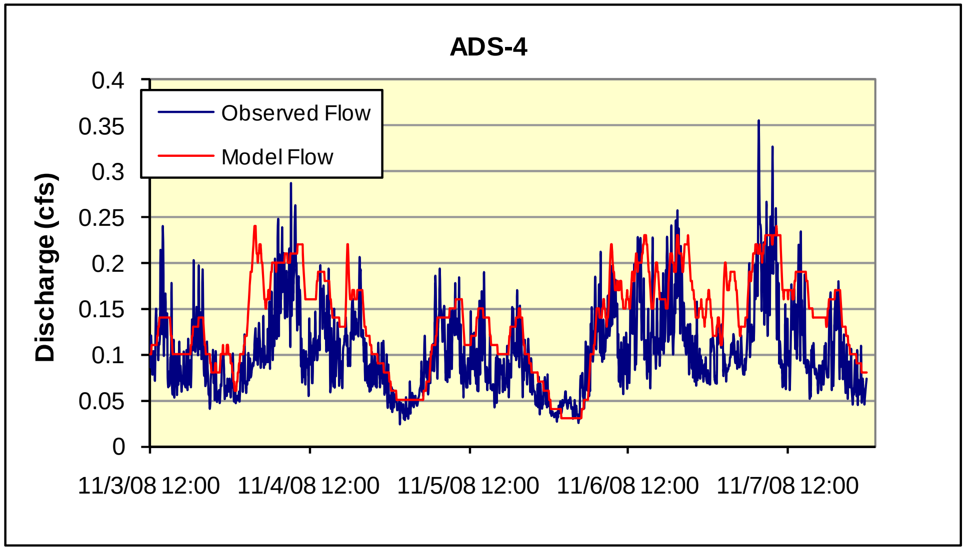

ADS-12
Observed Flow
Model Flow
Discharge (cfs)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10/2/08 13:00
10/3/08 13:00
10/4/08 13:00
10/5/08 13:00
10/6/08 13:00

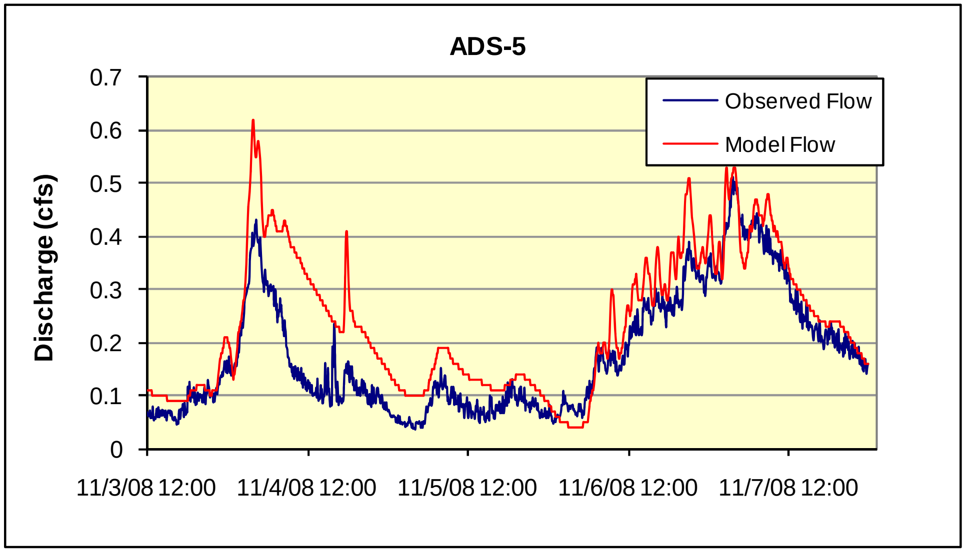
Storm 2

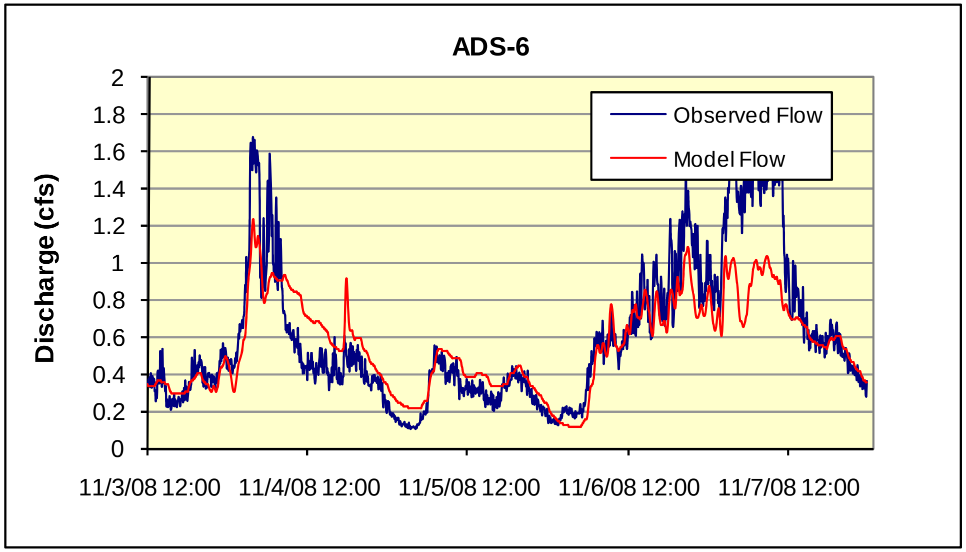

ADS-1
Discharge (cfs)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

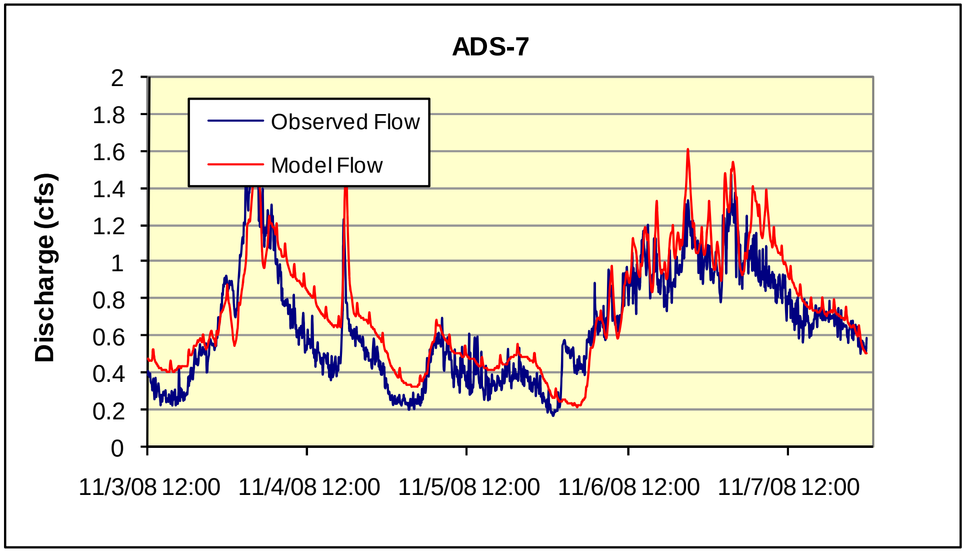

ADS-2
Discharge (cfs)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

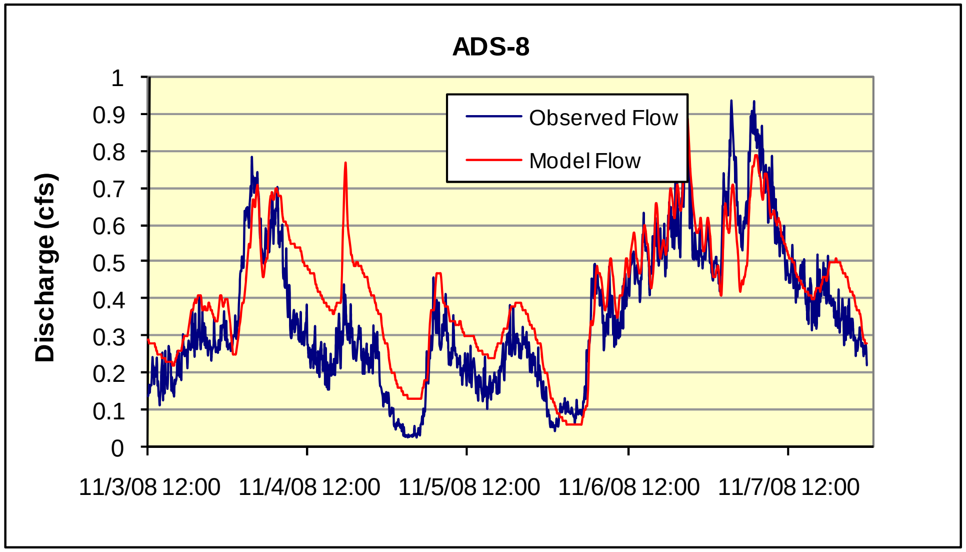

ADS-3
Discharge (cfs)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

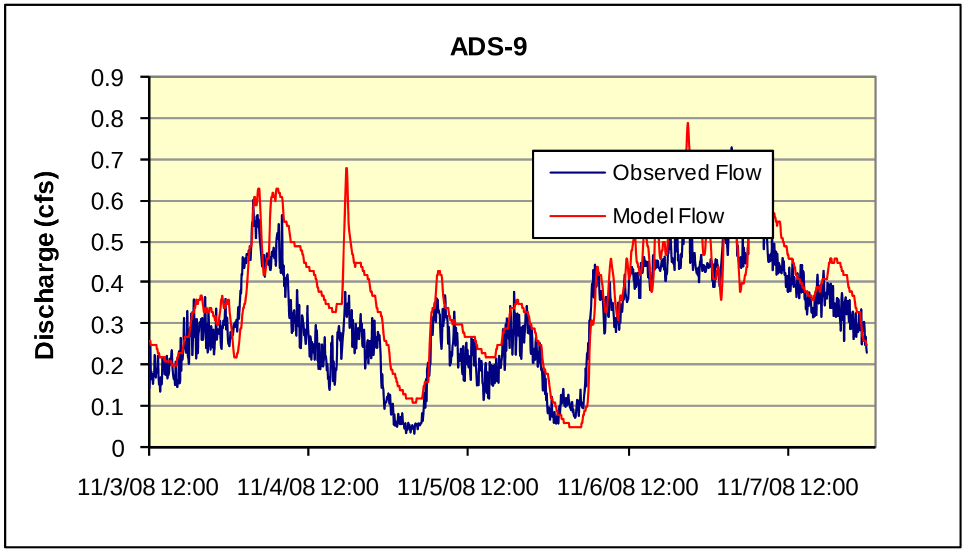

ADS-4
Discharge (cfs)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

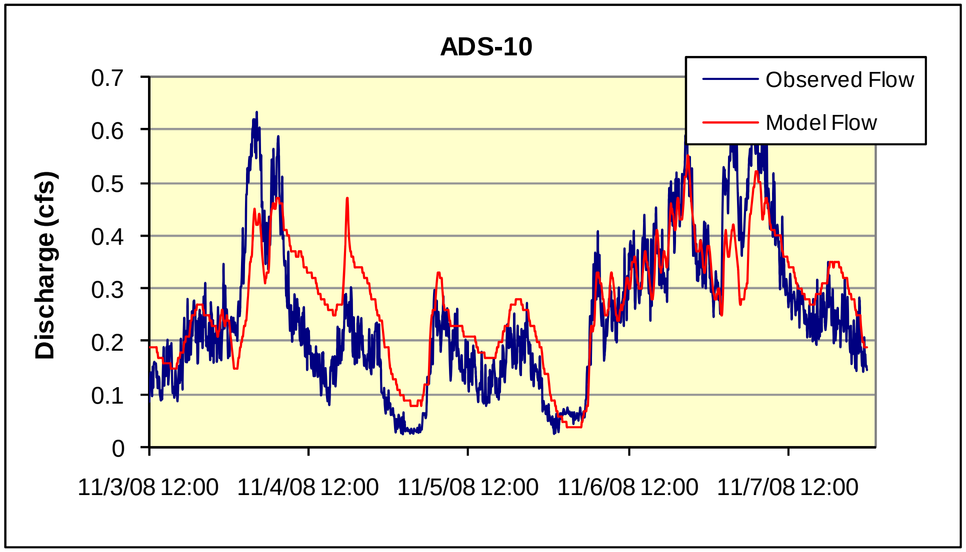

ADS-5
Observed Flow
Model Flow
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00

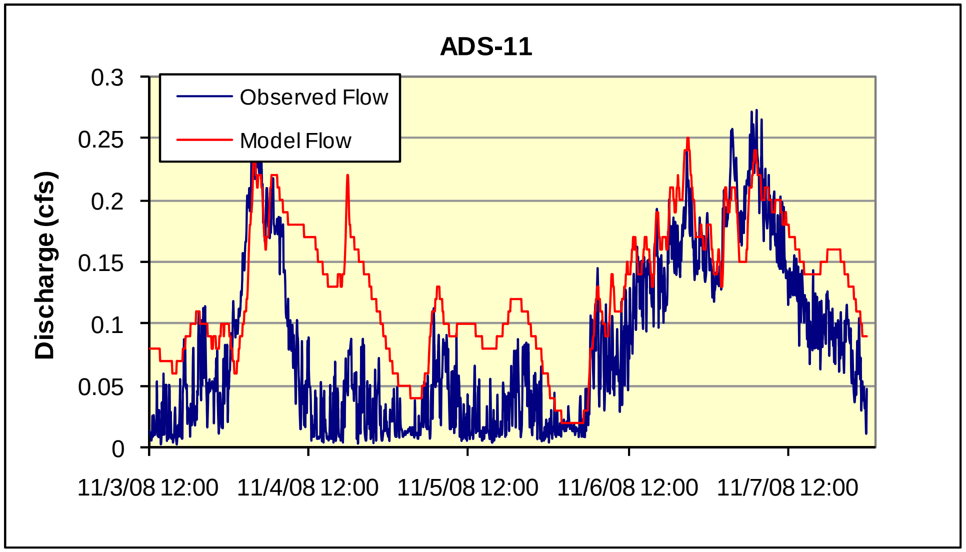

ADS-6
Observed Flow
Model Flow
Discharge (cfs)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00

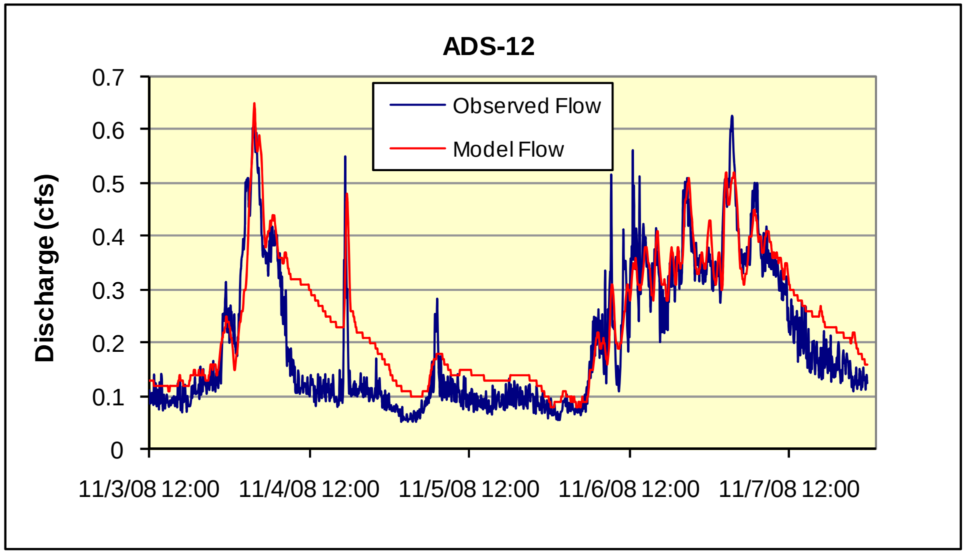

ADS-7
Observed Flow
Model Flow
Discharge (cfs)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00


ADS-8
Observed Flow
Model Flow
Discharge (cfs)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00

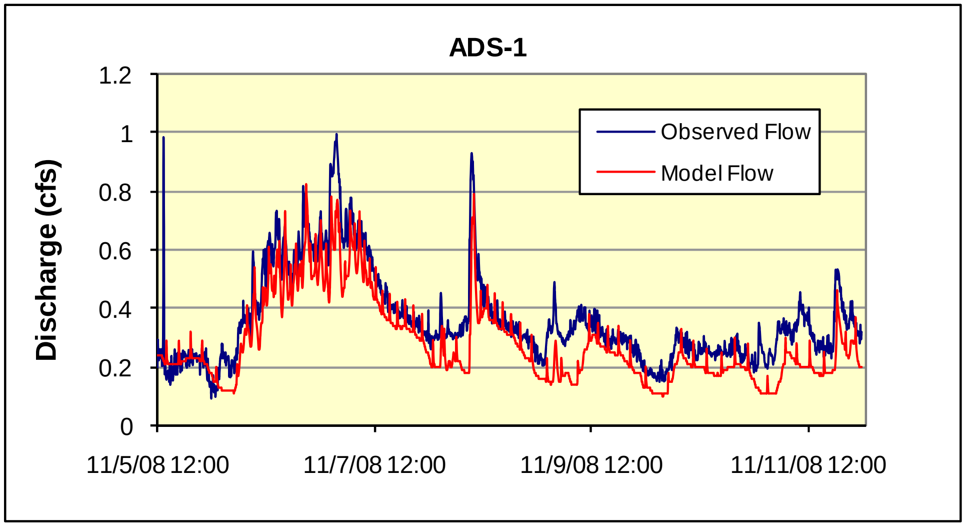

ADS-9
Discharge (cfs)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

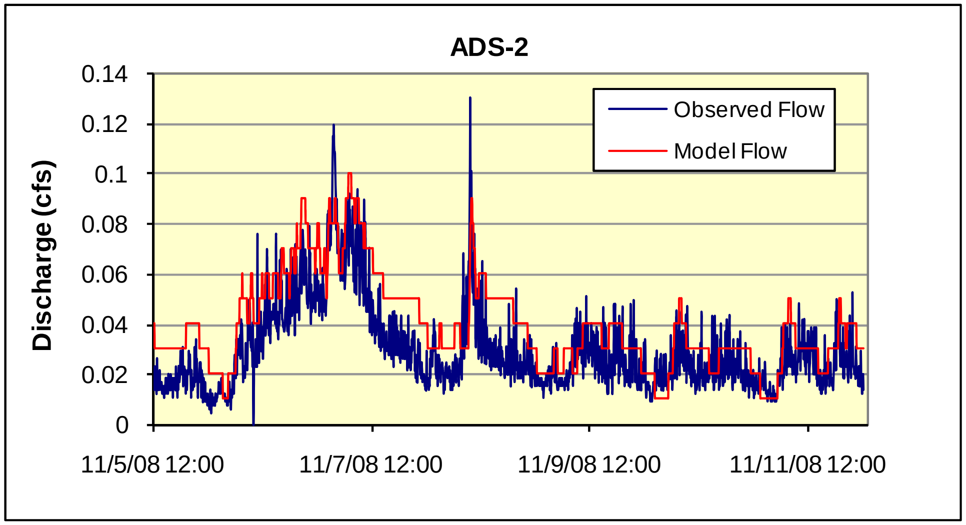

ADS-10
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

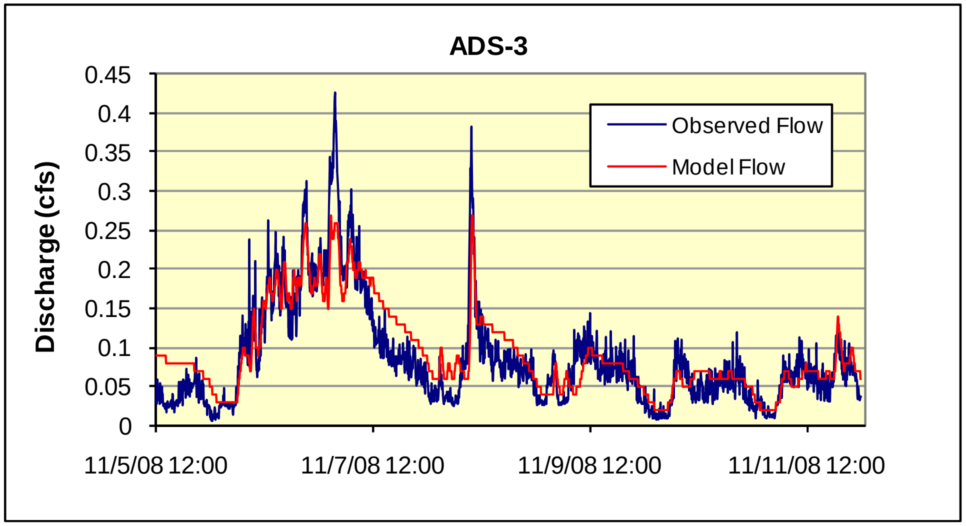

ADS-11
Discharge (cfs)
0.3
0.25
0.2
0.15
0.1
0.05
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

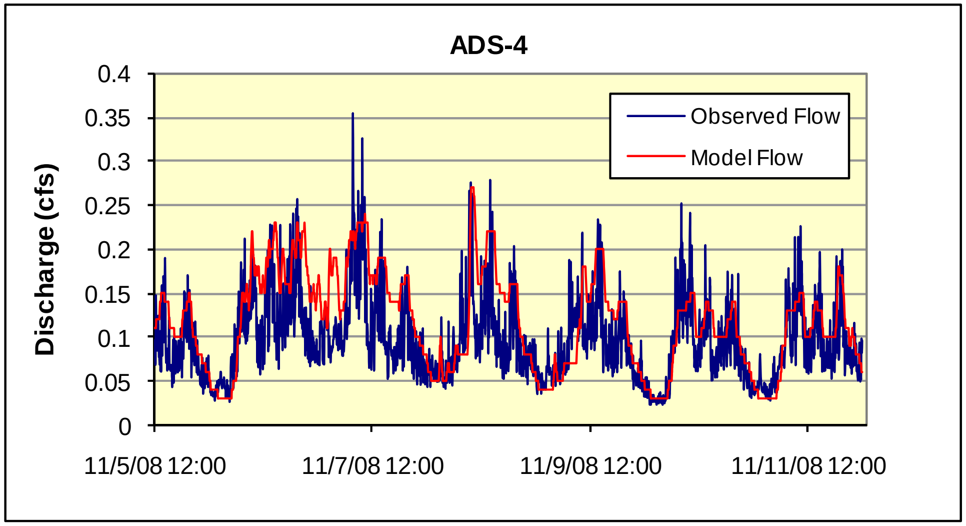

ADS-12
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/3/08 12:00
11/4/08 12:00
11/5/08 12:00
11/6/08 12:00
11/7/08 12:00
Observed Flow
Model Flow

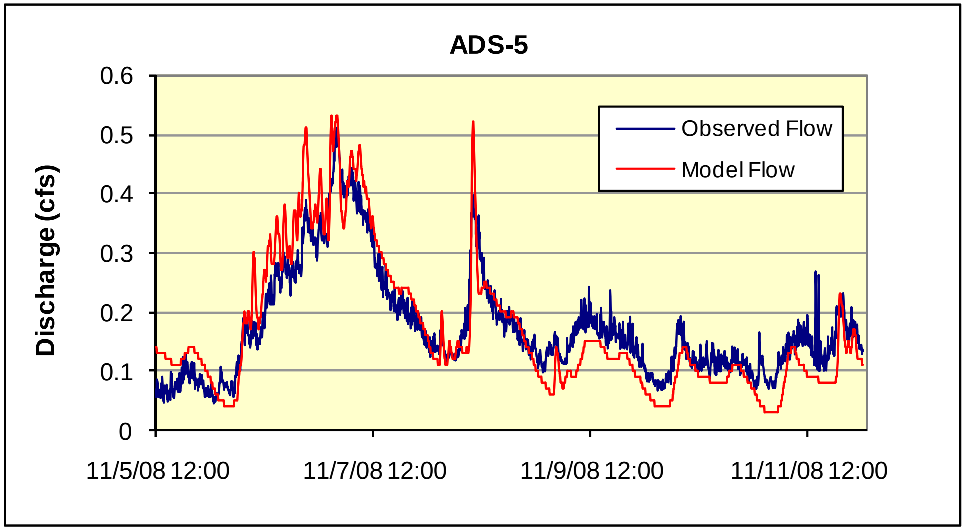
Storm 3

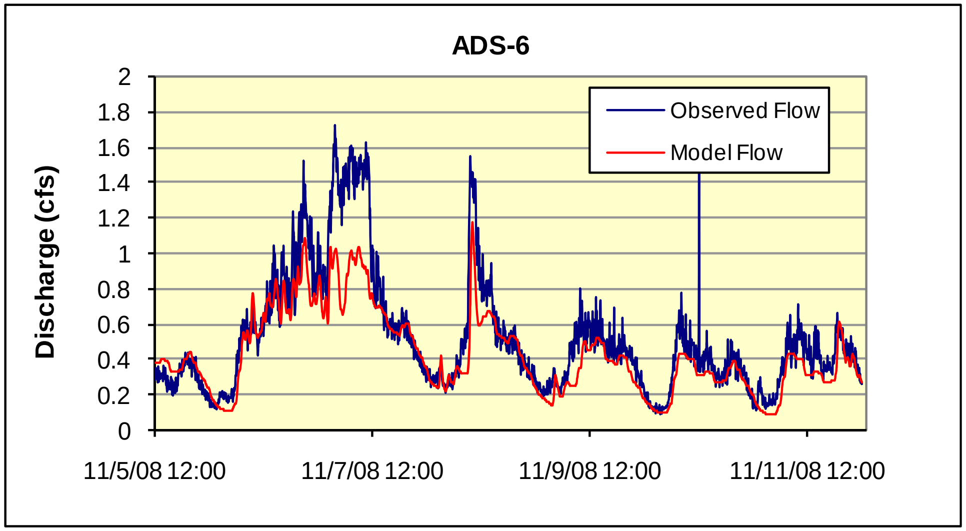

ADS-1
Discharge (cfs)
1.2
1
0.8
0.6
0.4
0.2
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00
Observed Flow
Model Flow

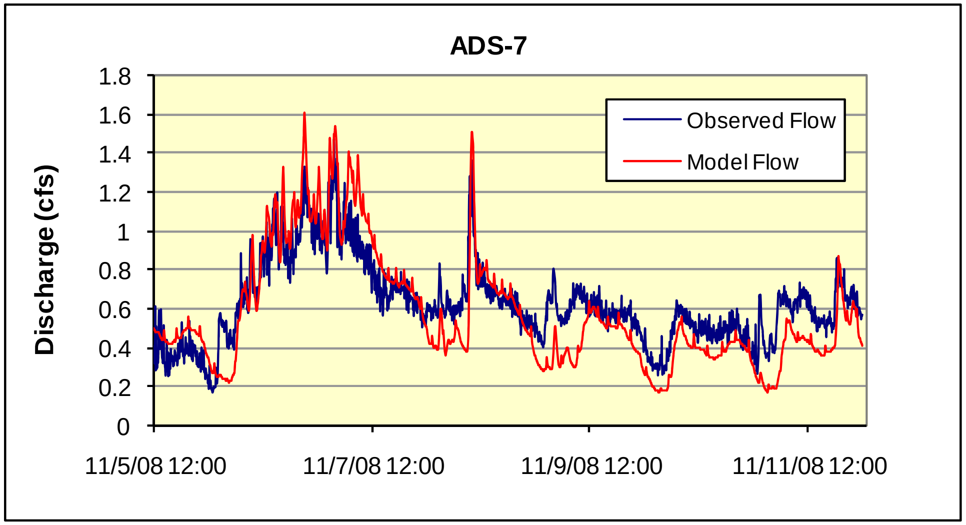

ADS-2
Discharge (cfs)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00
Observed Flow
Model Flow

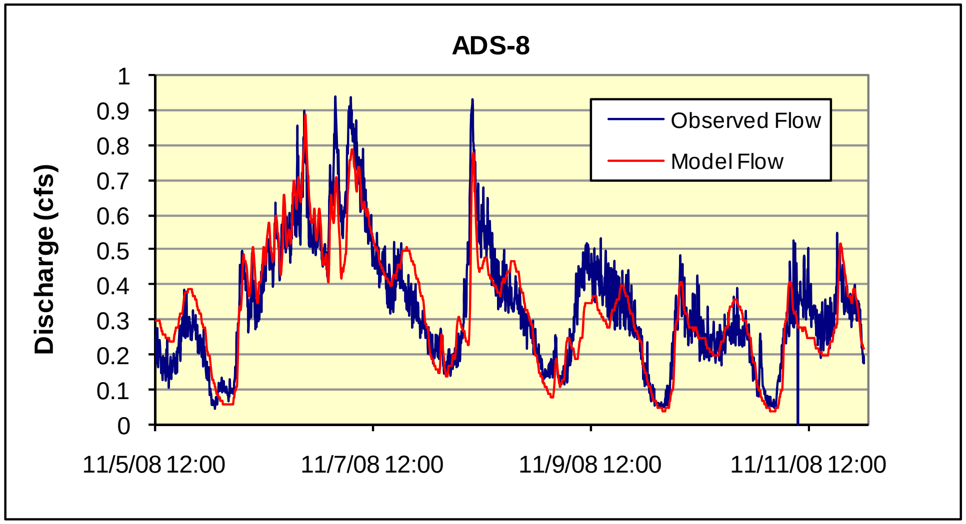

ADS-3
Discharge (cfs)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00
Observed Flow
Model Flow

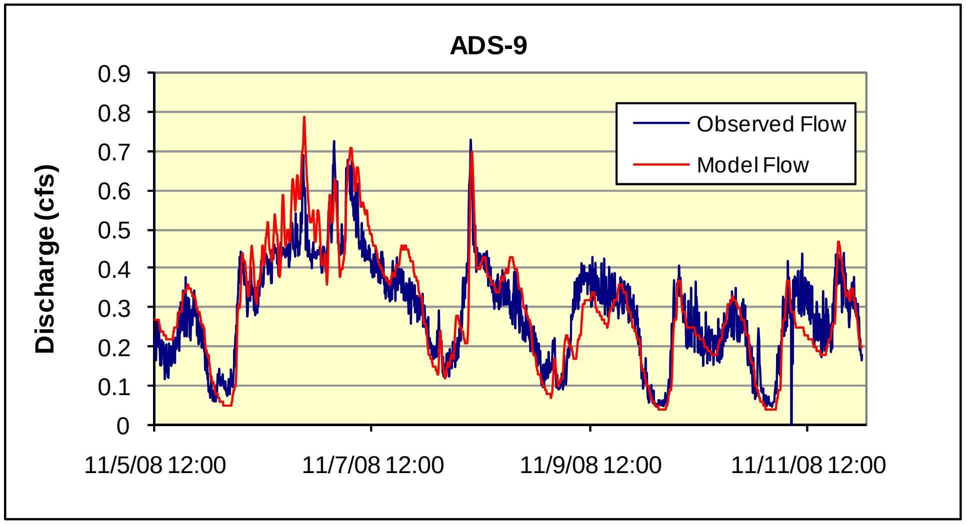

ADS-4
Discharge (cfs)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00
Observed Flow
Model Flow

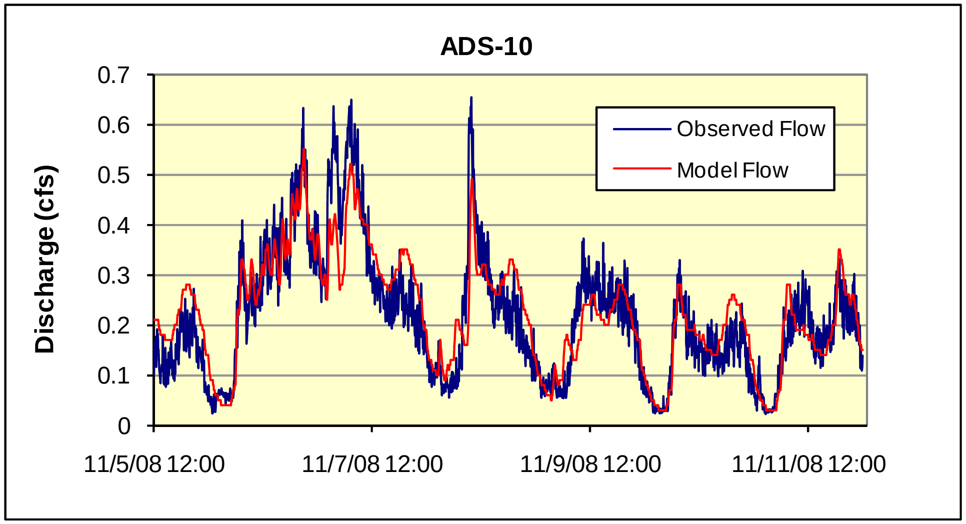

ADS-5
Observed Flow
Model Flow
Discharge (cfs)
0.6
0.5
0.4
0.3
0.2
0.1
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

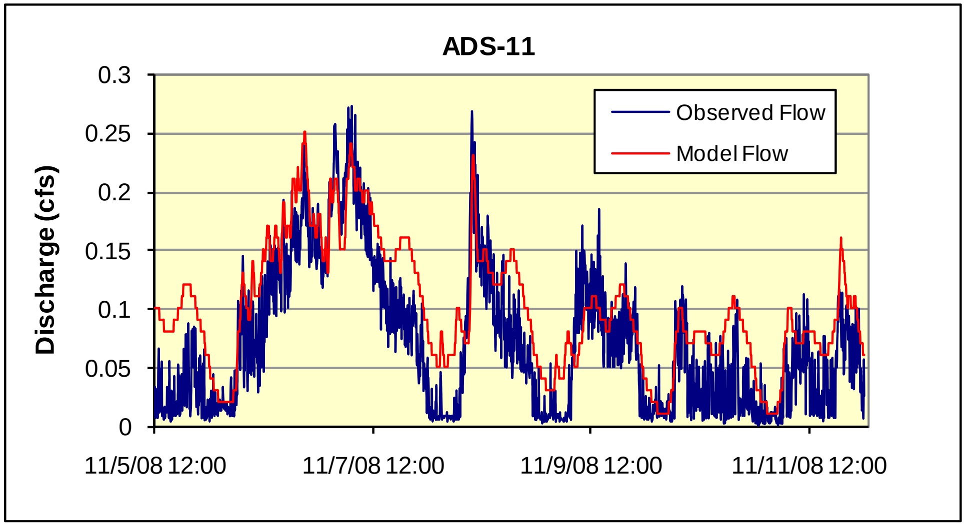

ADS-6
Observed Flow
Model Flow
Discharge (cfs)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

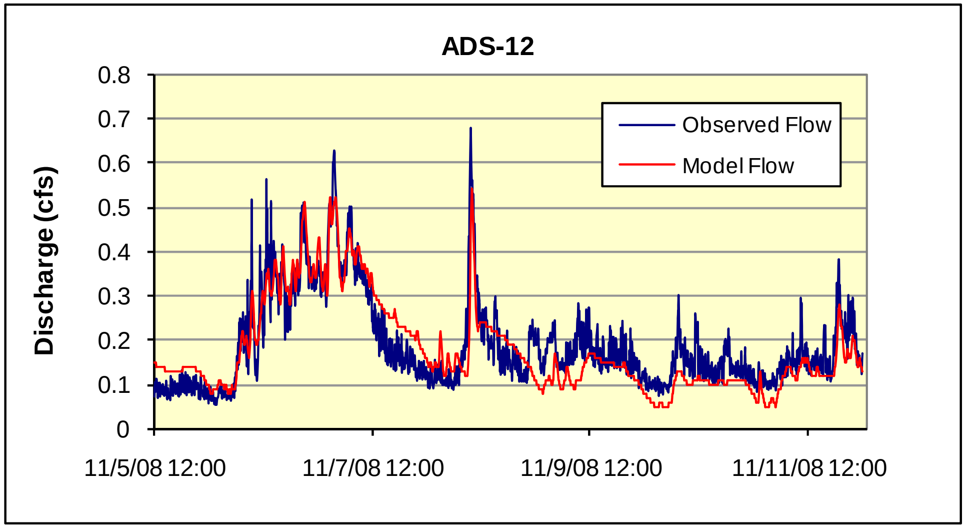

ADS-7
Observed Flow
Model Flow
Discharge (cfs)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00


ADS-8
Observed Flow
Model Flow
Discharge (cfs)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

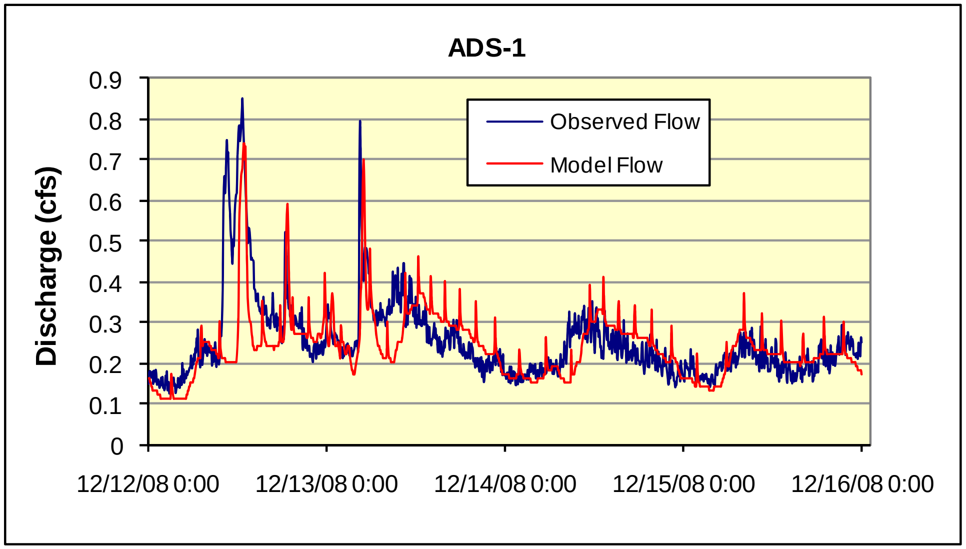

ADS-9
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Discharge (cfs)
Observed Flow
Model Flow
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

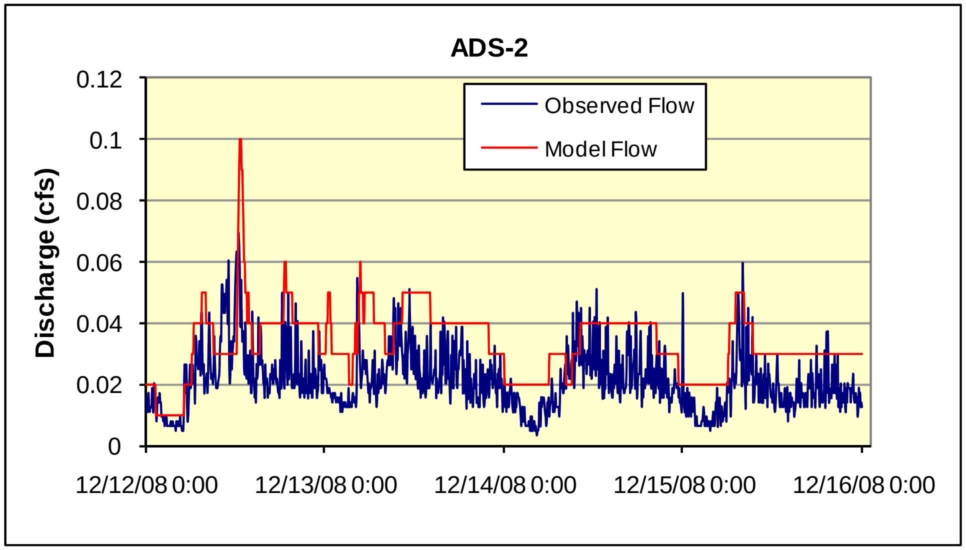

ADS-10
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Discharge (cfs)
Observed Flow
Model Flow
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

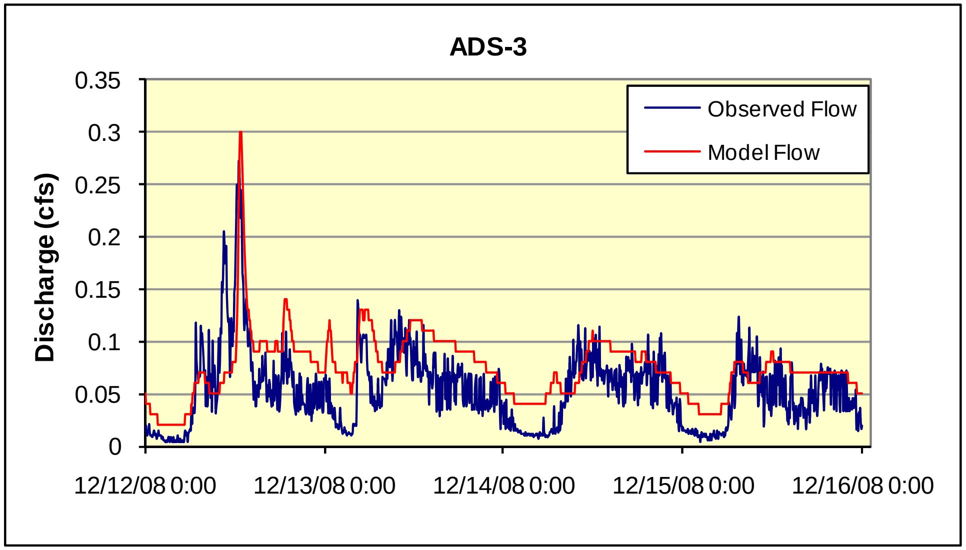

ADS-11
0.3
0.25
0.2
0.15
0.1
0.05
0
Discharge (cfs)
Observed Flow
Model Flow
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

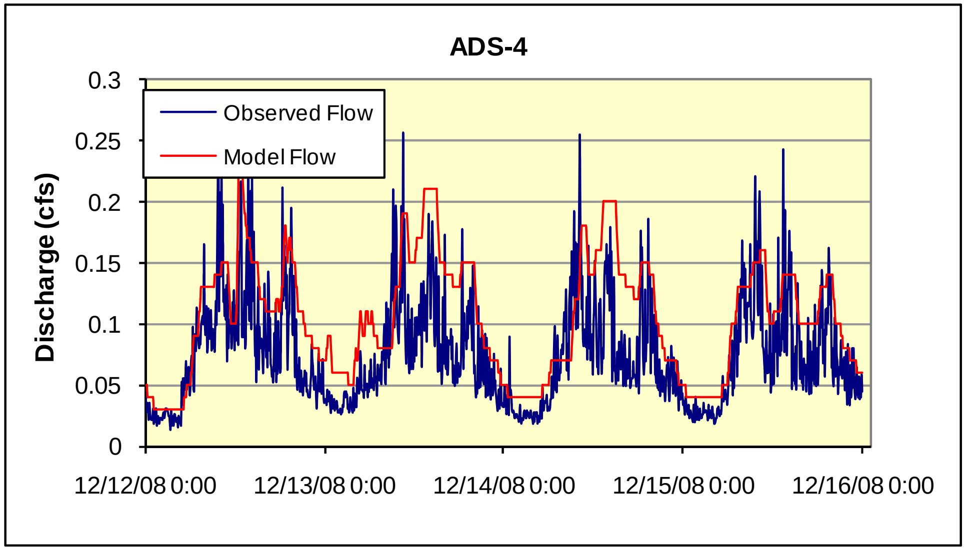

ADS-12
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Discharge (cfs)
Observed Flow
Model Flow
11/5/08 12:00
11/7/08 12:00
11/9/08 12:00
11/11/08 12:00

Storm 4









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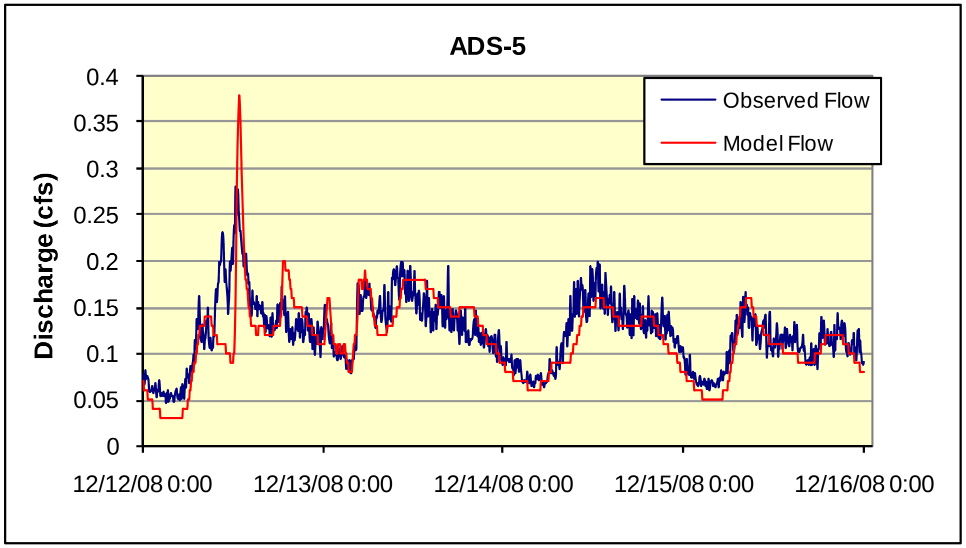
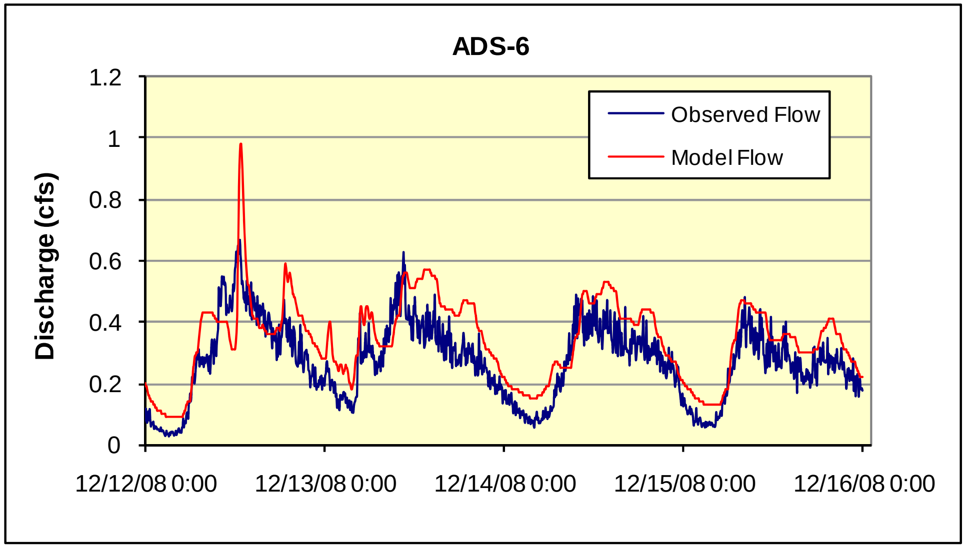
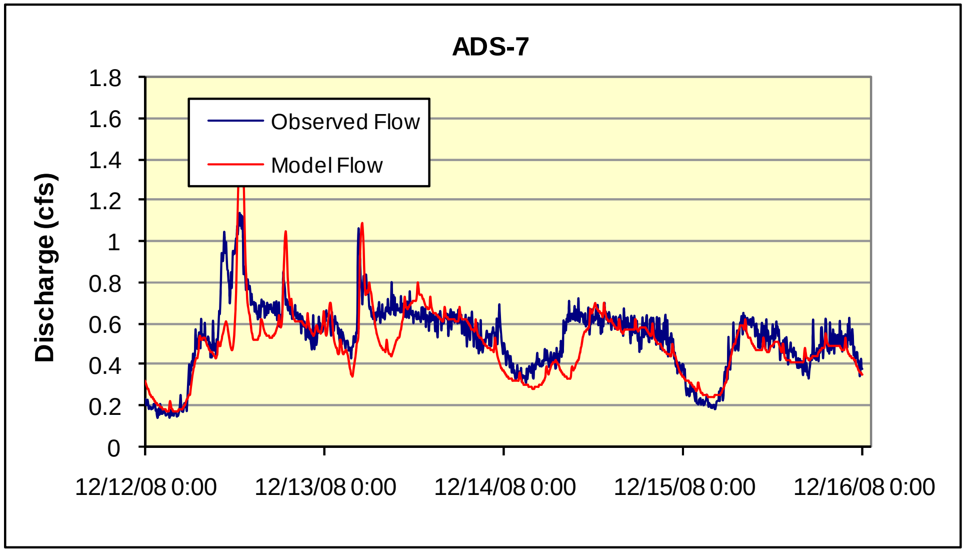


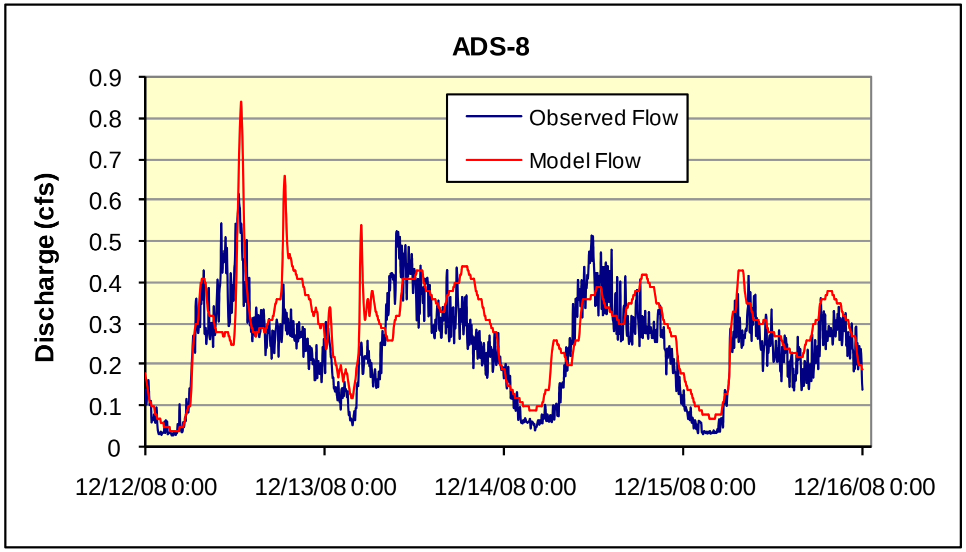
ADS-5
Discharge (cfs)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow



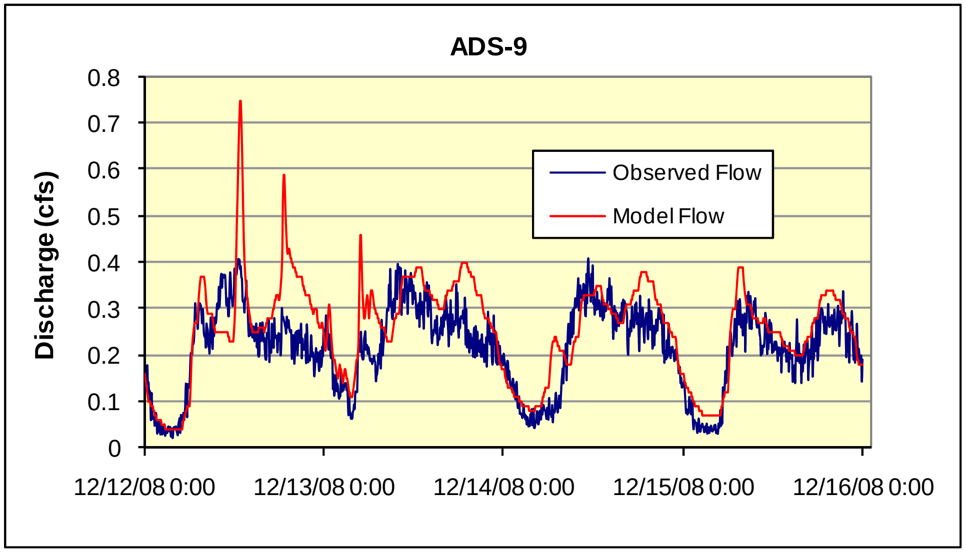
ADS-6
Discharge (cfs)
1.2
1
0.8
0.6
0.4
0.2
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

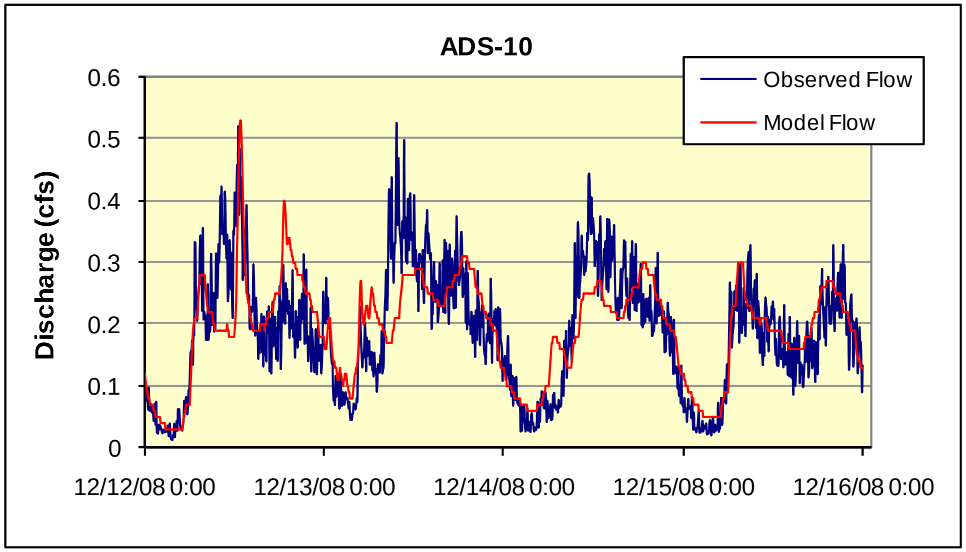


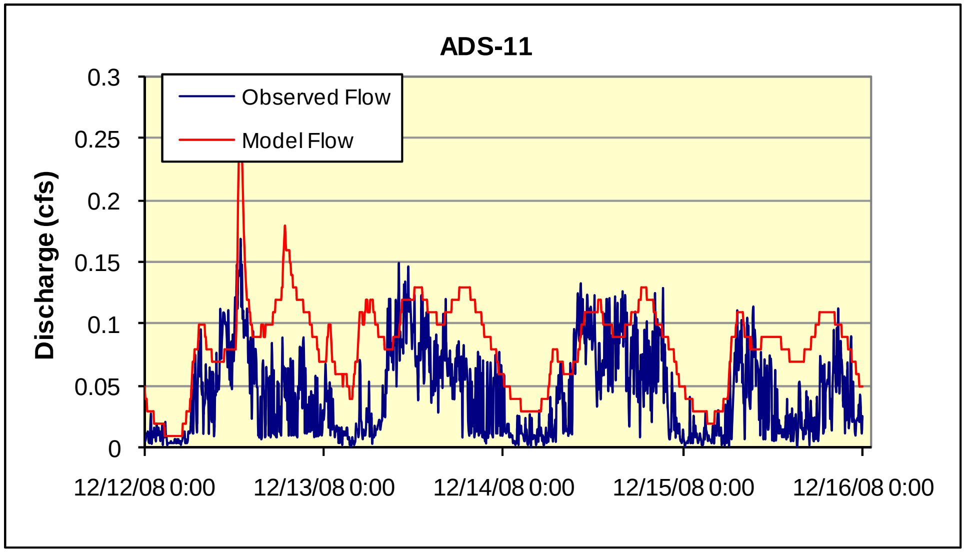
ADS-7
Discharge (cfs)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

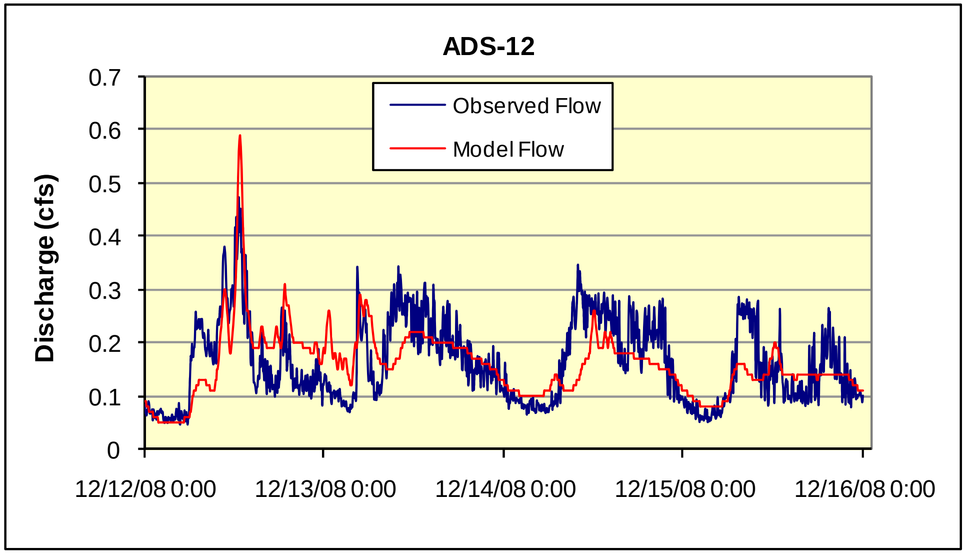


ADS-8
Discharge (cfs)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

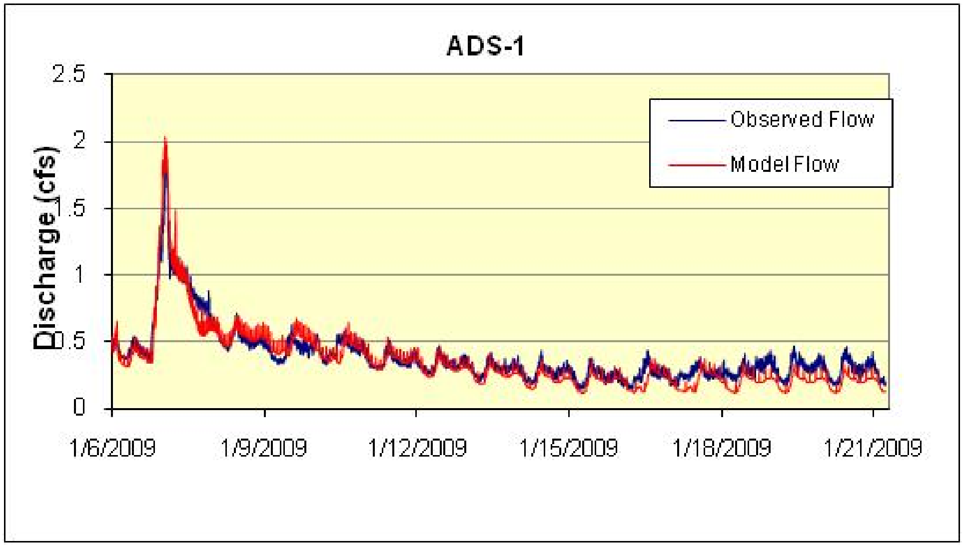

ADS-9
Discharge (cfs)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

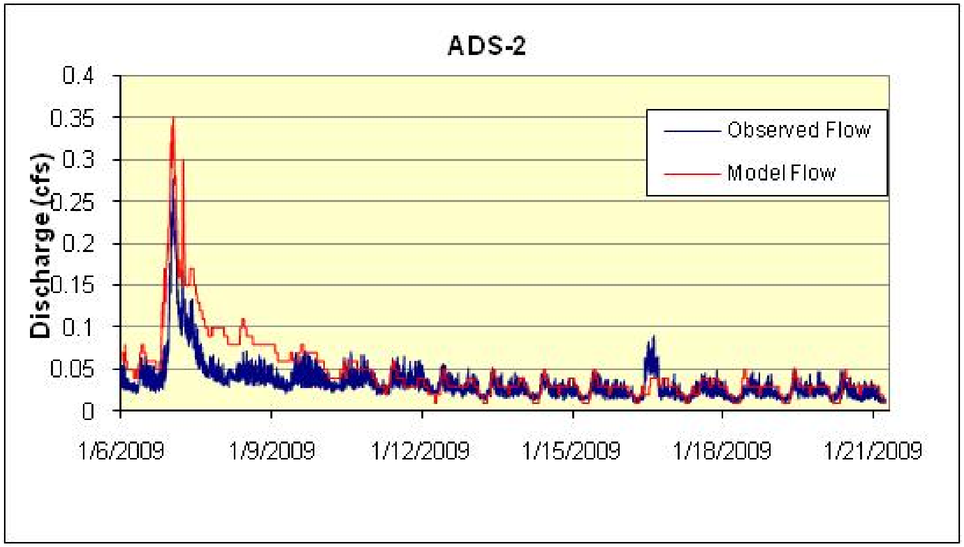

ADS-10
Discharge (cfs)
0.6
0.5
0.4
0.3
0.2
0.1
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

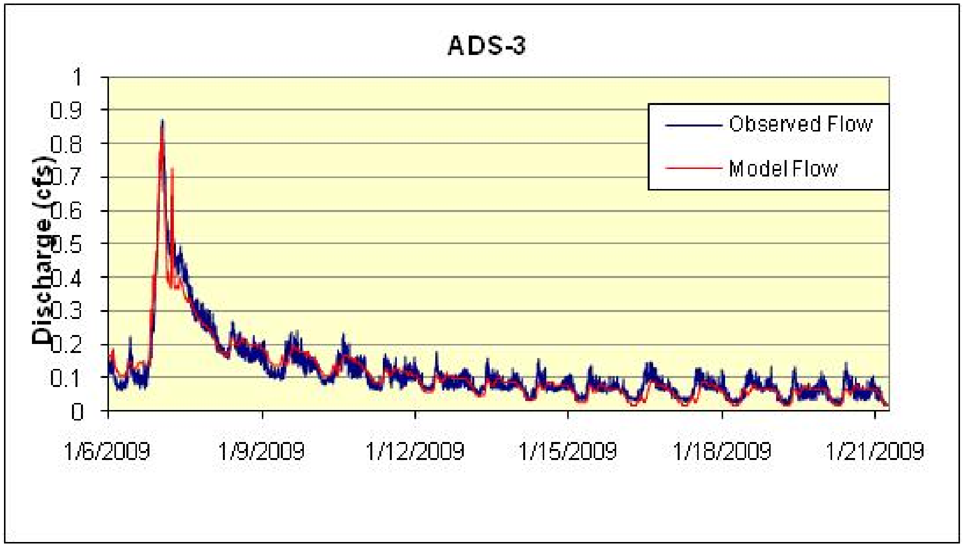

ADS-11
Discharge (cfs)
0.3
0.25
0.2
0.15
0.1
0.05
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

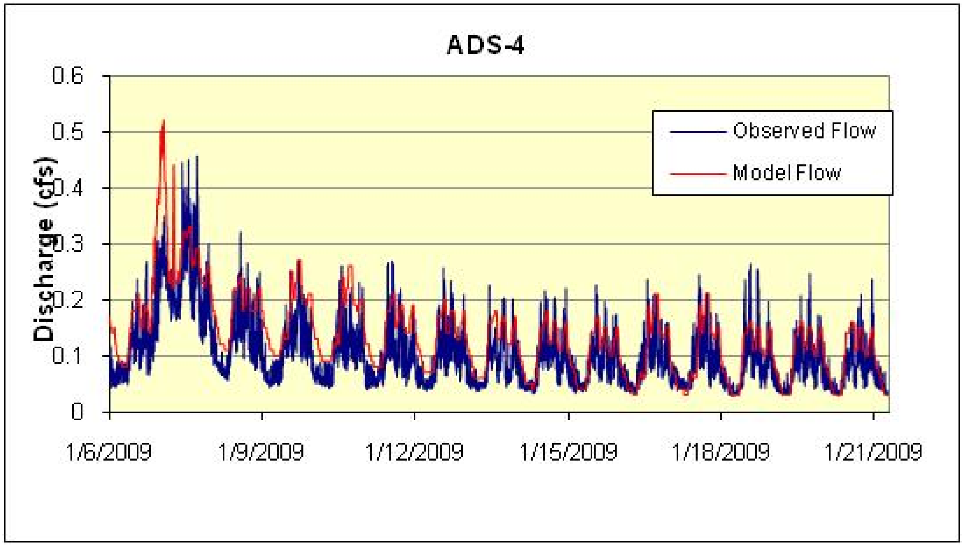

ADS-12
Discharge (cfs)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12/12/08 0:00
12/13/08 0:00
12/14/08 0:00
12/15/08 0:00
12/16/08 0:00
Observed Flow
Model Flow

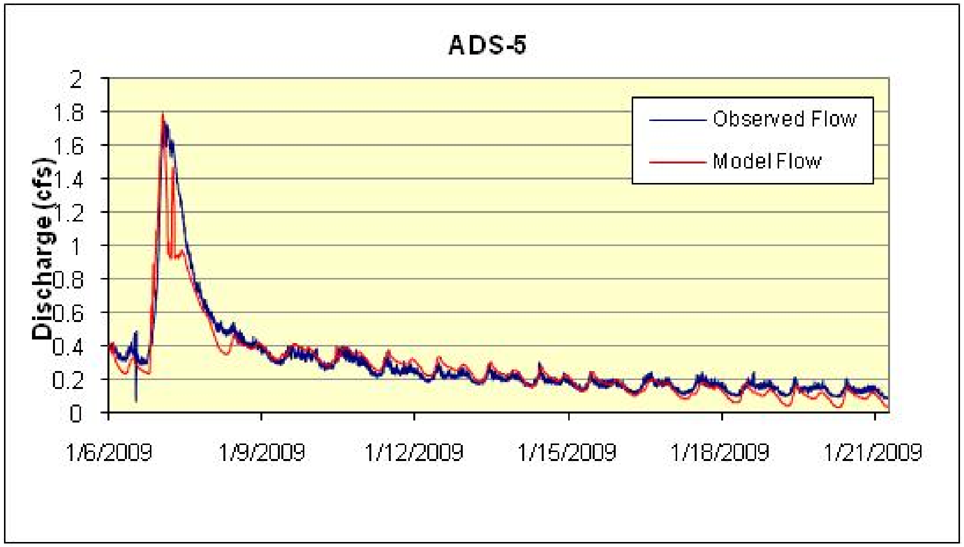
Storm 5

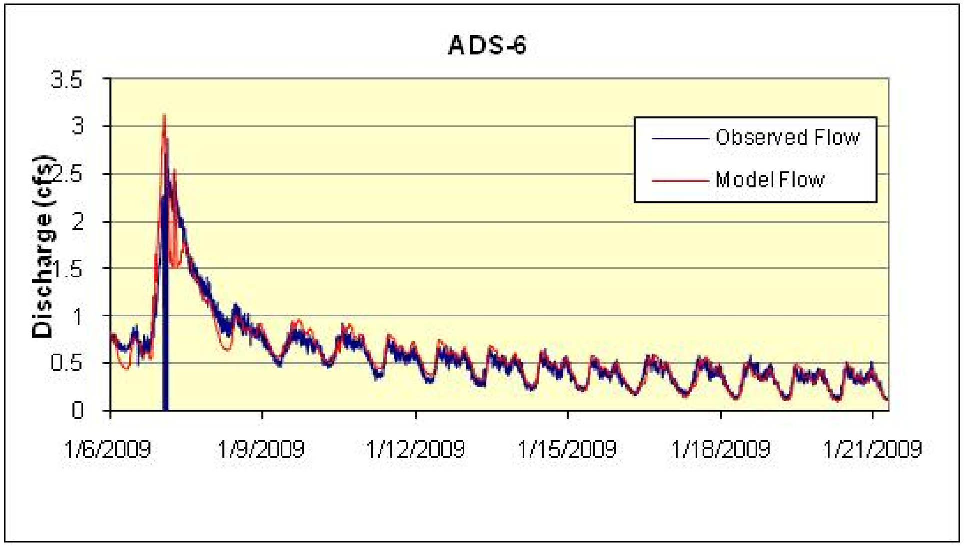

ADS-1
Discharge (cfs)
2.5
2
1.5
1
0.5
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009
Observed Flow
Model Flow

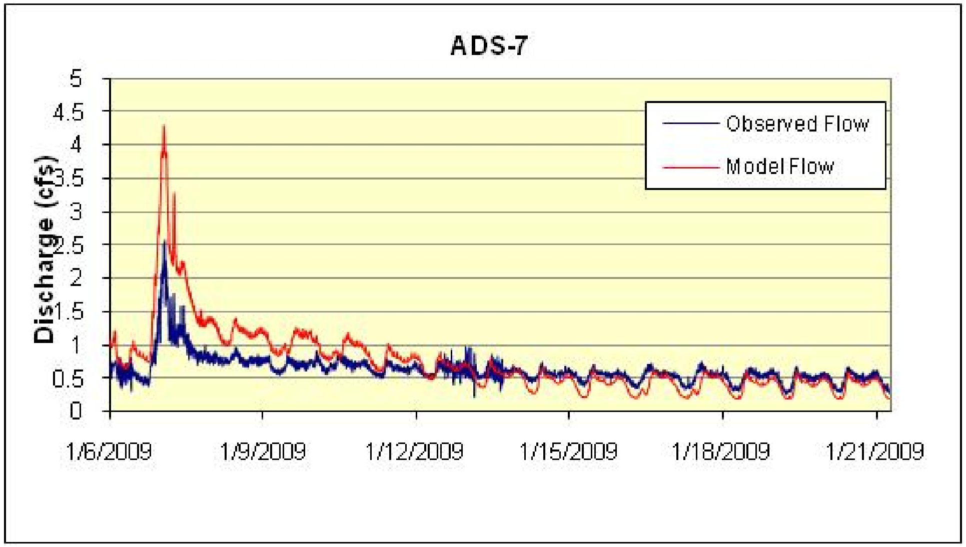

ADS-2
Discharge (cfs)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009
Observed Flow
Model Flow

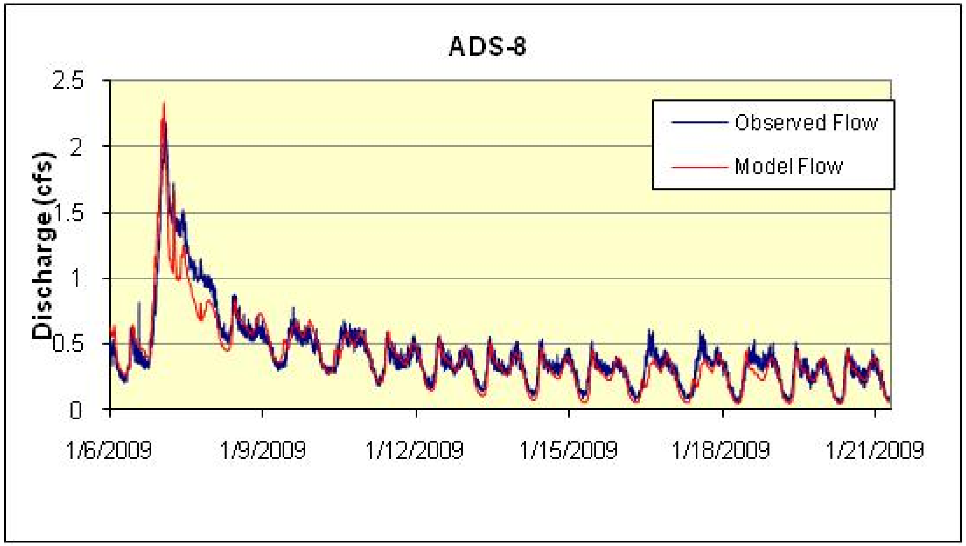

ADS-3
Discharge (cfs)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009
Observed Flow
Model Flow

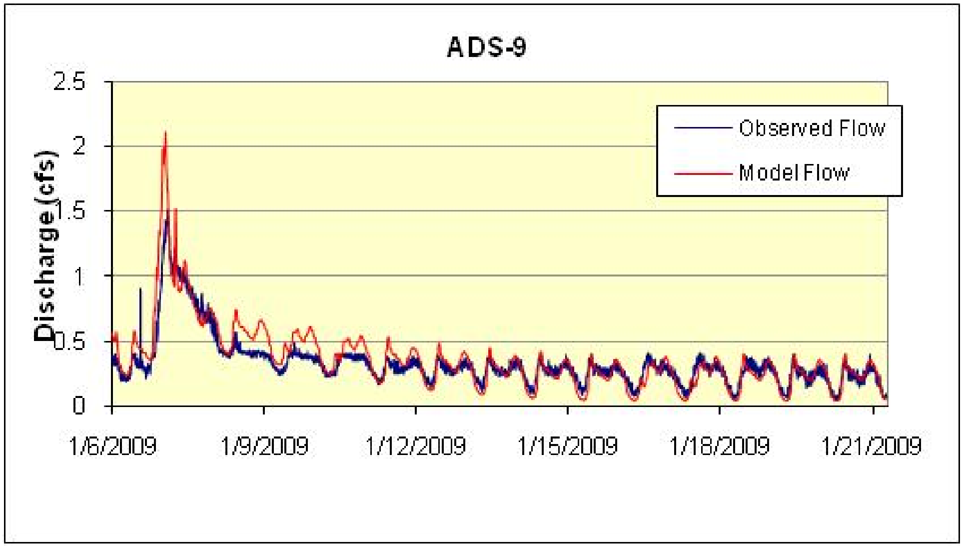

ADS-4
Discharge (cfs)
0.6
0.5
0.4
0.3
0.2
0.1
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009
Observed Flow
Model Flow

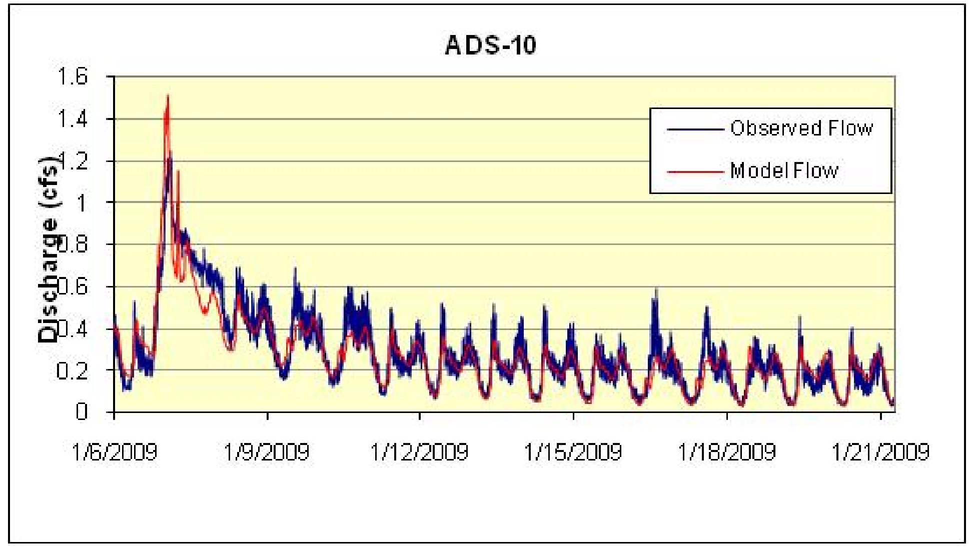

ADS-5
Observed Flow
Model Flow
Discharge (cfs)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009

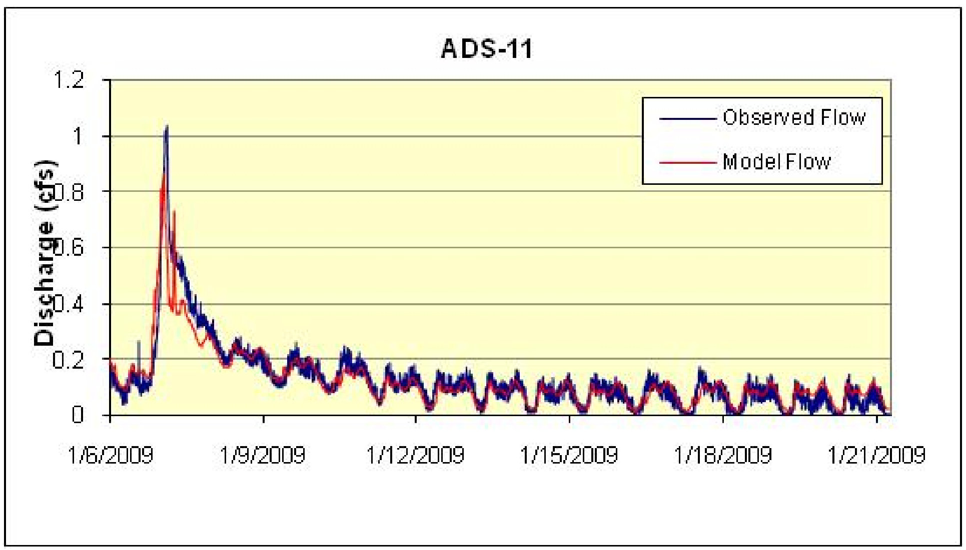

ADS-6
Observed Flow
Model Flow
Discharge (cfs)
0
0.5
1
1.5
2
2.5
3
3.5
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009

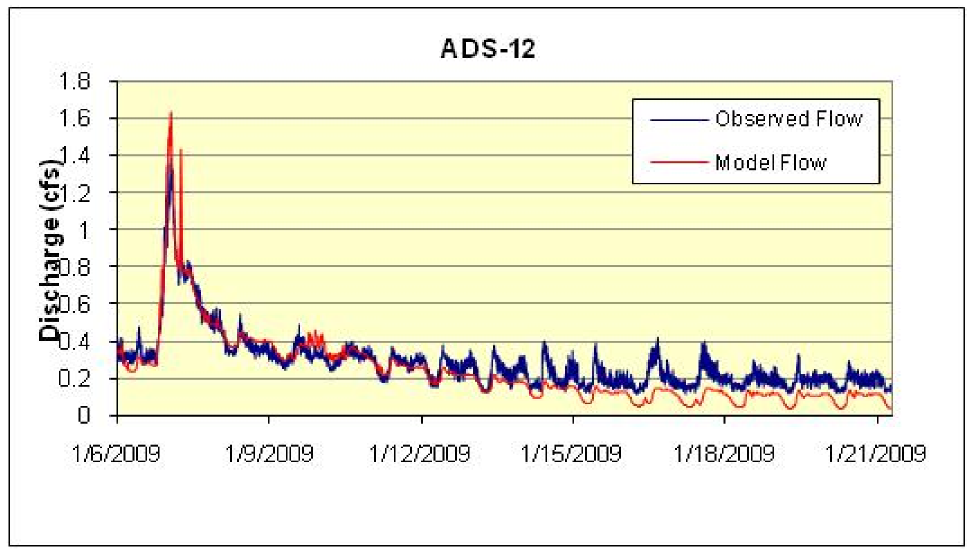

ADS-7
Observed Flow
Model Flow
Discharge (cfs)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009


ADS-8
Observed Flow
Model Flow
Discharge (cfs)
0
0.5
1
1.5
2
2.5
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009


ADS-9
Observed Flow
Model Flow
Discharge (cfs)
2.5
2
1.5
1
0.5
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009


ADS-10
Observed Flow
Model Flow
Discharge (cfs)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009


ADS-11
Observed Flow
Model Flow
Discharge (cfs)
1.2
1
0.8
0.6
0.4
0.2
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009


ADS-12
Observed Flow
Model Flow
Discharge (cfs)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1/6/2009
1/9/2009
1/12/2009
1/15/2009
1/18/2009
1/21/2009

APPENDIX D

Error Summary

Table D-1. Summary of flow routing continuity error in models for existing conditions and alternatives analysis

Alternative	Event	Flow Routing Continuity Error	Elements with Continuity Error > 1%
Existing Conditions	2-year	0.036%	
	25-year	0.026%	
	100-year	0.027%	Node 224-188 (1.02%)
Alternative 1	2-year	0.036%	
	25-year	0.026%	
	100-year	0.028%	Node 224-188 (1.02%)
Alternative 2-1	2-year	0.036%	
	25-year	0.026%	
	100-year	0.028%	Node 224-188 (1.02%)
Alternative 2-2	2-year	0.036%	
	25-year	0.026%	
	100-year	0.028%	Node 224-188 (1.01%)
Alternative 2-3	2-year	0.037%	
	25-year	0.032%	
	100-year	0.032%	Node 224-188 (1.11%)
Alternative 3-1	2-year	0.037%	
	25-year	0.031%	
	100-year	0.030%	
Alternative 3-2	2-year	0.039%	
	25-year	0.033%	
	100-year	0.034%	Node 224-188 (1.08%)
Alternative 3-3	2-year	0.042%	Node 224-371 (1.00%)
	25-year	0.037%	
	100-year	0.041%	