Delaware County Regional Water Quality Control Authority
CSO Long Term Control Plan Update

Sewer System Hydrologic and Hydraulic Model Report

June 2017

GREELEY AND HANSEN

REPORT SIGNATURE COVER SHEET

Signature of this cover signifies agreement with the content of the DELCORA Sewer System Hydrologic and Hydraulic Model Report.

I certify under penalty of law that the document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gathered and evaluated the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

DELCORA MANAGEMENT		
Executive Director	Robert J. Willert *Signature*	6/27/17 *Date*
DELCORA ENGINEERING		
Director of Engineering	Edwin Bothwell *Signature*	6/27/17 *Date*
DELCORA OPERATIONS AND MAINTENANCE		
Director of Operation and Maintenance	[illegible] *Signature*	6/27/17 *Date*

REVISION CONTROL

REV. NO.	DATE ISSUED	PREPARED BY	DESCRIPTION OF CHANGES

Table of Contents

Table of Contents

List of Tables

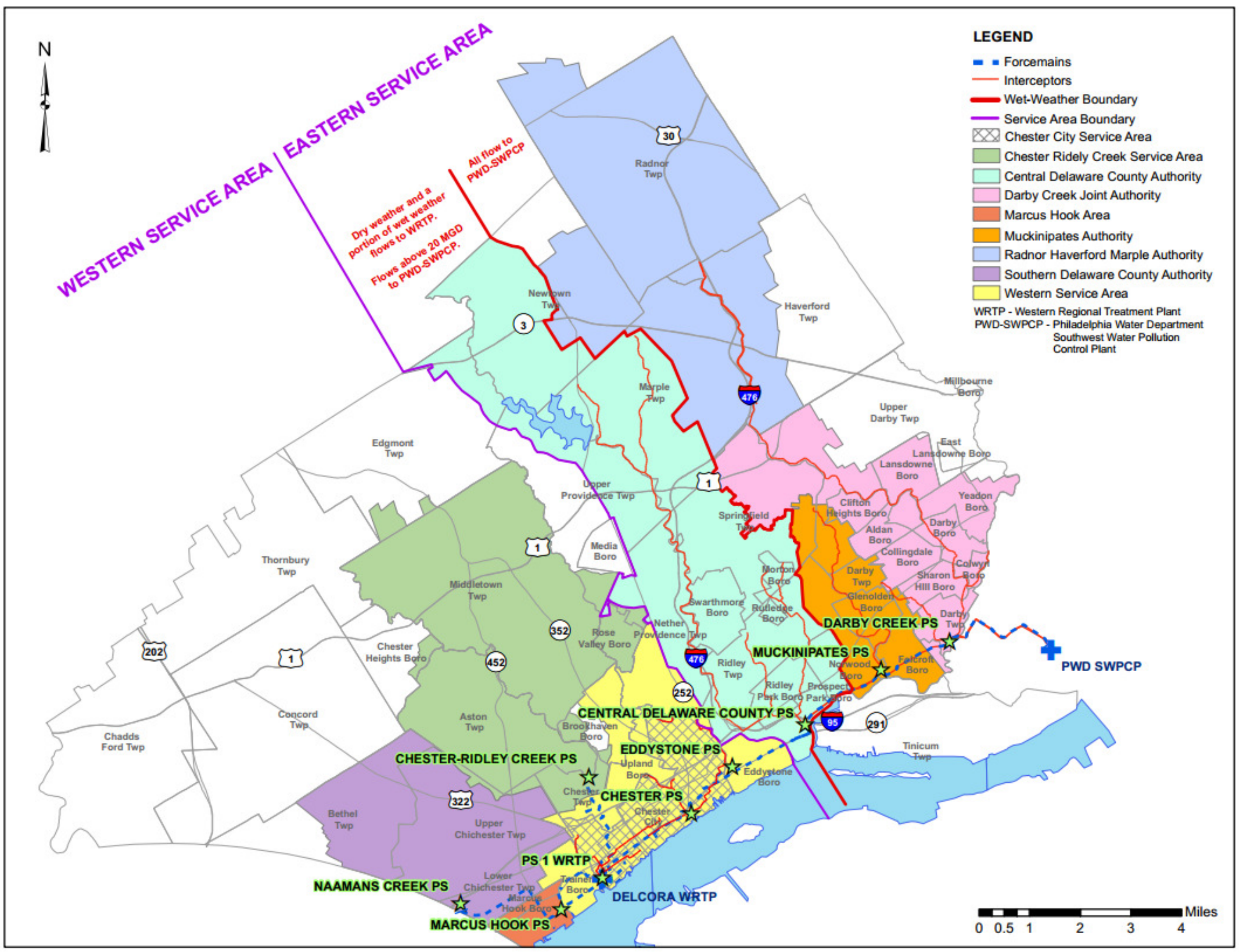
Table of Contents

List of Figures

Section 1 Introduction

1.1 DELCORA's Service Area

Delaware County Regional Water Quality Control Authority (DELCORA) is responsible for the safe collection, transmission, treatment and disposal of approximately 65 million gallons per day (MGD) of wastewater generated in southeastern Pennsylvania. DELCORA's facilities serve residential, commercial, institutional, and industrial customers in Delaware County. DELCORA owns and operates an extensive system of pump stations, force mains, and sewers that provide the core infrastructure for the transmission of wastewater to treatment facilities in Delaware County and the City of Philadelphia as shown diagrammatically in Figure 1-1. The interconnectivity coupled with the legal agreements that DELCORA maintains with the municipalities and conveyance authorities in Delaware County creates the complicated legal/financial framework under which DELCORA operates. The total service area served by DELCORA is approximately 82,977 acres, as shown on Figure 1-2: DELCORA'S Service Area



, which illustrates that DELCORA serves a significant and widespread portion of Delaware County. To support the service area, DELCORA owns and operates over 129 miles of separate and combined sewers. Included in the 129 miles of sewers are: 11.7 miles of an interceptor system; 3,209 manholes; and twenty-five (25) combined sewer outfall regulators controlling storm overflows. The combined sewer area simulated in the model, also shown in Figure 1-2, is located within the Chester City. It comprises approximately 49% of the Chester City's serviced area.

DELCORA has characterized its service areas as "Eastern" and "Western." Historically, the Eastern service area discharged to the Philadelphia Water Department's Southwest Water Pollution Control Plant (PWD-SWPCP) while the Western Service Area discharged to DELCORA's Western Regional Treatment Plant (WRTP). In 2002, DELCORA completed the installation of a force main that connects the Eastern Service Area's Central Delaware Pump Station (CDPS) to the Chester Force Main. This connection allows DELCORA to send flow from the CDPS to the WRTP. Dry weather flow and a portion of the wet weather flow from the Central Delaware County Authority in the Eastern Service Area now discharges to the WRTP while only those CDPS flows above 20 MGD are to be directed to the PWD-SWPCP.

Eastern Service Area

The DELCORA Eastern Service Area is composed of four subareas that are served by conveyance authorities: Radnor Haverford Marple (RHM) Authority, Darby Creek Joint Authority (DCJA), Muckinipates Authority (MA), and Central Delaware County Authority (CDCA) and are delineated in Figure 1-2. Each of these authorities has a legal agreement with their member municipalities to dispose of their wastewater. In turn, DELCORA has legal agreements with each of the authorities, except RHM, to receive, treat, and dispose of the collected wastewater. RHM discharges to the DCJA. DELCORA owns and operates three large pump stations that serve DELCORA's Eastern service area; they are the Central Delaware Pump Station, the Muckinipates Pump Station, and the Darby Creek Pump Station. These pump stations were originally designed to pump the wastewater from DELCORA's Eastern Service Area to PWD-SWPCP for treatment.

The Central Delaware Pump Station (serving CDCA) is rated for 40 MGD. It was constructed in the 1970s to discharge all flow through a force main that is routed northeast toward the Muckinipates Pump Station. The operation of the pump station had been modified in 2002 to allow for flow from the CDPS to be discharged to the WRTP. Currently the wastewater flows above 20 MGD are conveyed to PWD-SWPCP. The next pump station is the 24-MGD Muckinipates Pump Station (serving MA). Here, the force main increases to 48 inches in diameter and continues approximately 1.65 miles northeast to the Darby Creek Pump Station. Upon reaching the 60-MGD Darby Creek Pump Station (serving DCJA and RHM), the force main increases in diameter to 66 inches and continues approximately 2.5 miles for ultimate discharge at PWD-SWPCP.

Under National Pollutant Discharge Elimination System (NPDES) Permit No. PA0027103, issued and administered by the Pennsylvania Department of Environmental Protection (PADEP), DELCORA is authorized to discharge from the Western Regional Treatment Plant (Outfall 001), four storm water outfalls at the WRTP (028-031) and from 26 combined sewer overflow (CSO) outfalls (002-026, 032, 033) that ultimately discharge to the Delaware River, Chester Creek and/or Ridley Creek.

There are a total of 26 combined sewer overflow (CSO) outfalls listed with 25 discharge points (Outfalls 009 and 010 both discharge at Outfall 009) in DELCORA's existing NPDES Permit.

1.2 DELCORA's Consent Decree

DELCORA prepared and submitted their original Combined Sewer Overflow (CSO) Long Term Control Plan (LTCP) to the PADEP in 1999. This LTCP was subsequently approved by the PADEP, and DELCORA had started to implement the CSO control elements selected in the LTCP. In 2009, the United States Environmental Protection Agency (USEPA) informed DELCORA that the original LTCP was not in compliance with the requirements of the USEPA's CSO Policy. As such, DELCORA prepared and submitted a revised LTCP in April 2012. Subsequent to the receipt of the revised LTCP, DELCORA and the USEPA had corresponded various times including requests for additional information from the USEPA in accordance with Section 308 of the Clean Water Act. A Consent Decree was issued by the USEPA to DELCORA in June 2015. A Consent Decree was ultimately executed between DELCORA, the Pennsylvania Department of Environmental Protection (PADEP) and USEPA, was lodged on August 17, 2015 and was approved by the Federal District Court on November 10, 2015. The final Consent Decree requires that a new LTCP be prepared based on a 42-month schedule from the date of lodging (August 17, 2015), which includes interim deliverables and milestones that must be met.

DELCORA's original Hydrologic and Hydraulic Model (H&H Model) was updated to meet the requirements in Section V.A.14.a-f of the Consent Decree. These requirements along with a description of submissions made to comply with these requirements appear in Table 1-1.

Figure 1-1: DELCORA's Conveyance System

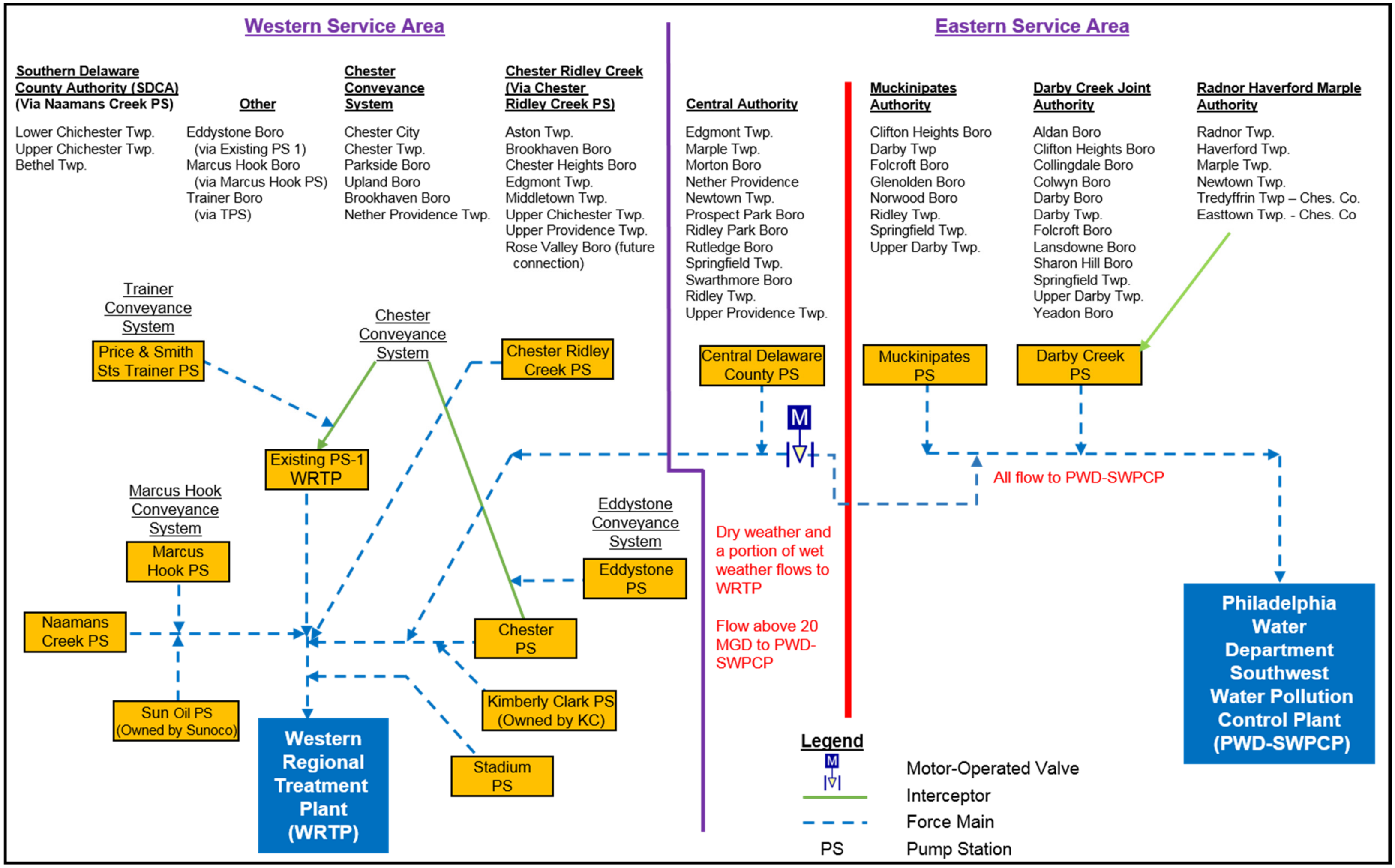


Figure 1-2: DELCORA'S Service Area

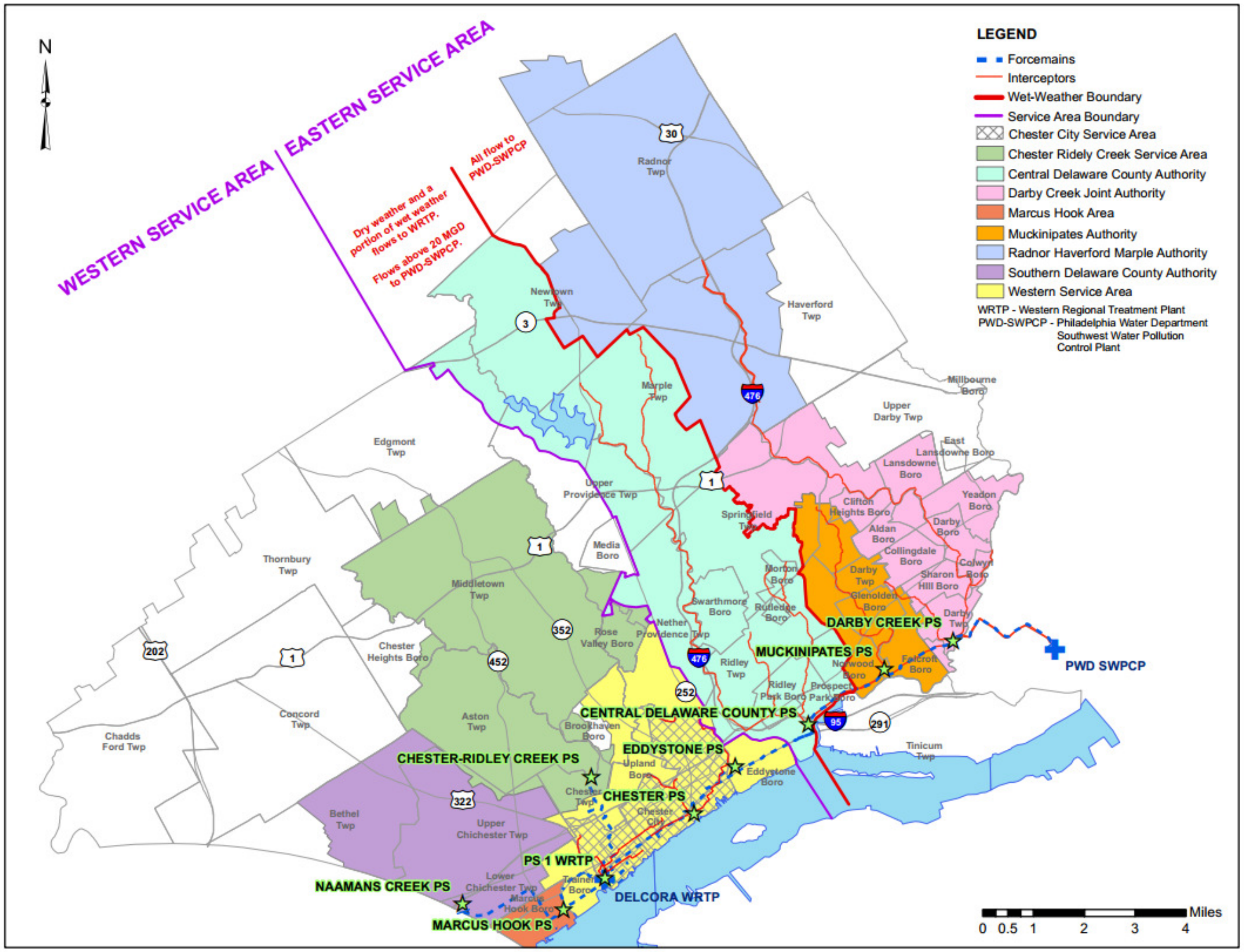


Table 1-1: Summary of Consent Decree Section V.A.14

Consent Decree Requirement	Submission Addressing Consent Decree Requirement
§V.A.14.a *a. Not later than sixty (60) Days after the Date of Lodging of this Consent Decree, DELCORA shall submit a detailed plan to update, calibrate, and validate the H&H Model to Plaintiffs for review and approval pursuant to Section VI (Review and Approval of Submittals). The plan shall address:* *(i) Model Update Methodology.* *(ii) Hydrologic and Hydraulic Model Refinement.* *(iii) Flow Data Assessment, and additional Rainfall and Flow Monitoring to be Carried Out.* *(iv) Dry Weather Flow Calibration, including quantitative and qualitative calibration criteria.* *(v) Wet Weather Flow Calibration, including quantitative and qualitative calibration criteria.* *(vi) Model Validation; and* *(vii) Schedule for model development and implementation, including integration into LTCP development consistent with other dates required pursuant to this Consent Decree.",*	Addressed through submission of the *Hydrologic and Hydraulic Model Update and Calibration Plan* (Greeley and Hansen, 2015) submitted on October 15, 2015 USEPA approved the plan on March 1, 2016. Schedule revised on July 28, 2016. Revised schedule can be found in Appendix A.
§V.A.14.b *b. The updated H&H Model shall specifically include hydrologic representation of all areas tributary to the entire Collection System, as well as all areas tributary to all municipal wastewater collection and transmission systems that are, as of the date the LTCP is submitted, hydraulically connected to, or that directly or indirectly influence flow to, the CSOs and/or the WRTP, regardless of who owns or operates the system(s), including but not limited to the entire "Western Service Area" and "Eastern Service Area" depicted on Figure 1-2 of the Long-Term Control Plan submitted by DELCORA in April 2012, and attached as Appendix A hereto (collectively, the "Model Area")."*	

Consent Decree Requirement	Submission Addressing Consent Decree Requirement
§V.A.14.c *c. The H&H Model shall accurately represent the response of the Model Area to wet weather events, including the flows that result from wet weather events to and from DELCORA's CSOs and to the WRTP. To accomplish this, the model shall explicitly include all interceptors, diversion structures, CSOs, pump stations and major trunk sewers within the Collection System, as well as such pipes and appurtenances within the areas outside the Collection System that are needed to ensure adequate H&H Model accuracy. The H&H Model shall also include all sewers required for model continuity and/or that hydraulically impact or are downstream of known chronic unpermitted releases. DELCORA shall investigate and collect current system attribute information as necessary to update the H&H Model.",*	Revisions to H&H model characterization of the system described in Section 3 of this report. Calibration and verification of model described in Section 4 of this report.
§V.A.14.d *d. Rainfall and flow monitoring shall be carried out in accordance with current good industry practice for a period of at least twelve (12) months, in accordance with the schedule included in the approved plan. Rainfall data shall be obtained at a minimum effective density of 1 gauge/virtual radar-based gauge per square kilometer, for the entire Model Area. Flow monitoring shall be carried out using sufficient monitors to allow the accurate characterization of dry and wet weather flows from the entire Model Area, and the response of each CSO to wet weather flows.*	Rainfall and flow monitoring approach described in Section 2 of this report Rainfall and flow monitoring data described in prior quarterly reports (see below) Minimum effective density of 1 gauge/virtual radar based gauge per square km was obtained as described in Section 2 of this report.
§V.A.14.e *e. For all rainfall and flow monitoring carried out in support of efforts to update and calibrate the H&H Model, DELCORA shall prepare and submit to Plaintiffs for review and comment in accordance with the requirements of Section VI (Review and Approval of Submittals) quarterly technical memoranda documenting the results and quality of the rainfall and flow monitoring data.*	Addressed through submission of the *Rainfall and Flow Monitoring Quarterly reports.* 1st Quarter: August 08, 2016 2nd Quarter: November 01, 2016 3rd Quarter: February 01, 2017 4th Quarter: May 01, 2017

Consent Decree Requirement	Submission Addressing Consent Decree Requirement
§V.A.14.f *Within 30 Days after the H&H Model is revised, calibrated, and validated in accordance with the schedule set forth in the plan, DELCORA shall submit a Sewer System H&H Model Report to Plaintiffs for review and approval in accordance with the requirements of Section VI (Review and Approval of Submittals). The Sewer System H&H Model Report shall specifically address each item set forth in Subparagraphs 14(a)(i)-(vii) hereof."*	Addressed through submission of the *Sewer System H&H Model Report.*

In order to comply with Sections V.A.14.d.and e of the Consent Decree, the 12-month rainfall and flow monitoring period was completed on March 31, 2017 and quarterly rainfall and flow monitoring memoranda were submitted.

The outstanding requirements described in Sections V.A.14b, c and f will be addressed in this Sewer System H&H Model Report (hereinafter referred to as Report). This Report will evaluate the Model Area comprising those areas hydraulically connected to the WRTP. Section V.A.14.b of the Consent Decree describes the Model Area as follows:

> *"b. The updated H&H Model shall specifically include hydrologic representation of all areas tributary to the entire Collection System, as well as all areas tributary to all municipal wastewater collection and transmission systems that are, as of the date the LTCP is submitted, hydraulically connected to, or that directly or indirectly influence flow to, the CSOs and/or the WRTP, regardless of who owns or operates the system(s), including but not limited to the entire "Western Service Area" and "Eastern Service Area" depicted on Figure 1-2 of the Long-Term Control Plan submitted by DELCORA in April 2012, and attached as Appendix A hereto (collectively, the "Model Area")."*

As shown in the schematic of DELCORA's conveyance system (see Figure 1-1), the conveyance system is divided into the Western Service Area and the Eastern Service Area. The Western Service Area discharges to DELCORA's WRTP and is therefore included in the Model Area. The Eastern Service Area is served by three pumps stations: the Central Delaware Pump Station, the Muckinipates Pump Station and the Darby Creek Pump Station. Up to 20 MGD (which includes both dry and wet weather flows) from the Central Delaware Pump Station can be pumped to, and thus is hydraulically connected to, DELCORA's WRTP. Therefore, municipalities connected to the Central Delaware Pump Station are considered part of the Model Area. Sewage from the Muckinipates Pump Station and the Darby Creek Pump Station flows to the PWD-SWPCP and cannot pump flow to the WRTP. Therefore, municipalities connected to these pump stations are not hydraulically connected to the WRTP and do not directly or indirectly influence CSOs or flow to the WRTP, and, therefore, are not considered part of the Model Area. In summary, the Model Area includes the municipalities in the Western Service Area plus those municipalities that are connected to the Central Delaware Pump Station, as described in Table 1-2.

Table 1-2: Model Area

Municipality ID No.	Municipality	Service Area
1	Aston Township	Western
2	Bethel Township	Western
3	Brookhaven Borough	Western
4	Chester City	Western
5	Chester Township	Western
6	Eddystone Borough	Western
7	Edgmont Township	Eastern
8	Lower Chichester Township	Western
9	Marcus Hook Borough	Western
10	Marple	Eastern
11	Middletown Township	Western
12	Morton	Eastern
13	Nether Providence*	Eastern and Western
14	Newtown Township	Eastern
15	Parkside Borough	Western
16	Prospect Park	Eastern
17	Ridley Park Borough	Eastern
18	Ridley Township	Eastern
19	Rose Valley Borough	Western
20	Rutledge	Eastern
21	Springfield	Eastern
22	Swarthmore	Eastern
23	Trainer Borough	Western
24	Upland Borough	Western
25	Upper Chichester Township	Western
26	Upper Providence Township	Eastern and Western

As outlined in the *Hydrologic and Hydraulic Model Update and Calibration Plan* (Greeley and Hansen, 2015) and in conformance with Section V.A.14.c, the original H&H model was evaluated and updated as necessary to ensure inclusion of necessary components of the collection and conveyance system.

In addition, this Report includes results of the gauge-adjusted rainfall analysis (GARR) to demonstrate compliance with the requirement of Sections V.A.14.d that "*…Rainfall data shall be obtained at a minimum effective density of 1 gauge/virtual radar-based gauge per square kilometer, for the entire Model Area.*"

1.3 Contents in This Report

This report was prepared based on the requirements listed in the Consent Decree. The purpose of this document is to describe the development, calibration and validation of the updated sewer collection system H&H model. The 2012 H&H model was expanded to the Model Area and updated as needed to reflect current hydrologic and hydraulic conditions of DELCORA's collection system. After updating, the revised model was calibrated and validated with the additional rainfall and flow monitoring data so it can then be used to assist the Delaware County Regional Water Authority (DELCORA) throughout its combined sewer overflow (CSO) long-term control plan (LTCP) update process. Table 1-3 lists individual sections of this Report and their contents.

Table 1-3: DELCORA Sewer System H&H Model Report

Section	Description
Section 1 Introduction	Section 1 introduces DELCORA's system, Consent Decree requirements and the purpose of this report.
Section 2 Rainfall and Flow Monitoring	Section 2 provides an overview of the rain gauge and flow monitoring program and data analysis process for model input.
Section 3 DELCORA H&H Model Update	Section 3 summarizes the review of the original H&H model, describes general methodology used in the model update, and details the model updates made to the service area delineation, combined and separated area delineation, model network extension, regulator, and model inputs.
Section 4 DELCORA H&H Model Calibration and Validation	Section 4 provides a description of calibration and validation, lists criteria for dry weather and wet weather calibration, and illustrates calibration and validation method and results.
Section 5 Conclusion	Section 5 provides a short summary of the H&H Model Update, including model calibration results.

Section 2 Rainfall and Flow Monitoring

As per the Consent Decree, DELCORA was required to perform a Rainfall and Flow Monitoring program for at least 12 months and submit quarterly reports to document the findings of the program. This program started on March 18, 2016 and was completed on April 4, 2017. The rainfall and flow monitoring data were collected on a monthly basis. This section will discuss the network of rainfall and flow monitoring instrumentation, outline the monitoring program, and describe how the data collected for the Rainfall and Flow Monitoring Program was analyzed for use in the H&H Model calibration and validation.

2.1 Rainfall Monitoring and Analysis

A total of six (6) rain gauges were used for the monitoring program. As shown in Figure 2-1, the gauges are stationed at the following locations:

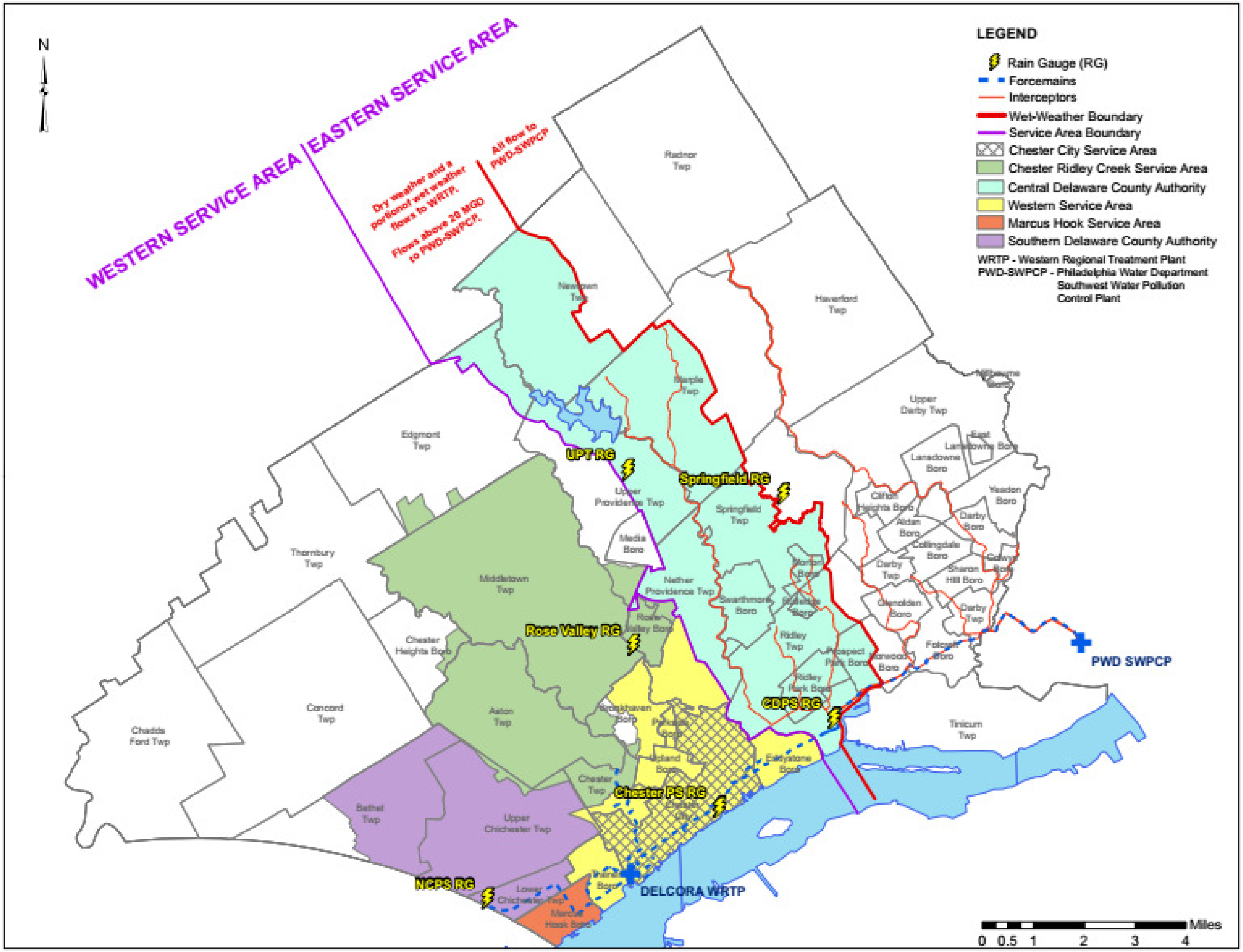
- Rose Valley
- Chester Pump Station (CPS)
- Naaman's Creek Pump Station (NCPS)
- Springfield
- Upper Providence Township (UPT)
- Central Delaware County Pump Station (CDPS)

Five out of six of the gauges provided data at 5 minute intervals. One rain gauge provided data on 15-minute intervals. According to the Consent Decree, rainfall data to be used for calibration and validation of the model *"…shall be obtained at a minimum effective density of 1 gauge/virtual radar-based gauge per kilometer"*. In order to achieve this density, Gauge-Adjusted Radar Rainfall (GARR) was employed. The rain gauges used to complete the flow monitoring program and choose the wet weather events used in calibration and validation were also used in the GARR analysis which provided effective spatial coverage of the entire Model Area. The gauge rainfall data from the six rain gauges installed throughout the DELCORA service area was analyzed and used to:

- Document rainfall and flow monitoring locations,
- Overview flow monitoring data quality,
- Analyze rainfall data to identify dry weather and wet weather conditions and to characterize individual rainfall event for precipitation depth, duration, maximum intensity, and return frequency,
- Analyze flow data to determine dry weather flow and diurnal pattern, wet weather flow and peak factor, and system response to wet weather events, and
- Determine the wet weather events for H&H Model calibration and validation.

An inter-event time of 48 hours was used to identify individual rainfall events. The inter-event time specifies the minimum duration in which precipitation does not occur. Based on this criterion, a dry weather time period and the number of total rainfall events were identified. The rainfall events during the

Figure 2-1: Rain Gauge Locations



flow monitoring periods had a wide variation in terms of total depth, intensity, duration, and antecedent conditions to provide a large dataset for balanced model calibration and validation.

The rainfall events were characterized by event start time, event end time, rainfall depth, duration, maximum intensity, and return frequency. As an initial screening criterion, rainfall events with a minimum of 0.9 inches of rainfall were identified. Further screening based on requiring at least two dry days prior to the event resulted in an initial list of ten (10) candidate events for calibration and validation (see Table 2-1).

Table 2-1: Top 10 Rainfall Events

Event	Event Start	Event End	Chester-PS Rainfall (in)	Duration (hr)	Max Intensity (in/hr)
E1	5/29/16 19:00	5/30/16 5:00	1.82	11.00	0.78
E2	9/28/16 12:00	9/30/16 10:00	2.36	47.00	0.37
E3	11/29/16 7:00	11/29/16 20:00	1.08	14.00	0.21
E4	3/30/17 21:00	4/1/17 3:00	1.83	31.00	0.25
E5	5/21/16 11:00	5/22/16 21:00	1.71	35.00	0.33
E6	7/28/16 15:00	7/29/16 9:00	1.26	19.00	0.74
E7	9/19/16 8:00	9/19/16 16:00	0.96	9.00	0.42
E8	3/13/16 18:00	3/14/16 14:00	1.08	21.00	0.25
E9	5/6/16 4:00	5/7/16 11:00	1.18	32.00	0.24
E10	10/8/16 14:00	10/9/16 11:00	1.00	22.00	0.15

2.2 Flow Monitoring

DELCORA owns and operates a flow monitoring network across the DELCORA Service Area. The monitoring network includes various types of flow meters located throughout DELCORA's Eastern Service Area and Western Service Area, at the WRTP, in each of the Pump Stations, and at the tie-in points where other municipal collection systems tie-into the collection system. Seven existing flow meters in the separated area (outside the CSO area), eight existing flow meters at pump stations and one existing flow meter at WRTP were used for the calibration and validation of the H&H Model. In addition, temporary flow meters were installed at 38 new locations to characterize surface runoff from the combined area and CSO discharges. The locations of flow meters installed specifically for the flow monitoring program and the H&H Model calibration and validation can be categorized into the following five categories:

1. Located on the influent pipe to CSO regulators, this is to measure the influent flow to CSO regulators and for combined area runoff calibration. Sixteen (16) meters were installed for this category.
2. Located on the effluent pipe and overflow pipe of CSO regulators, this is to measure the CSO overflows and calibrate CSO regulator parameters. Twelve (12) meters were installed for this category. They are on the effluent and overflow pipe of CSOs 02, 03, 05, 08, 14, & 19.
3. Located on the side-line from the combined areas (flows from the combined area tie into interceptor instead of CSO regulator). This is to measure flows from the combined area and to calibrate combined area runoff parameters. Two (2) meters were installed for this category.

4. Located upstream of the combined area, this is to measure flows from the upstream separated area for RDII characterization. Three (3) meters were installed for this category.
5. Located in the main interceptors to measure level and flows in the major interceptors. Five (5) meters were installed for this category.

Table 2-2 lists the flow meter locations and location categories of the meters. Figures 2-2 and 2-3 show the locations of the flow meters that were used for H&H Model calibration and validation. After initial installation of the new temporary flow meters, difficulties were encountered at Manhole MH3029. The site was severely surcharged during field investigation. Meanwhile it was found that at Manhole MH3002 (four manholes upstream of MH3029, approximately 800 feet upstream) another existing flow meter (Ridley Creek MH-28) was already installed for DELCORA. Instead of installing a new temporary flow meter around the site, the existing meter Ridley Creek MH-28 was used for the flow monitoring program. Data was gathered from a total of 55 flow meters, 38 of which were newly installed as part of the flow monitoring program.

The network of flowmeters can be grouped to define metersheds where flow from a given area discharges through a common flowmeter. Subcatchments associated with each metershed are shown in Table 2-3 along with the associated metershed acreage. Rainfall and flow data gathered for each metershed will be used to calibrate the associated subcatchments in the H&H Model.

2.3 Dry Weather Flow (DWF) Analysis

A “dry weather” condition was defined as a period with no precipitation that begins 48 hours after the last wet weather event and lasts until the beginning of the next precipitation event. Dry weather flow periods based on this definition are illustrated in the hydrograph shown in Figure 2-4**.**

Average dry weather flow was calculated by averaging the monitored flows from the dry weather periods identified in the rainfall data analysis. The overall and monthly DWFs for all monitoring sites were analyzed and used as inputs in the H&H Model.

Table 2-2: Flow Monitoring Locations

Flow Meter	Approximate Location	Category
In-02	Influent pipe to CSO 02 Regulator	On the influent pipe to regulator
In-03	Influent pipe to CSO 03 Regulator	On the influent pipe to regulator
In-05	Influent pipe to CSO 05 Regulator	On the influent pipe to regulator
In-08	Influent pipe to CSO 08 Regulator	On the influent pipe to regulator
In-09	Influent pipe to CSO 09 Regulator	On the influent pipe to regulator
In-10	Influent pipe to CSO 10 Regulator	On the influent pipe to regulator
In-11	Influent pipe to CSO 11 Regulator	On the influent pipe to regulator
In-13	Influent pipe to CSO 13 Regulator	On the influent pipe to regulator
In-14	Influent pipe to CSO 14 Regulator	On the influent pipe to regulator
In-16	Influent pipe to CSO 16 Regulator	On the influent pipe to regulator
In-17	Influent pipe to CSO 17 Regulator	On the influent pipe to regulator
In-18	Influent pipe to CSO 18 Regulator	On the influent pipe to regulator
In-19-1	Influent pipe to CSO 19 Regulator (from East)	On the influent pipe to regulator
In-19-2	Influent pipe to CSO 19 Regulator (from West)	On the influent pipe to regulator
In-25	Influent pipe to CSO 25 Regulator	On the influent pipe to regulator
In-26	Influent pipe to CSO 26 Regulator	On the influent pipe to regulator
INT- 2nd St	2nd Street Interceptor	On the interceptor pipe
INT-DRI	Delaware River Interceptor	On the interceptor pipe
INT-Ridley 2	Ridley Creek Interceptor	On the interceptor pipe
INT-Ridley 3	Ridley Creek Interceptor	On the interceptor pipe
INT-West End	West End Interceptor	On the interceptor pipe
Side-1	Side line on Penn St. to 2nd St. Interceptor	On the side-line from the combined area
Side-2	Side line on Highland Ave. to West End Interceptor	On the side-line from the combined area
Sep-1	Upstream of the CSO 02 Drainage	On the separated area
Sep-2	Upstream of the CSO 05 Drainage	On the separated area
Sep-3	Upstream from Upland Borough	On the separated area
Sep-4 (Existing MH-28 after first quarterly report)	Upstream from Eastern Chester	On the separated area
CSO-02	Outfall pipe from CSO 02 Regulator	On the outfall pipe
CSO-03	Outfall pipe from CSO 03 Regulator	On the outfall pipe
CSO-05	Outfall pipe from CSO 05 Regulator	On the outfall pipe

Flow Meter	Approximate Location	Category
CSO-08	Outfall pipe from CSO 08 Regulator	On the outfall pipe
CSO-14	Outfall pipe from CSO 14 Regulator	On the outfall pipe
CSO-19	Outfall pipe from CSO 19 Regulator	On the outfall pipe
Eff-02	Effluent pipe for CSO-02 Regulator	On the effluent pipe
Eff-03	Effluent pipe for CSO-03 Regulator	On the effluent pipe
Eff-05	Effluent pipe for CSO-05 Regulator	On the effluent pipe
Eff-08	Effluent pipe for CSO-08 Regulator	On the effluent pipe
Eff-14	Effluent pipe for CSO-14 Regulator	On the effluent pipe
Eff-19	Effluent pipe for CSO-19 Regulator	On the effluent pipe
BR MH-1 (Existing)	Upstream from Brookhaven MH-1	On the separated area
BR MH-3 (Existing)	Downstream from Brookhaven MH-3	On the separated area
BR MH-5 (Existing)	Downstream from Brookhaven MH-5	On the separated area
BR MH-6 (Existing)	Downstream from Brookhaven MH-6	On the separated area
RC MH-26 (Existing)	Ridley Creek Interceptor	On the interceptor pipe
RC MH-30 (Existing)	Ridley Creek Interceptor	On the interceptor pipe
RC MH-32 (Existing)	Ridley Creek Interceptor	On the interceptor pipe
WRTP (Existing)	At WRTP	At WRTP

Figure 2-2: DELCORA Flow Meters

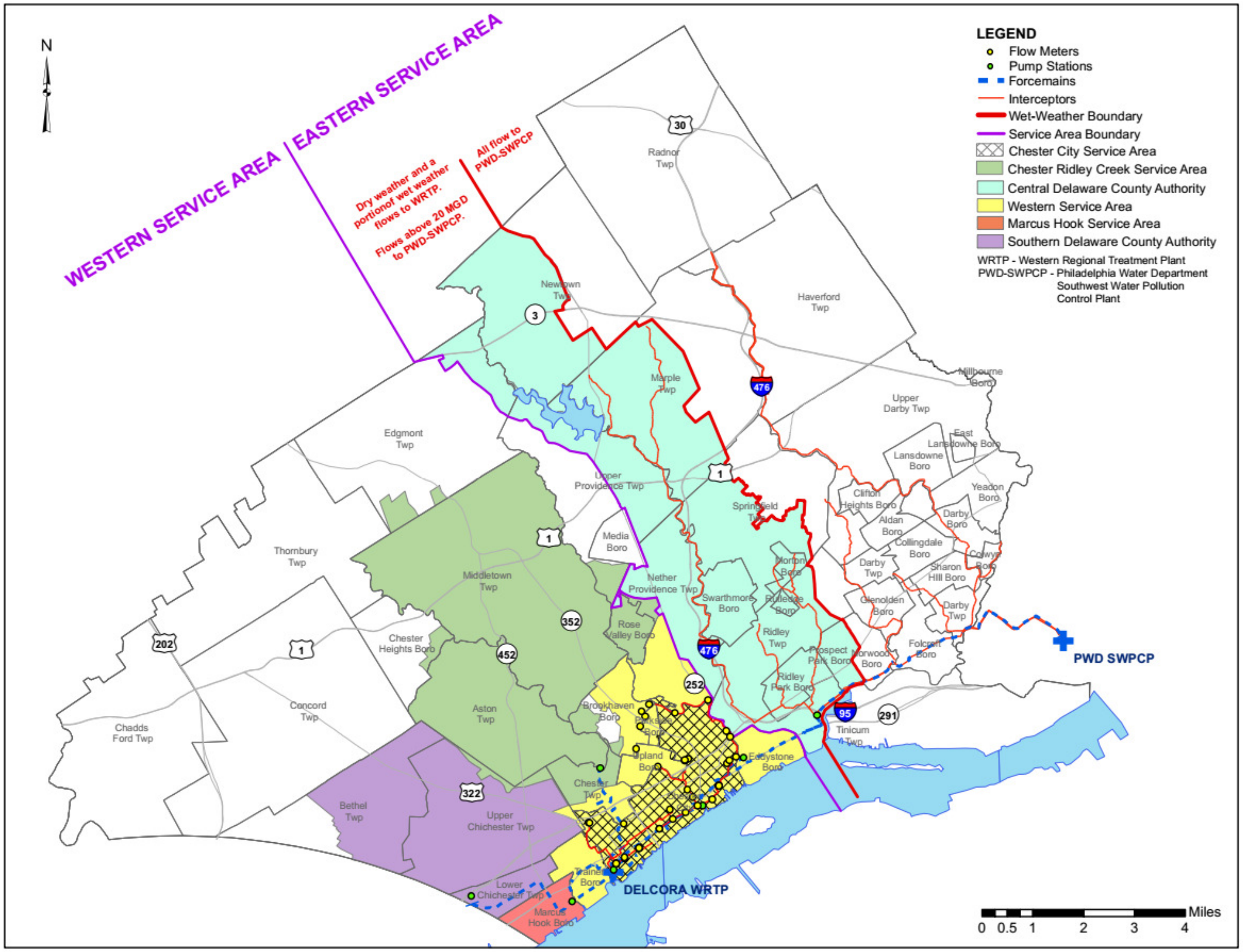


Figure 2-3: Enlarged Map of Flow Meters

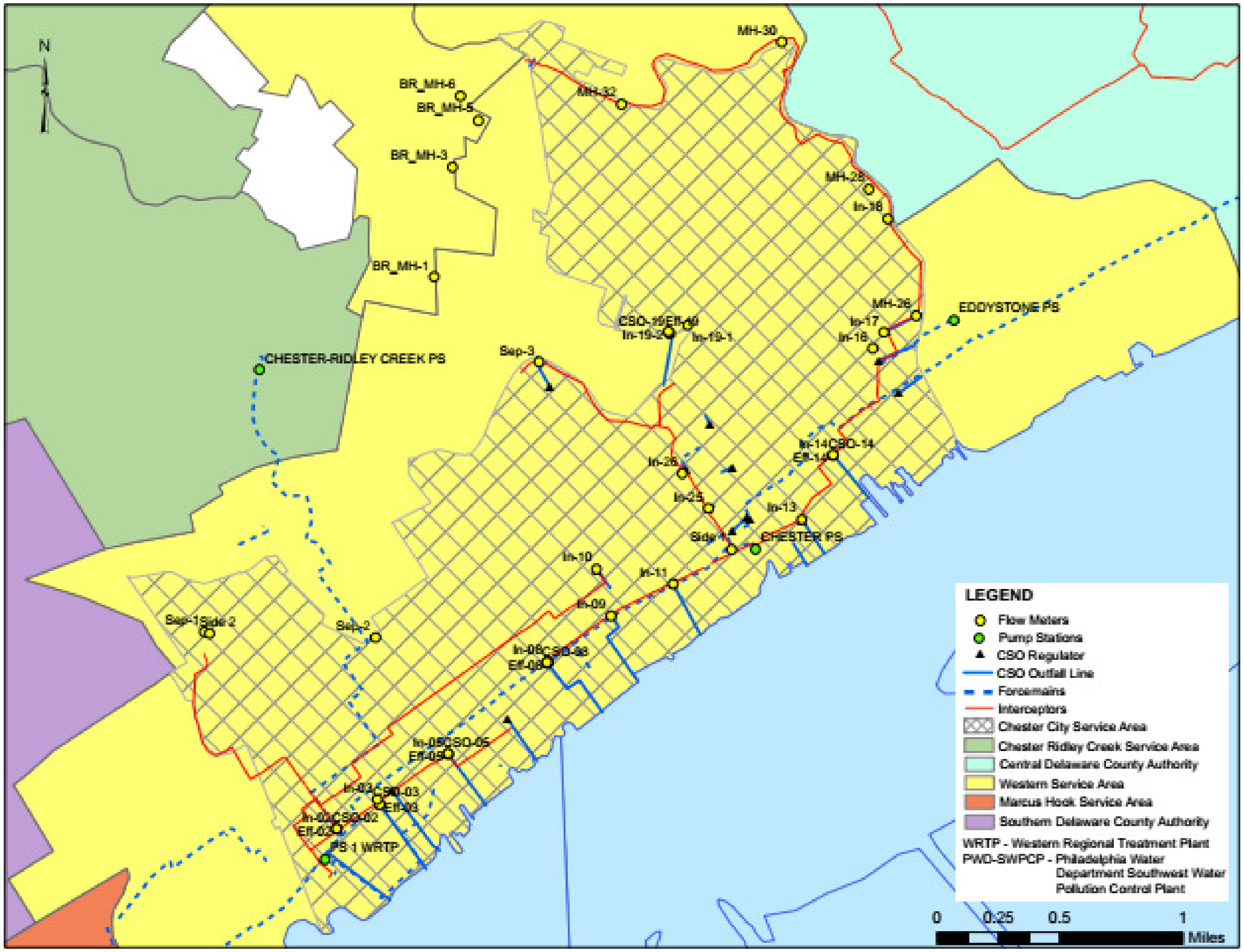


Table 2-3: Metersheds in the H&H Model

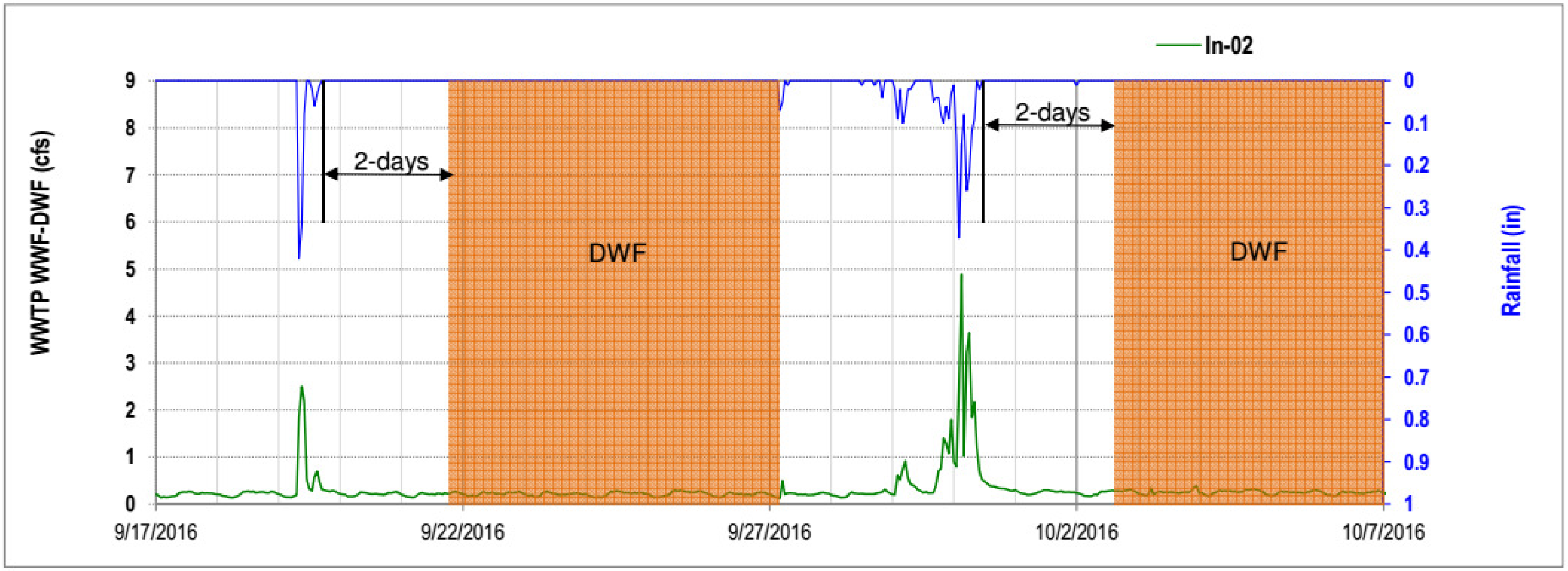
Metershed ID	Subcatchment ID	Metershed Area (ac)
BR_MH-1	BR_TWP_2	48.52
BR_MH-3	BR_TWP_3	236.08
BR_MH-5	BR_TWP_4	21.13
BR_MH-6	BR_TWP_5	43.55
In-02	02A	107.36
	02B	
	SC1	
In-03	03B	87.37
	03C	
	03D	
In-05	05C	160.31
	05D	
	CH_TWP_2	
In-08	08A	236.44
	08B	
	CH_CTY_12	
In-09	09A	27.02
In-10	10A	59.93
In-11	11A	43.54
In-13	13A	50.43
	13C	
In-14	14A	52.99
	14B	
	14C	
In-16	16A	2.18
In-16,In-17	16/17A	77.41
	16/17B	
In-17	17A	11.83
In-18	18A	29.71
	18B	

Metershed ID	Subcatchment ID	Metershed Area (ac)
In-19-1	18C	320.84
	CH_CTY_08	
	19B	
	19D	
	PA_BORO_1	
In-19-2	19E	94.48
	19G	
In-25	25A	11.84
In-26	26A	37.1
INT-2nd St	24A	6.24
INT-DRI	04A	57.01
	04B	
	07A	
	07B	
INT-Ridley 2	15A	9.72
	31A	
	RC1	
INT-Ridley 3	21A	51.8
	22A	
	23A	
	12A	
INT-West End	DR1A	25.69
	DR1C	
	CH_CTY_10	
MH-26	CH_CTY_07	46.62
MH-28 (Sep-4)	CH_CTY_04	135.72
MH-30	CH_CTY_06	1023.46
	NP_TWP_2	
MH-32	PA_BORO_2	523.12
	33A	
	BR_TWP_6	
	CH_CTY_05	

Metershed ID	Subcatchment ID	Metershed Area (ac)
Central PS (PS-1)	CH_CTY_02	502.62
	CH_CTY_03	
Eddystone PS (PS-10)	EDD_BORO_1	652.4
Marcus Hook PS (PS-11)	LC_TWP_1	1393.13
	MH_BORO_1	
Naamans Creek PS (PS-15)	BE_TWP_1	6503.31
	UC_TWP_1	
Chester Ridley Creek PS (PS-24*)	EDG_TWP_2	14369.97
	MI_TWP_1	
	NP_TWP_3	
	RV_BORO_1	
	UPR_TWP_2	
	AS_TWP_1	
	BR_TWP_7	
	CH_BORO_1	
	CH_TWP_4	
	UC_TWP_3	
Existing PS-1 (PS-3)	TR_BORO_1	987
	DR1B	
	CH_CTY_01	
Central Delaware PS Total and Central Delaware PS to WRTP (PS-7)	EDG_TWP_1	18644.24
	MA_TWP_1	
	MO_BORO_1	
	NE_TWP_1	
	NP_TWP_1	
	PR_BORO_1	
	RI_TWP_1	
	RP_BORO_1	
	RU_BORO_1	
	SP_TWP_1	
	SW_BORO_1	
	UPR_TWP_1	

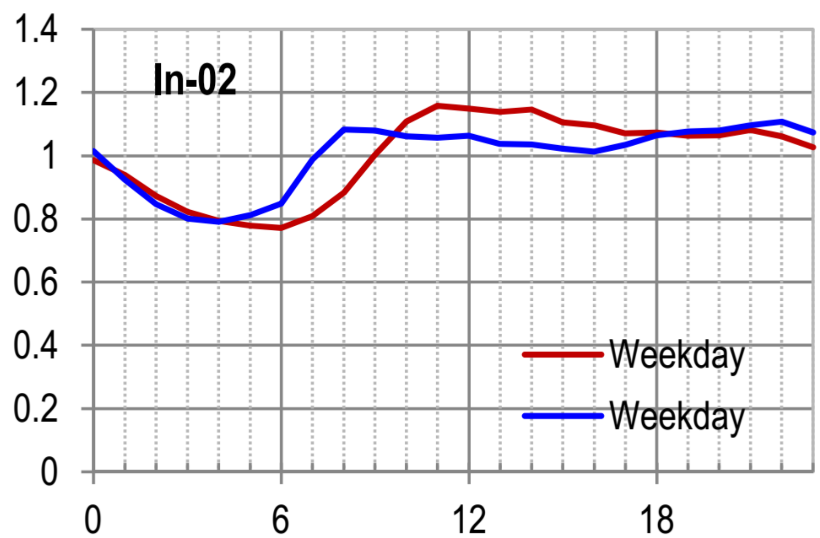
Metershed ID	Subcatchment ID	Metershed Area (ac)
Sep-1	CH_TWP_3	293.29
	UC_TWP_2	
Sep-2	CH_CTY_09	74.57
	CH_TWP_1	
Sep-3	BR_TWP_1	471.58
	CH_CTY_13	
	PA_BORO_3	
	UPL_BORO_1	
Side-1	20A	56.87
	CCE1	
	CCW1	
	CCW2	
	PS1	
	PS3	
	CH_CTY_11	
Side-2	BS3	31.75
	BS2	

Figure 2-4: Hydrograph to Show Dry Weather Flow



The dry weather flows vary throughout the day, with the highest flows normally occurring around noon and the lowest rates between midnight and early morning. Flow data from the dry weather periods were used to develop a flow diurnal pattern for each flow meter site. Diurnal patterns were analyzed for both weekdays and weekends. In the plot shown on Figure 2-5, the weekend DWF peak and valley have a 3-hour lag compared to the weekday pattern.

Figure 2-5: Weekday and Weekend Dry Weather Flow Diurnal Pattern (Example Plot)

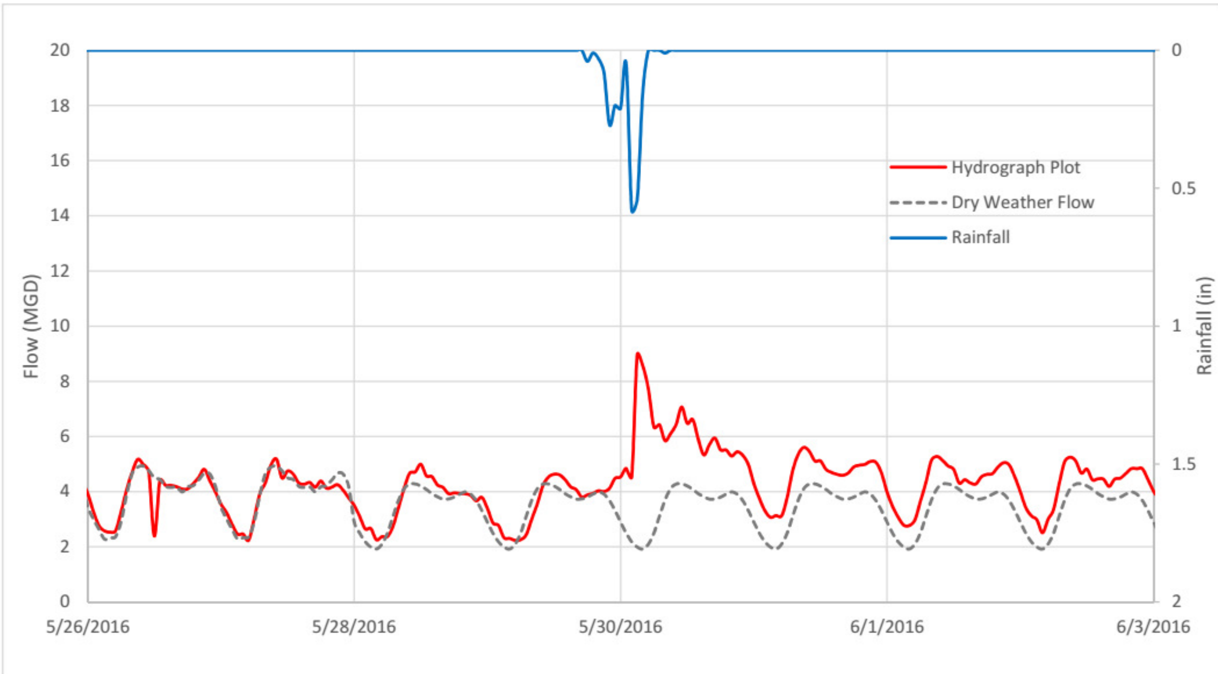


2.4 Wet Weather Flow Analysis

Wet weather flows are the combination of dry weather flows and additional flows that enter the system during wet weather conditions. The additional flows are from combined area surface runoff and RDII. Inflow normally occurs when rainfall enters the system through direct connections such as roof leaders, yard drains, catch basins, sump pumps, manhole covers and frame seals or indirect connections with storm sewers. Inflow is usually recognized graphically by large magnitude, short duration spikes immediately following a rain event. Infiltration occurs during wet weather conditions when water enters a sewer system from the ground through means which include, but not limited to, deteriorated pipes, pipe joints, connections, or manholes. It is significantly influenced by the size and duration of the rainfall event. Infiltration is often recognized graphically by a gradual increase in flow after a wet weather event. The increased flow typically sustains for a short period after rainfall has stopped and then gradually drops off.

The peaking factor represents the ratio of the peak wet weather flow to the average dry weather flow. Usually, an hourly peaking factor is used to represent the wet weather peaking factor. Peaking factors were analyzed for each flow monitoring site. The peaking factors in the separated area can be used to determine the extent of the RDII within a particular basin. Figure 2-6 is a flow hydrograph plot showing an hourly peaking factor of approximately 4.5 for the monitoring site. This high peaking factor indicates that a significant amount of RDII enters the collection system. The immediate flow increase shortly after the rainfall indicates significant inflow into the collection pipes, and the long tail back to the base flow indicates infiltration occurrence at the site as well.

Figure 2-6: Hydrographs of Flow Meters in Separated Area (Example Plot)



2.5 Wet Weather Event Selection for Model Calibration and Validation Flow Analysis

Based on the rainfall and flow monitoring data analysis, the rainfall events shown in Table 2-4 were selected for model calibration and validation. The events were selected to cover variations in terms of rainfall depth, intensity, duration and antecedent conditions. .

Table 2-4: Calibration and Validation Rainfall Events

Event	Start	End
E1	5/29/16 19:00	5/30/16 5:00
E2	9/28/16 12:00	9/30/16 10:00
E3	11/29/16 7:00	11/29/16 20:00
E5	5/21/16 11:00	5/22/16 21:00
E6	7/28/16 15:00	7/29/16 9:00

Section 3 DELCORA H&H Model Update

The original DELCORA H&H model was developed and calibrated for the 1999 LTCP. The model was updated and expanded over the years to account for changes in the CSO system, but it was not re-calibrated during the development of the 2012 LTCP (Weston, 2012). The project team reviewed the 2012 model in order to:

- Assess adequacy of the original model for use in DELCORA's LTCPU,
- Identify gaps with the original model in meeting the requirements in the Consent Decree,
- Identify updates required to reflect current hydrologic and hydraulic conditions of DELCORA's collection system, and
- Determine refinements needed for the model update.

Results from the review of the 2012 H&H Model were presented in the *Hydrologic and Hydraulic Model Update and Calibration Plan* (Greeley and Hansen, 2015). The purpose of this section of the Report is to describe the model update methodology and summarize the revisions incorporated into the updated model.

3.1 Model Update Methodology

3.1.1 Hydrologic Representation

Instead of including only the combined area for the subcatchments as in the original model, the updated model has subcatchments for both combined and separated service areas. All the areas that contribute dry weather flow and/or wet weather flow to DELCORA's CSOs and/or the WRTP were included in the service area for the model. Wet weather flows generated from surface runoff in the combined area and RDII in the separated areas were simulated in the updated model.

3.1.2 Hydraulic Representation

The 2012 H&H model included only the combined sewer system (CSS) area of DELCORA's collection system, which is located within the boundaries of the City of Chester. The CSS area is shown in Figure 3-1. The combined CSS area according to the original model is shown in in Figure 3-2. Per the requirements of the Consent Decree, the H&H model was updated to include the Model Area. Pipe networks in the updated model were extended to the updated service areas for both the combined and separated areas. All hydraulic structures that control flows in the collection system, including pump stations, regulator orifices and weirs, and their operating rules, were simulated in the updated model.

3.2 Model Refinement

A number of hydraulic modeling software packages are available, including EPA SWMM5, InfoSWMM, InfoWorks, Mike Urban and PCSWMM. For this H&H Model update, EPA SWMM, Version 5.0, Build 5.0.022 and Innovyze InfoSWMM Version 14.5 Update 4 were selected as the modeling software. EPA

SWMM5 is a fully dynamic model and has been used extensively throughout the United States and abroad to assess CSO, flooding and water quality issues. It can be applied to simulate single events or long periods of time in a continuous mode. InfoSWMM uses the current EPA SWMM 5 engine as its computational solution and is fully integrated with ArcGIS which provides greater flexibility of importing model network from existing GIS database and preparing initial model inputs from existing datasheets. InfoSWMM was used during the model development and the calibration phase.

The model update is based on information obtained from a variety of sources including DELCORA's input, GIS, record drawings and field survey. Other documents pertaining to standard/actual operating procedures for CSO regulators, pump stations and the WRTP were also used to set up real time controls in the model. The model network consists of all major interceptors and force mains and extends to all active overflow points. The datum for the model is NGVD 29.

3.2.1 Delineation of Model Area and Combined Area

DELCORA's latest GIS database, survey and record drawings were used to perform the desktop CSS delineation to verify the boundaries. The total acreage of the model area is approximately 50,000 acres and the updated combined sewer area is approximately 1,460 acres as of May 2017.

Metersheds were delineated for the purpose of dry weather flow allocation and model calibration. A metershed means the geographical area served by a system of sanitary drains, storm drains, private interceptor, main sewers, and public sewers that drain to a common monitoring point (flow meter location). Metershed delineation was performed based on the location of flow meter, sewer connectivity, and city contours. A listing of metersheds, their acreage and their associated subcatchments can be found in Table 2-3.

Sewersheds (subcatchment) are delineated based on the drainage network, area characteristics, and flow monitor locations. Each sewershed has a dry weather and a wet weather flow input to the model network. The model network comprises 111 sewersheds (subcatchments), including 54 combined and 57 separated subcatchments.

3.2.1.1 Delineation of Model Area

The updated H&H model will evaluate the Model Area comprising those areas hydraulically connected to the WRTP. As shown in the schematic of DELCORA's conveyance system (see Figure 1-1), the conveyance system is divided into the Western Service Area and the Eastern Service Area. The Western Service Area discharges to DELCORA's WRTP and is therefore included in the Model Area. The Eastern Service Area is served by three pumps stations: the Central Delaware Pump Station, the Muckinipates Pump Station and the Darby Creek Pump Station. Up to 20 MGD (which includes both dry and wet weather flows) from the Central Delaware Pump Station can be pumped to, and thus is hydraulically connected to, DELCORA's WRTP. Therefore, municipalities connected to the Central Delaware Pump Station are considered part of the Model Area. Sewage from the Muckinipates Pump Station and the Darby Creek Pump Station flows to the PWD-SWPCP rather than to the WRTP. Therefore, municipalities connected to these pump stations are not hydraulically connected to the WRTP and do not directly or indirectly influence CSOs or flow to the WRTP, and, therefore, are not considered part of the Model Area.

Eastern Service Area

Within the Eastern Service Area, only the municipalities in the Central Delaware County Authority contribute flows to the WRTP and are, therefore, only these municipalities are included in the Model Area. These municipalities include Marple Township, Morton Borough, Nether Providence Township, Newtown Township, Prospect Park Borough, Ridley Park Borough, Rutledge Borough, Springfield Township, Swarthmore Borough, Ridley Township, and Upper Providence Township. In October 2012, DELCORA signed an agreement with Edgmont Township to provide sewer service to the eastern portion of the Township. The sanitary sewage of the Township will be collected and transported using the Crum Creek Sewer District System through the CDCA collection and conveyance facilities to the DELCORA System for treatment and ultimate disposal and discharge.

Western Service Area

DELCORA's Western Service Area (shown in Figure 3-1) contributes flow to their WRTP and is therefore considered part of the Model Area. DELCORA owns and operates the collection system in the following communities in the Western Service Area.

- Chester City
- Chester Township (parts of)[1]
- Marcus Hook Borough
- Parkside Borough
- Rose Valley Borough[1]
- Upland Borough
- Trainer Borough

DELCORA does not own or operate the collection system in the following communities in the Western Service Area, however, these communities will be included as part of the service areas in the updated H&H model because they contribute flows to the WRTP.

- Brookhaven Borough
- Lower Chichester Township
- Nether Providence Township
- Eddystone Borough

Model Area Summary

In summary, the Model Area includes the municipalities in the Western Service Area plus those municipalities in the Eastern Service Area that are connected to the Central Delaware Pump Station, as described in Table 3-1. The Model Area is illustrated in Figure 3-1. A schematic of the facilities and conveyance network are shown in Figure 1-1.

---

[1] - DELCORA owns only a portion of Chester Township's collection system, but all flow comes to WRTP as some goes through the CRC PS service area.
- Rose Valley Borough collection system discharges to its own treatment plant (this portion will be discharged to the CRC PS service area in future) and the remaining portion is discharged to the Western Service Area to the WRTP.

Figure 3-1: DELCORA's Western Regional Treatment Plant (WRTP) Model Area

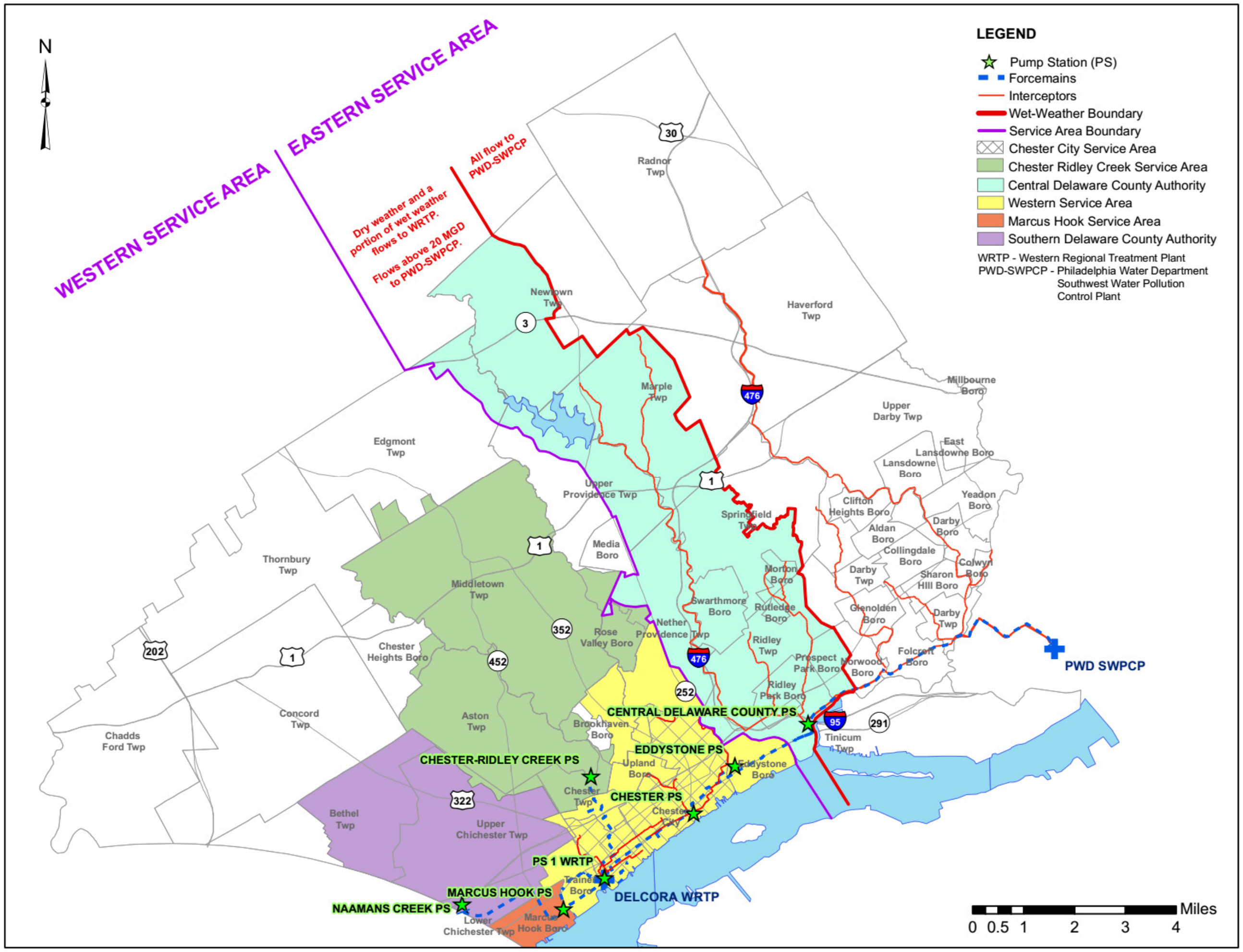


Table 3-1: Model Area

Municipality	Service Area
Aston Township	Western (CRCSA)
Bethel Township*	Western (SDCA)
Brookhaven Borough*	Western
Chester City	Western
Chester Township	Western (CRCSA)
Eddystone Borough	Western
Edgmont Township*	Eastern (CDCA)
Lower Chichester Township	Western (SDCA)
Marcus Hook Borough	Western (MHSA)
Marple Township*	Eastern (CDCA)
Middletown Township	Western (CRCSA)
Morton Borough	Eastern (CDCA)
Nether Providence Township	Eastern (CDCA) and Western
Newtown Township*	Eastern (CDCA)
Parkside Borough	Western
Prospect Park Borough	Eastern (CDCA)
Ridley Park Borough	Eastern (CDCA)
Ridley Township*	Eastern (CDCA)
Rose Valley Borough	Western
Rutledge Borough	Eastern
Springfield Township*	Eastern (CDCA)
Swarthmore Borough	Eastern (CDCA)
Trainer Borough	Western
Upland Borough	Western
Upper Chichester Township	Western (SDCA)
Upper Providence Township*	Eastern (CDCA) and Western

*Indicates that only a portion of the municipality contributes flow to WRTP
CDCA: Central Delaware County Authority
CRCSA: Chester Ridley Creek Service Area
MHSA: Marcus Hook Service Area
SDCA: Southern Delaware County Authority

3.2.1.2 Delineation of Combined Sewer System Area

The entire combined sewer system (CSS) area of DELCORA's collection system is located in the City of Chester and consists of a drainage area of approximately 1,460 acres. It comprises approximately half of Chester City's serviced area. To support this service area, DELCORA owns and operates over 129 miles of separate and combined sewers. Included in the 129 miles of sewers are: 11.7 miles of an interceptor system; 3,209 manholes; and twenty-five[2] (25) combined sewer outfall regulators controlling storm

[2] DELCORA's NPDES permit includes 26 regulators. After the NPDES permit was issued, CSO regulator 033 was disconnected from the CSS.

overflows. The location of the CSS area is shown in Figure 3-1. An enlarged view of the CSS area according to the 2012 H&H model is shown in Figure 3-2.

The CSS area delineation was updated with separation projects completed in recent years. The latest GIS database, survey, and record drawings were used to perform the desktop combined sewer area check. Some areas have separated systems with trunk sewers that subsequently connect to the CSS. For this situation, these particular separate sewer system areas were included within the delineation of the CSS. The revised CSS delineation is illustrated in Figure 3-3.

3.2.2 Model Network Extension

The collection system network in the original model has been updated with the following.

- Extended sewers to the updated delineation of the combined and separated areas
- Included all pump stations that control flows in the DELCORA collection system, and
- Reflect actual configuration of the CSO regulators.

3.2.2.1 Sewer Lines and Manholes

3.2.2.2 Regulators

Since the approval of the first LTCP in 1999, DELCORA has under-taken a program to replace and/or rehabilitate CSO regulators and tide gates in the City of Chester CSO system. In some cases, regulators have been eliminated. The updated model includes twenty-five[2] (25) CSO regulators, which were modeled as weirs and orifices. The configuration of CSO regulators was obtained from both record drawings and field surveys.

As indicated in Table 3-2, the majority of the City's CSO regulators are Brown & Brown type regulators. The operation of the CSO regulators has been changed from being controlled by the level in the trunk sewer entering the CSO regulator chamber to being controlled by the level in the interceptor. This change is being implemented as part of the CSO regulator replacement program. This ensures that the flow sent to the WRTP for treatment is maximized.

During dry-weather operations, the sewage flow levels entering the CSO regulator chamber are below the top of the diversion weir and will pass through the CSO regulator gate. Once through the CSO regulator gate, the flow typically passes through an orifice plate and then will be sent to the WRTP via the interceptors. During wet-weather events, the level in the combined sewer (Type A regulator) or in the interceptor (Type B regulator) will begin to rise thus raising the float assembly and beginning to close the CSO regulator gate. For cases where the regulator float and gate have been removed, dry weather flow and some portion of the wet weather flow will pass through the opening previously covered by the now removed gate. Flow through this opening will be modeled as an orifice. When weather flow exceeds the

Table 3-2: CSO Regulator Information

CSO Regulator No.	CSO Regulator Location	CSO Receiving Water	CSO Regulator Type
002	Front & Booth	Delaware River	Brown & Brown
003	Front & Highland	Delaware River	Brown & Brown
004	Front & Hayes	Delaware River	McNulty
005	Front & Townsend	Delaware River	Brown & Brown
007	Delaware & Reaney	Delaware River	Brown & Brown
008	2nd & Tilghman	Delaware River	Brown & Brown
009	2nd & Lloyd	Delaware River	Brown & Brown
010*	5th & Pusey	Delaware River	Brown & Brown
011	2nd & Parker	Delaware River	Brown & Brown
012	2nd & Edgmont	Delaware River	Brown & Brown
013	2nd & Welsh	Delaware River	Brown & Brown
014	3rd & Upland	Delaware River	Brown & Brown
015	4th & Melrose	Ridley Creek	Brown & Brown
016	8th & McDowell	Ridley Creek	Brown & Brown
017	9th & Campbell	Ridley Creek	Brown & Brown
018	Sun Dr. & Hancock	Ridley Creek	Brown & Brown
019	14th & Crozer Hospital	Chester Creek	Brown & Brown
020	Kerlin & Finland	Chester Creek	Brown & Brown
021	9th & Sproul	Chester Creek	Brown & Brown
022	6th & Sproul	Chester Creek	Brown & Brown
023	3rd & Edgmont	Chester Creek	Brown & Brown
024	3rd & Dock	Chester Creek	Brown & Brown
025	5th & Penn	Chester Creek	Brown & Brown
026	7th & Penn	Chester Creek	Brown & Brown
032	2nd & Avenue of the States	Delaware River	No CSO Regulator
033	Elkington Blvd. and Ridley Creek	Ridley Creek	No CSO Regulator

Notes:
- CSO Regulator 010 discharges at Outfall 009.
- CSO Regulators 006 ad 007 have been disconnected from CSS and removed from NPDES permit
- CSO Regulator 033 has been disconnected from the CSS but had not been removed from NPDES permit at the date of this Report

Figure 3-2: CSS Area Delineation in the Original Model

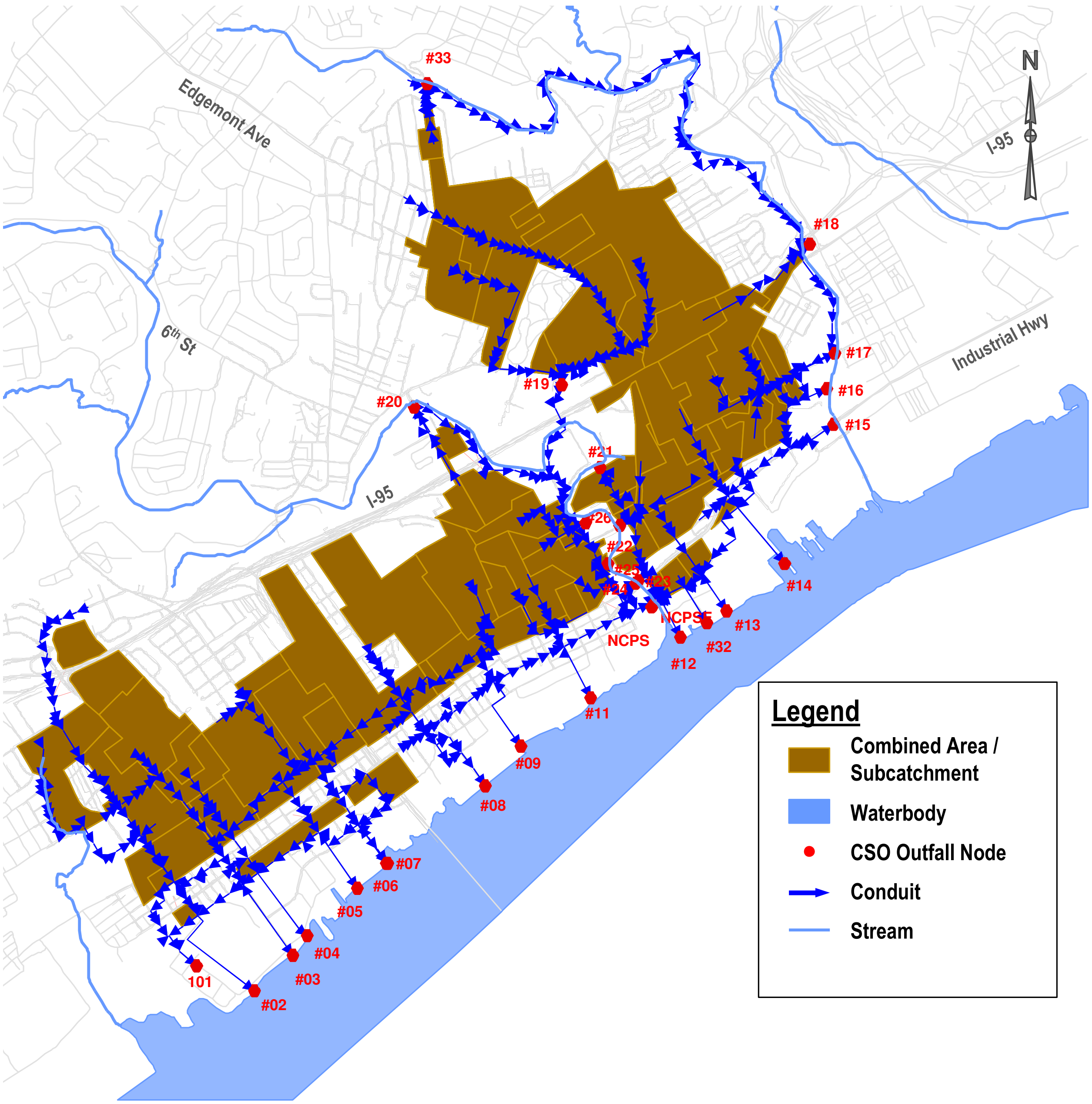
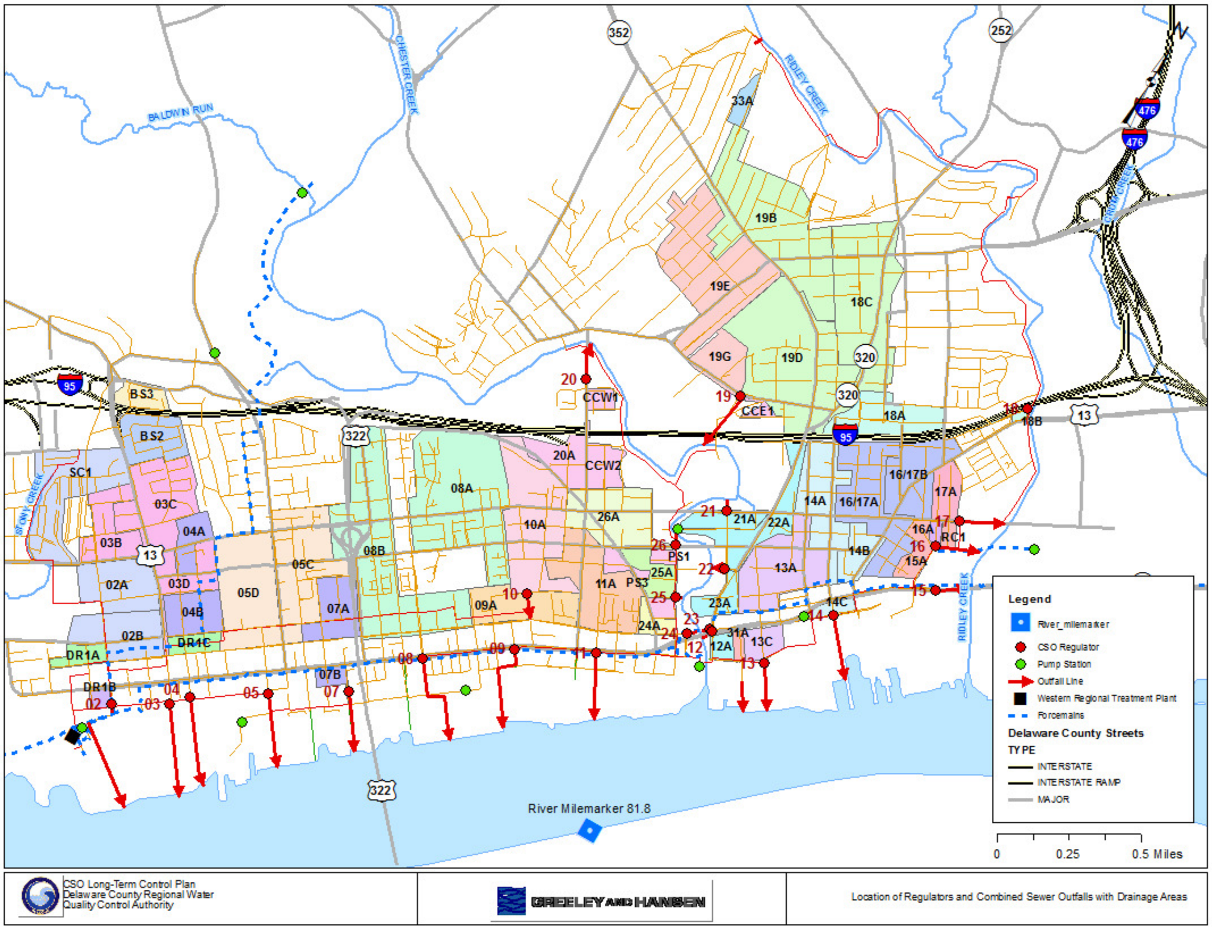


Figure 3-3: CSS Area Delineation in the Revised Model



capacity of the orifice, the level in the sewer will continue to rise until it is high enough for a portion of the flow to pass over the weir be discharge through the associated outfall.

Regulator gates, diversion weirs, and operating rules are simulated in the updated model.

3.2.3 Pump Stations

Major pump stations in the Western Service Area and the Central Delaware Pump Station in the Eastern Service Area were added to the updated model, as well as force mains connecting the pump stations to the interceptor/WRTP. The list of the pump stations includes (Figure 3-4):

- Chester PS
- Existing PS-1 WRTP
- Marcus Hook PS
- Naamans Creek PS

- Eddystone PS
- Central Delaware PS
- Chester Ridley Creek PS

The following pump stations were excluded from the H&H Model:

- Price & Smith Street Trainer PS
- Sun Oil PS (Owned by Sunoco)
- Kimberly Clark PS (Owned by KC)
- Stadium PS

Flow from the Price & Smith Street Trainer PS discharges to the downstream existing PS-1 Pump Station (EPS-1) where it is re-pumped. The updated H&H model assumes that all flow from subcatchments associated with the Price and Smith Street Trainer PS can be treated as an input to EPS-1.

Flow from the Stadium PS is sanitary sewage with no wet weather flow. The Stadium PS discharges flow only during events held at the stadium. Due to the limited flow, its sporadic nature and the lack of wet weather flow, the Stadium PS is expected to have negligible effect on the wet weather capacity of the CSS. Therefore, the Stadium PS was not included in the H&H Model.

DELCORA owns or operates a number of lift stations that contribute to the Western Service Area and whose flows are handled by the above list of pumps stations. It was determined that the behavior of these lift stations would not require modeling and that inflow can be assumed to equal outflow to the downstream conduit.

3.2.4 Model Input

3.2.4.1 Subcatchments

The following subcatchment information is required by the model:

- Area
- Percent of directly connected impervious area (effective impervious area)
- Width
- Slope
- Manning's roughness coefficient (n) for both pervious and impervious areas
- Depression storage for both pervious and impervious areas (initial abstraction)
- Soil and soil infiltration parameters
- Rainfall dependent inflow and infiltration (RDII) parameters
- Base flow

Area

Area of the combined sewer subcatchment is the geographical area of the subcatchment. It was estimated from the GIS by geometry calculation of the area of the subcatchment. Subcatchment areas for the updated H&H model are depicted in Figure 3-3.

Percent of Directly Connected Impervious Area

Directly connected impervious area means the impervious area that is effectively connected to the sewer collection system. As a result, runoff from these areas is completely captured by the collection system. Runoff from the rest of the impervious area is deemed not to be captured by the system due to various potential reasons including, but not limited to, drains to pervious areas/creeks/streams, limited number and capacity of stormwater inlets, and bypassing. For model construction, the percent imperviousness was calculated using the high resolution land cover raster published by the Chesapeake Conservancy (Chesapeake Conservancy, 2017) as well as the land use shapefile published in 2015 by the Delaware Valley Regional Planning Commission as the initial inputs. Then, the impervious percentage values were adjusted during the model calibration process (see Section 4) to best simulate the observed hydrologic response over the selection of precipitation events.

The initial percent imperviousness for the combined area was calculated based on the impervious coverage shape file and the subcatchment shape file. The subcatchment delineations were overlaid on the land cover designation and the percent impervious within each subcatchment was evaluated with the results presented in Table 3-3.

For the separated area, the initial percent imperviousness will be set at 0% because the impervious area in the separated area is not contributing runoff to the CSS, therefore it is not effectively connected. *Subcatchment parameters mentioned hereafter will be set at default values for the separated subcatchments*.

Width

The width of a subcatchment relates to sheet flow path and affects time of concentration and the shape of the runoff hydrograph. The initial estimate of the width was made by dividing the subcatchment area by the representative overland flow length. Width is one of the calibration parameters for runoff.

Slope

The slope of a subcatchment should reflect the average slope along the pathway of overland flow to inlet locations. For the combined sewer subcatchments, slopes from the 2012 H&H model were retained for use in the updated model.

Figure 3-4: Pump Stations Included in the Updated Model

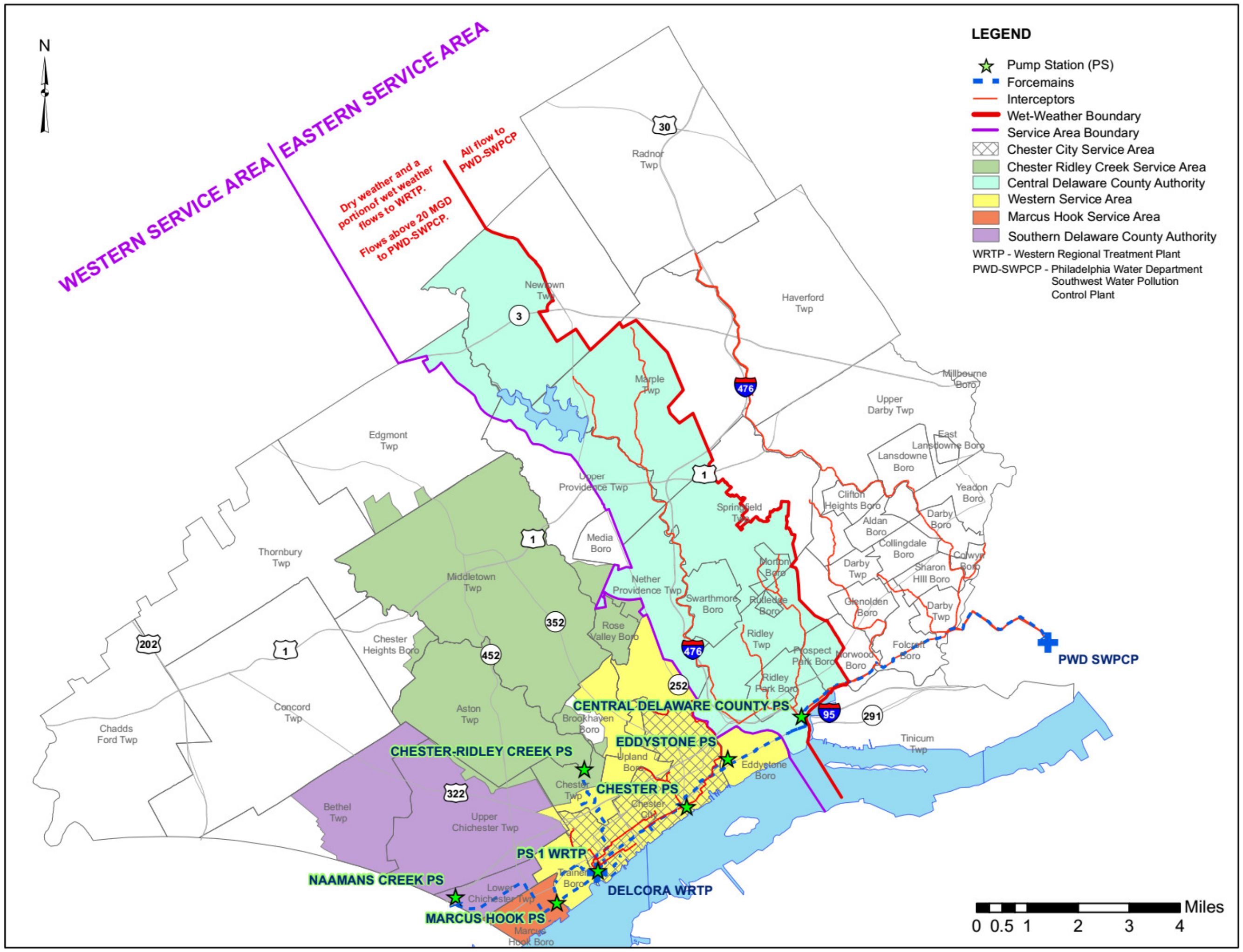


Table 3-3: Percent Imperviousness Applied to Subcatchments

Subcatchment ID	Percent Imperviousness
02A	74%
02B	60%
03B	69%
03C	55%
03D	72%
04A	80%
04B	66%
05C	72%
05D	44%
07A	70%
07B	72%
08A	52%
08B	60%
09A	65%
10A	60%
11A	70%
12A	91%
13A	89%
13C	88%
14A	61%
14B	52%
14C	79%
15A	63%
16/17A	55%
16/17B	65%
16A	76%
17A	79%
18A	58%
18B	70%
18C	64%
19B	57%
19D	49%
19E	58%
19G	34%
20A	64%
21A	85%
22A	85%
23A	93%
24A	60%
25A	76%
26A	77%
31A	91%
BS2	51%
BS3	50%
CCW1	69%
CCW2	58%

Subcatchment ID	Percent Imperviousness
DR1A	69%
DR1B	51%
DR1C	68%
PS1	52%
PS3	64%
RC1	64%
SC1	44%
CCE1	1%

Manning's roughness coefficient (n)

Manning's roughness coefficient (n) was estimated for both pervious and impervious overland flow. The initial values were set to 0.013 for impervious surfaces and 0.15 for pervious surfaces. A typical range of Manning's n suggested by the SWMM is 0.011-0.024 for impervious area and 0.06-0.80 for pervious area. Roughness is an empirical value and may be treated as a calibration parameter if necessary.

Depression Storage

Depression storage is the rainfall abstraction volume that must be filled prior to the occurrence of runoff. It represents the loss (initial abstraction) caused by surface ponding, surface wetting, etc. The initial values of depression storage were set to 0.05 for impervious surfaces and 0.15 for pervious surfaces. Typical depression storage values are 0.05-0.10 for impervious surfaces and 0.10-0.30 for pervious surfaces. Depression storage is an empirical value and may be treated as a calibration parameter, especially to adjust runoff volumes.

In the model, the subcatchment was divided into three subareas: pervious area with depression storage, impervious area with depression storage, and impervious area without depression storage. The initial percent of the impervious area without depression storage was set to 0.10.

Soil and Soil Infiltration Parameters

Soil information was obtained to estimate infiltration in the pervious areas of the CSS. The rate of infiltration is a function of soil properties and antecedent soil conditions. Three infiltration methods are available in the software: Horton method, Green-Ampt method, or National Resources Conservation Service (NRCS) Curve Number method. The Horton method has been extensively used for similar type of modeling work and it was used in this modeling effort to estimate infiltration. The required soil parameters for Horton method include:

- Maximum Infiltration rate (in/hr)
- Minimum Infiltration Rate (in/hr)
- Decay Constant (/hr)
- Drying time (d)
- Maximum Infiltration Volume Possible (inch)

To determine the Horton infiltration parameters, a soil map was first obtained from the NRCS (USDA, 2017). The soil types were then correlated to standard hydrologic soil groups.[3] A map of the hydrologic soil groups found in the CSS is presented in Figure 3-5. Hydrologic soil groups found in DELCORA's CSS are groups A, B, C, B/D and C/D. Horton's infiltration parameters for these soil groups were estimated based on typical values from literature and are shown in Table 3-4.

Table 3-4: Horton Infiltration Parameters

Horton Infiltration Parameter	Soil A	Soil B	Soil C	Soil B/D	Soil C/D
Max Infiltration Rate (in/hr)	5	3	2	2	1.5
Min Infiltration Rate (in/hr)	1.18	0.43	0.2	0.22	0.06
Decay Constant (1/hr)	4	4	4	4	4
Drying Time (d)	2	3	8	8	10.5
Max Volume (in)	14	13.2	12.5	9.8	7.0

3.2.4.2 Manhole

Sewer manholes were simulated as junction nodes in the model. The following information is required:

- Node ID
- Invert
- Maximum Depth (approximated as the difference from manhole rim and manhole invert)
- Surcharge Depth

Manhole ID was inherited from the name of the manhole in the sewer GIS. The naming convention is "MH_XXXX". Manhole input information was updated based on the latest available GIS information.

Manhole input parameters, including invert and rim were found or estimated from record drawings, design drawings, and the sewer manhole shape file. For water tight manholes or manholes with bolted down covers, a surcharge depth of 50-ft will be applied.

[3] Soil types can be categorized into standard hydrologic soil groups A, B, C and D, with group A having the lowest runoff potential and group D having the highest runoff potential. Dual rated groups are group D in their natural state, but can behave according to the first letter if the area is drained. Additional information regarding hydrologic soil group descriptions can be found in the Appendix.

3.2.4.3 Sewer Mains

Sewer mains are the conveyance element and were simulated as conduits in the model. The following input information was needed:

- Conduit ID
- Shape
- Number of barrels
- Upstream and downstream nodes
- Upstream and downstream offset
- Dimension (length, diameter/depth)
- Manning's roughness coefficient
- Minor loss coefficient (entry loss, exit loss, average loss)
- Flap gate installed or not (set at no flap gate for most of the sewer mains)

Conduit ID was inherited from the 2012 H&H Model.

Most of the pipe input parameters, including upstream and downstream nodes, dimension, shape, number of barrels, and flap gate information, were found or estimated from record drawings, design drawings and sewer gravity main GIS shapefiles. For pipes that do not begin or end at the invert of the upstream or downstream node, an offset value was provided to describe the difference from the invert of the pipe to the invert of the upstream or downstream node.

Manning's roughness coefficient is related to the pipe material. The initial input of the Manning's n for different materials is summarized in Table 3-5. The Manning's n may be changed during calibration to account for minor loss or additional sediment depositions in the pipe.

The initial minor loss for pipe will be set at zero for most pipes. For those pipes with sharp turns, a higher minor loss was applied.

If sewer main information was not available, sewer length was estimated in GIS geometry measurement; sewer size were assumed based on upstream and downstream sewers; sewer upstream and downstream offsets were estimated based on sewer connectivity assuming constant slope.

Figure 3-5: Hydrologic Soil Groups for CSS Area

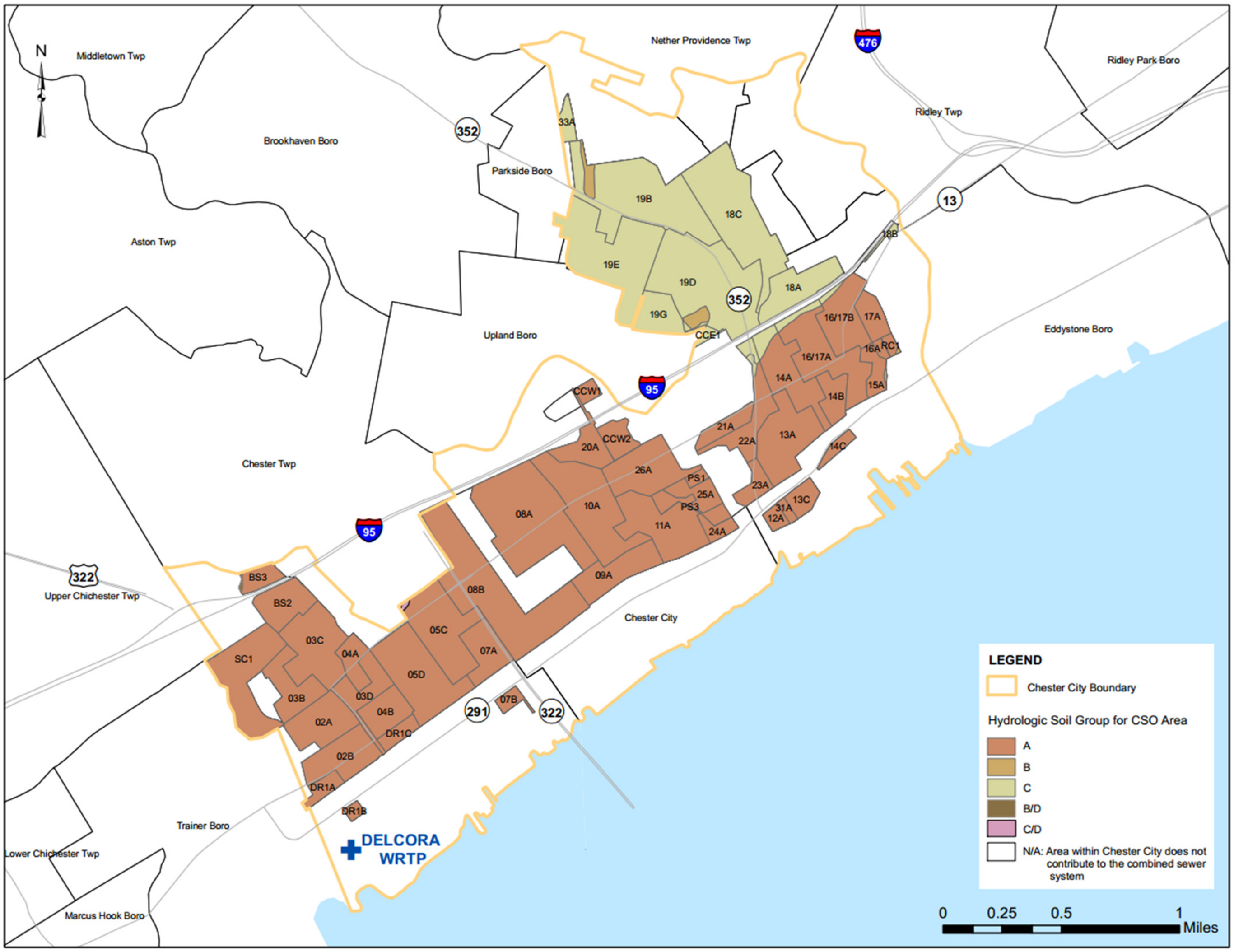


Table 3-5: Manning's Roughness Coefficient for Sewer Mains

Pipe Material	Manning's N
Polyvinyl Chloride (PVC)	0.011
Reinforced Concrete Pipe (RCP)	0.013
Ductile Iron (DI)	0.013
Cast Iron (CI)	0.013
Corrugated Metal Pipe (CMP)	0.020
Masonry	0.025
Unknown	0.013

3.2.4.4 CSO Outfalls

CSO outfalls will be simulated as outfall nodes in the model. The following information is required:

- Outfall ID
- Type (free, normal, fixed stage, tidal stage, time series, stage-flow, flap gate)
- Invert
- Boundary conditions

Outfalls are the discharge points in the model. The outfalls can either be free outfalls without any boundary conditions or the outfalls can have a boundary condition that the head needs to overcome for outflow to occur. The outfalls in the DELCORA's collection system are mostly in the tidal river reach. Therefore, appropriate tidal stages from NOAA data were used to set boundary conditions. Outfalls can have a flap gate at the end to prevent backflow.

Outfall ID will be named according to the CSO regulator overflow points. For example, the outfall for CSO regulator 002 will be named "NREG-002". The inverts of outfalls will be estimated based on record drawings and design drawings, and will be confirmed/adjusted from the field survey, if necessary.

A summary of the outfall data used in the model is contained in Table 3-6. One regulator (Regulator 010) does not have its own outfall, but rather discharges through the same outfall (Outfall 009) as Regulator 009. Also, Regulator 033 has been disconnected from the CSS and, therefore, its outfall is not included in the updated H&H model. As a result, there are a total of 24 CSO outfalls in the updated H&H model.

Table 3-6: CSO Outfall Characteristics Summary

Outfall No.	CSO Receiving Water	Invert at Regulator	Invert at Receiving Stream
002	Delaware River	7.00	-3.5
003	Delaware River	7.98	-3.5
004	Delaware River	8.80	-3.5
005	Delaware River	4.74	-4.5
007	Delaware River	0.81	0.21
008	Delaware River	2.79	0.01
009	Delaware River	2.61	-4
010*	Delaware River	22.5	*
011	Delaware River	7.09	-4
012	Delaware River	1.46	-2
013	Delaware River	1.86	-4
014	Delaware River	-1.09	-4
015	Ridley Creek	0.52	-3
016	Ridley Creek	0.11	-5
017	Ridley Creek	0.09	0.09
018	Ridley Creek	6.28	-5.0
019	Chester Creek	18.00	12.28
020	Chester Creek	8.78	-4
021	Chester Creek	5.78	-1.5
022	Chester Creek	11.5	-3.5
023	Chester Creek	1.33	-3.0
024	Chester Creek	1.21	-4.0
025	Chester Creek	-1.08	-4.0
026	Chester Creek	9.00	-4.0
032	Delaware River	1.00	-4.0
033	Ridley Creek	N/A	N/A

Notes:
*CSO regulator 010 discharges at Outfall 009.
N/A: Not Applicable

3.2.4.5 Flow Diversion Structure

As described in Section 3.2.2.2, most of the flow diversion structures are similar to Brown and Brown type regulators. The key components required for modeling these structures include float-operated gates, orifice plates and diversion weirs. Schematic representations of the flow diversion structures are shown in Figure 3-6.

Regulator Gates

Regulator gates will be simulated as orifices in the updated model. The following information is required to model a regulator gate in the model:

- Regulator Gate ID
- Upstream and downstream nodes
- Type
- Shape (two shapes: circle, rectangular)
- Dimension (Height, Width)
- Discharge Coefficient

Regulator gate ID is named according to the CSO regulator points. For example, the regulator gate for CSO regulator 003 is named "REG_003_Gate." All regulator gates are modeled as side-type orifices and have been assigned a discharge coefficient of 0.65. All regulator gates are modeled as rectangular except for REG_004_Gate which is modeled as a circular orifice. The updated model includes real time control rules for opening and closing of the gates based on levels in the float chamber and regulator limit settings. A summary of regulator gate characteristics is shown in Table 3-7.

Orifices

The following information is required to model an orifice in the model:

- Orifice ID
- Upstream and downstream nodes
- Type (two types: side, bottom)
- Shape (two shapes: circle, rectangular)
- Dimension (Height, Width, Crest Height)
- Discharge Coefficient

Orifice ID will be named according to the CSO overflow points. For example, the orifice for CSO 03 will be named "REG_03_Orifplate". All orifices in the collection system are side orifice type, rectangular in shape and were assigned a discharge coefficient of 0.65. The dimensions are based on record drawings.

A summary of the orifice data used in the model is contained in Table 3-8. The update H&H model has 20 orifices. All orifices are side type and are rectangular in shape. Regulators 004, 015, 017 018 and 032 do not have an orifice plate. Regulators 006, 027 and 033 are no longer connected to the CSS and therefore do not have any orifices, weirs or outfalls included in the H&H model.

Figure 3-6: Flow Diversion Structure Schematic

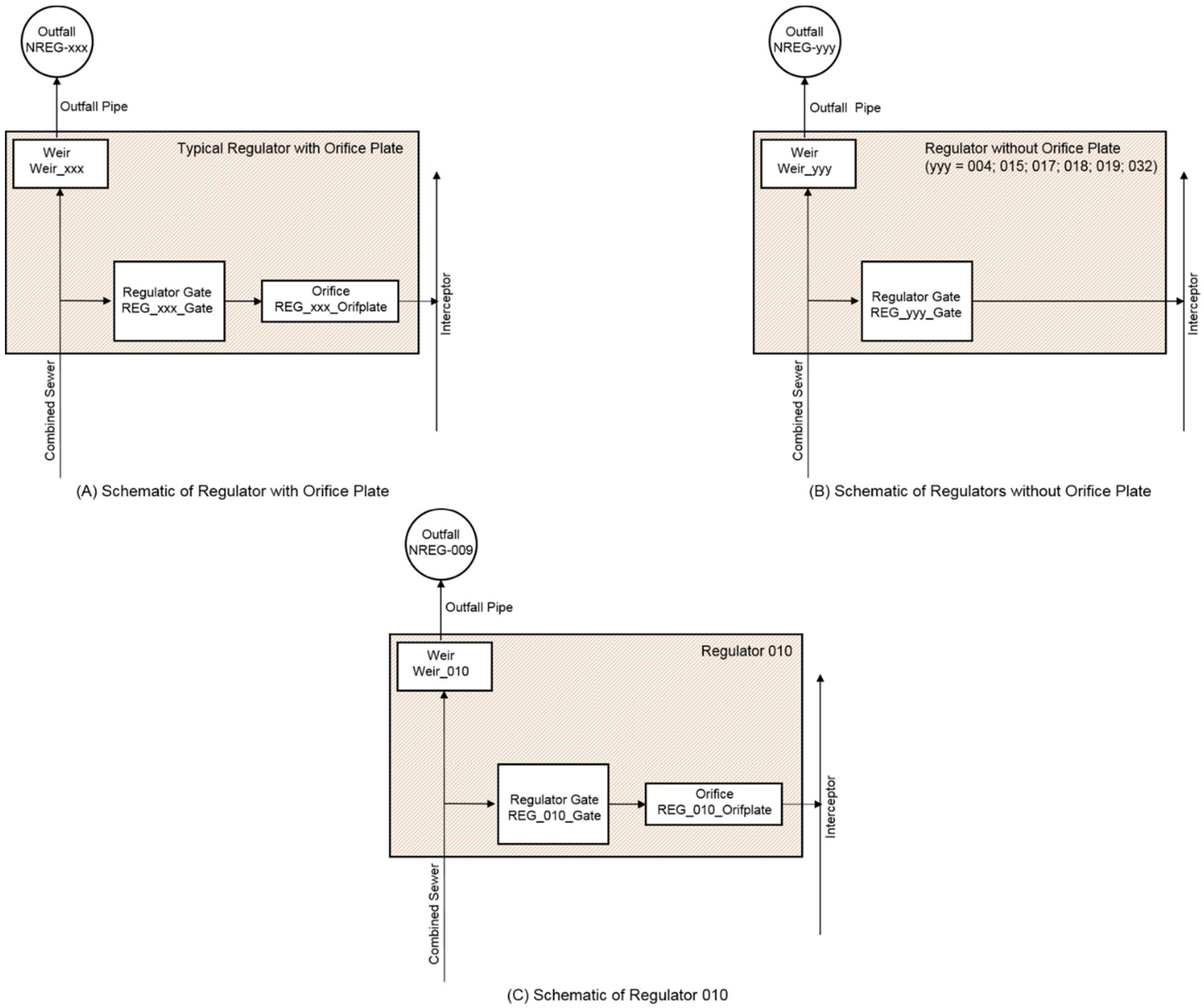


Table 3-7: Regulator Gates Characteristics

Regulator Gate ID No.	Dimensions		Invert EL (ft.)
	Height	Width	
002	5.0 in.	7.5 in.	6.29
003	7.5 in.	7.75 in	7.18
004	8.0 in. dia.	N/A	7.89
005	12.0 in.	12.0 in.	3.99
007	5.0 in.	6.00 in.	0.50
008	7.5 in.	12.375 in.	2.63
009	5.0 in.	7.5 in.	2.45
010*	7.5 in.	15.375 in.	21.50
011	5.0 in.	9.25 in.	6.99
012	2.50	9.25 in.	0.50
013	7.5 in.	7.75 in.	0.84
014	12.0 in.	15.00 in.	-2.50
015	5.0 in.	6.00 in.	0.46
016	7.5 in.	12.375 in.	-0.55
017	5.0 in.	6.00 in.	0.09
018	5.0 in.	6.00 in.	6.06
019	7.5 in.	15.38 in.	16.89
020	7.5 in.	7.75 in.	8.06
021	7.5 in.	7.75 in.	4.56
022	5.00 in.	6.00 in.	10.47
023	7.5 in.	7.75 in.	0.50
024	5.0 in.	9.25 in.	0.50
025	5.0 in.	6.00 in	-2.25
026	7.5 in.	12.375 in.	7.91
032	*	*	-0.20
033	N/A	N/A	N/A
*Gate removed; no data for gate opening dimensions. Regulator modeled as pipe with same diameter as upstream sewer			

Table 3-8: Orifice Characteristics

Orifice ID No.	Orifice Type	Dimensions		Invert EL (ft.)
		Height	Width	
002	Side	4 5/8 in.	6 in.	5.78
003	Side	6 ¼ in.	7 in.	6.68
004	None	N/A No Orifice Plate		N/A
005	Side	7 ½ in.	12 in.	3.49
007	Side	3 ½ in.	5 in.	0
008	Side	6 7/8 in.	18 in.	2.13
009	Side	3 ½ in.	8 in.	1.95
010*	Side	10.563 in.	15 in.	21.09
011	Side	5 7/8 in.	8 in.	6.49
012	Side	4 5/8 in.	14 in.	0.00
013	Side	4 ½ in.	16 in.	0.34
014	Side	7 ½ in.	16 in	-3
015	None	N/A No Orifice Plate		N/A
016	Side	9 1/8 in.	30 in.	-1.05
017	None	N/A No Orifice Plate		N/A
018	None	N/A No Orifice Plate		N/A
019	None	N/A No Orifice Plate		N/A
020	Side	12.15 in.	8 in.	7.41
021	Side	11.33 in.	15 in.	4.47
022	Side	2.9 in.	8 in.	9.97
023	Side	5.75 in.	14 in.	0.00
024	Side	7.5 in.	16 in.	-2.75
025	Side	4.61 in.	5 in.	7.41
026	Side	7.69 in.	30 in.	
032	None	N/A No Orifice Plate		N/A
033	N/A	N/A No longer connected to CSS		N/A

Weirs

Diversion weirs will be simulated as weirs in the model. The following information is required to model a weir in the model:

- Weir ID
- Upstream and downstream nodes
- Type (four potential weir types: transverse, sideflow, V-notch, trapezoidal)
- Dimension (Height, Weir Length, Weir Crest Height)
- Coefficient of Discharge
- Number of End Contractions

Weir ID will be named according to the CSO overflow points. For example, the weir for CSO 03 will be named "Weir_03". Weir information will be obtained from record drawings and will be field verified, if necessary. All weirs were found to be of the transverse type with no end contractions. All weirs are assigned a discharge coefficient of 3.33.

A summary of the weir data used in the model is contained in Table 3-9.

3.2.4.6 Pump Stations

The wet wells in the pump stations were simulated as storage nodes, and pumps were simulated as ideal pumps in the model. Dimensions of the storage nodes were based on record drawings. For pumps, the following information is required:

- Pump ID
- Startup Depth
- Shutoff Depth

Pump startup depth and shutoff depth will be set up in the model according to the typical pump operation.

Table 3-9: Weir Characteristics

Weir ID No.	Dimensions		
	Height	Length	Crest Height
002	2.50 ft.	2.24 ft.	1.21 in.
003	2.50 ft.	2.24 ft.	1.30 in.
004	2.74 ft.	1.69 ft.	1.17 in.
005	3.50 ft.	2.65 ft.	1.25 in.
007	3.50 ft.	2.65 ft.	0.81 in.
008	4.98 ft.	3.54 ft.	1.23 in.
009	3.25 ft.	3.12 ft.	0.94 in.
010*	2.50 ft.	2.24 ft.	1.50 in.
011	2.44 ft.	3.9 ft.	1.76 in.
012	1.58 ft.	1.73 ft.	1.46 in.
013	3.40 ft.	2.65 ft.	1.62 in.
014	2.75 ft.	2.52 ft.	2.33 in.
015	2.79 ft.	1.53 ft.	0.27 in.
016	3.58 ft.	4.51 ft.	2.08 in.
017	2.17 ft.	2.63 ft.	0.96 in.
018	4.33 ft.	2.58 ft.	0.25 in.
019	3.17 ft.	2.05 ft.	1.44 in.
020	2.50 ft.	2.24 ft.	1.44 in.
021	0.63 ft.	1.48 ft.	1.72 in.
022	2.53 ft.	2.24 ft.	1.53 in.
023	1.50 ft.	2.24 ft.	1.25 in.
024	3.00 ft.	2.45 ft.	1.13 in
025	2.50 ft.	2.24 ft.	1.67 in.
026	0.95 ft.	2.43 ft.	2.64 in.
032	2.75 ft.	1.66 ft.	1.54 in.
033	N/A	N/A	N/A

*Height (H) measured from weir crest to pipe crown; Crest Height (H) measured from invert of upstream node to weir crest

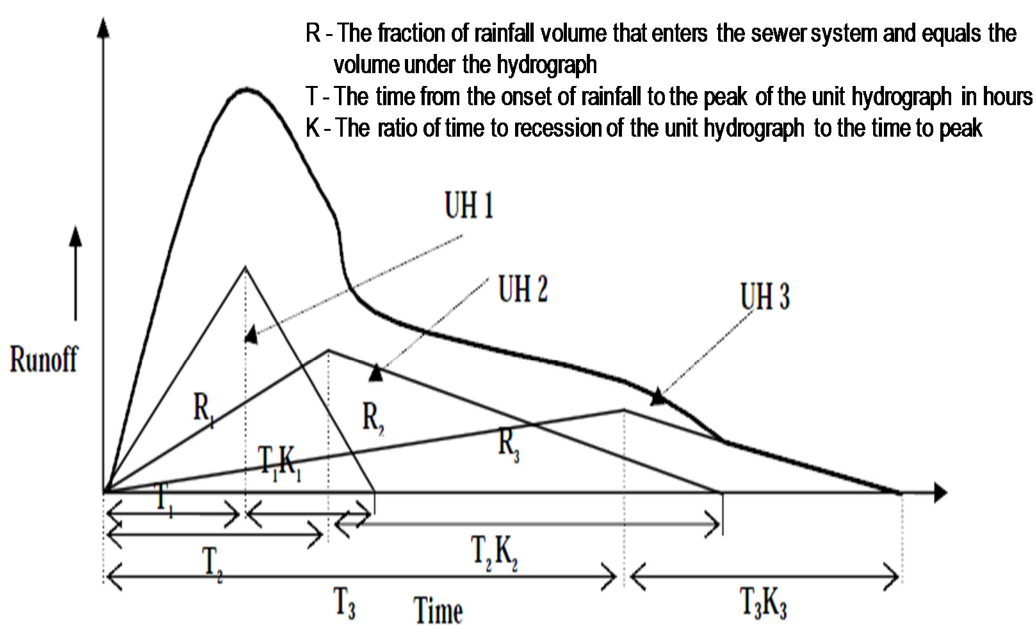
3.2.4.7 Modeling of Separated Areas - Rainfall Derived Infiltration and Inflow (RDII)

The model will use the RTK unit hydrograph (UH) to estimate RDII into the separated area sewer systems. As shown in Figure 3-7 (Muleta & Boulos, 2008), a RTK UH set contains up to three hydrographs: one for a short-term response (UH1), one for an intermediate-term response (UH2), and one for a long-term response (UH3). UH1 represents the most rapidly responding inflow component and has a short T value, UH2 includes both inflow and infiltration and has a longer T value, and UH3 includes infiltration that may continue long after the storm event has ended and has the longest T value. The unit hydrograph is defined by the following three parameters:

- R: the fraction of rainfall volume that enters the sewer system and equals to the volume under the hydrograph,
- T: the time from the onset of rainfall event to the peak of the unit hydrograph in hours, and
- K: the ratio of time to recession of the unit hydrograph to the time to peak.

The same set of RDII parameters will be applied in the same metershed because of the availability of the flow hydrograph for model calibration. The initial values of RTK will be estimated using the RDII Analyst tool in the InfoSWMM. The RTK values are calibration parameters to be refined during model calibration.

Figure 3-7: RTK Unit Hydrographs



Source: M.K. Muleta and P.F. Boulos, Analysis and Calibration of RDII and Design of Sewer Collection Systems, ASCE Conference Proceedings 316, 642 (2008)

3.3 Summary

The 2012 H&H model was updated as described above. A summary of the key revisions is presented in Table 3-10. The detailed layout of the updated model is shown in Figure 3-8 and Figure 3-9.

Table 3-10: Summary of Revised H&H Model

Review Item	2012 Model Review Observation	Comments	Updated Model
Model Software	- EPA SWMM 5.0		Innovyze InfoSWMM version 14.5
Vertical Datum	- NAVD 88	- To be verified	- NGVD29
General Sub Models	- EPASWMM for the runoff model - Horton Equation for the infiltration model - Hydrodynamic wave for the flow routing model	- All these choices are commonly seen in collection system modeling practices	
Rain Gauge	- One (1) rain gage, located at the Western Regional Treatment Plant (WRTP)	- One rain gauge is not sufficient for the entire service area in the model	- Seven (7) rain gauges, as shown in Section 2 - Additional GARR analysis performed
Service Area	- 67 subcatchments, all for combined area - One set of Horton infiltration parameters are applied to most of the subcatchments (66 out of 67 subcatchments) - The infiltration parameters applied in the model is equivalent to infiltration parameters for soil type C/D	- All service area including separated area that contribute flow to the DELCORA collection system should be included in the model - Combined area delineation will be checked to include any changes along the years - Soil type need to be checked to verify Horton infiltration parameters in all subcatchments	- 111 subcatchments, 54 for combined area and 57 for separated areas - Combined area was modified to include newly separated areas. - Horton infiltration parameters applied to 54 out of 111 subcatchments - Horton infiltration parameters varied based on identified soil types -

Review Item	2012 Model Review Observation	Comments	Updated Model
Sewer Manhole	- 736 storage nodes. - All sewer manholes are simulated as storage units in the model. - The majority of the storage units (732 out of the 736) have a diameter of 4-ft, and the rest (4 units) have a surface area of 100 square feet (sf.) (equivalent to 10'x10'). - All storage units are set-up with a ponding area of 9,999 sf. to allow excess water to collect atop of the nodes and be re-introduced into the system as conditions permit.	- Sewer manholes will be simulated as common junction node - This will help with SSO evaluation in the collection system	- 860 common junction nodes. - The majority of the common junction nodes (836 out of the 860) have a diameter of 4-ft, and the rest (4 units) have a surface area of 100 square feet (sf.) (equivalent to 10'x10'). - There are 35 imaginary junctions created to receive flow from the subcatchments gravity network not included in the model network
CSO Outfall	- 29 outfall nodes - All CSO outfalls are free outfall	- All outfalls are located in the Delaware River in the tidal reach, a tidal stage instead of free outfall should be assigned to the outfalls - Outfall ID 101 has dry weather input of 1.76 cfs, it represents WRTP in the model	- 24 CSO outfall nodes - Tidal data is assigned to 24 outfalls using time series - Wherever tide gates are installed, a real time control is applied

Review Item	2012 Model Review Observation	Comments	Updated Model
Sewer Mains	- 735 conduit links. - Negative slopes at Nodes 73803 and 70709 not matching the GIS. - Pipe connectivity is not consistent with the GIS in Subcatchment EA1, 25A. - Pipe size and connectivity is not consistent with the GIS around Node: 5201242, 5201234. - Pipe size is not consistent with the GIS around Node: 52018-52015. - Pipe size is not consistent with the GIS around Node: 531-527, 522-517, 516-513, 510020301-5100202, 403-NCPS, 40801-40801A, 32405-32404, and 1110402-11103. - Pipe size and slope are not consistent with the GIS around Node: 422-4140. - NREG06 outfall pipe direction is opposite.	- All the negative slopes and inconsistencies need to be checked with the most updated GIS and record drawings during the model update	- 817 conduit links. - 45 imaginary conduit links created to receive flows from subcatchment gravity network not included in the model

Review Item	2012 Model Review Observation	Comments	Updated Model
CSO Regulators	- 34 orifice links. - All CSO regulators are simulated using orifices to intercept dry weather flows and partial wet weather flows to the collection system, and with elevated conduits to convey extra flows to the CSO outfalls. - Approximately 75% of the orifices (25 out of 34) are modeled with Real Time Control (RTC) to mimic regulator gate opening based on level. - None of the regulator diverting weir structures is simulated in the model.	- Diverting weir structures need to be added in the model - The slopes of all overflow pipes connected to the CSO outfalls need to verified - All orifice opening dimensions verified will be verified - All the RTC rules regulating orifice opening will be verified with actual operation	- 44 orifice links. - CSO regulators are simulated using orifices and float-operated gates to intercept dry weather flows and partial wet weather flows to the collection system, and with conduits set a verified inverts to convey extra flows to the CSO outfalls. Exceptions occur at several regulators where orifices have been removed and at one regulator where the float and gate have been removed. - Approximately 57% of the orifices (25 out of 45) are modeled with Real Time Control (RTC) to mimic regulator gate opening based on level. - Regulator diverting weir structures added to the model. - All orifice opening dimensions were verified using record drawings excepting Orifice 024 which was field verified.
Pump Station	- No pump station is included in the model	- All pump stations that contribute flow to the DELCORA collection system should be added to the model, with related force mains	- Pump stations added to model. - Related force mains added to model

Review Item	2012 Model Review Observation	Comments	Updated Model
Dry Weather Flow	- 94 dry weather flow (DWF) inputs - Total DWF is 7.01 MGD - No diurnal curve - DWF does not include all the separated service areas that contribute to the DELCORA system -	- DWF should be updated to include all the service areas that contribute to the DELCORA system - Weekday and weekend diurnal curve should be included in the model to effectively simulate dry weather diurnal pattern	- 111 dry weather flow (DWF) inputs - Total DWF is 24.6 MGD - DWF analysis was performed on all flow meters in separated and combined areas as well as pump stations - Weekday and weekend diurnal curves were generated as well as overall, weekday, weekend and monthly DWF factors.
RDII	- No rainfall-derived infiltration/inflow (RDII) element was found in the model	- RDII should be included in the model to estimate reasonable wet weather inflow from RDII	- RDII was included in the model to estimate reasonable wet weather inflow from RDII

Figure 3-8: Updated H&H Model Layout

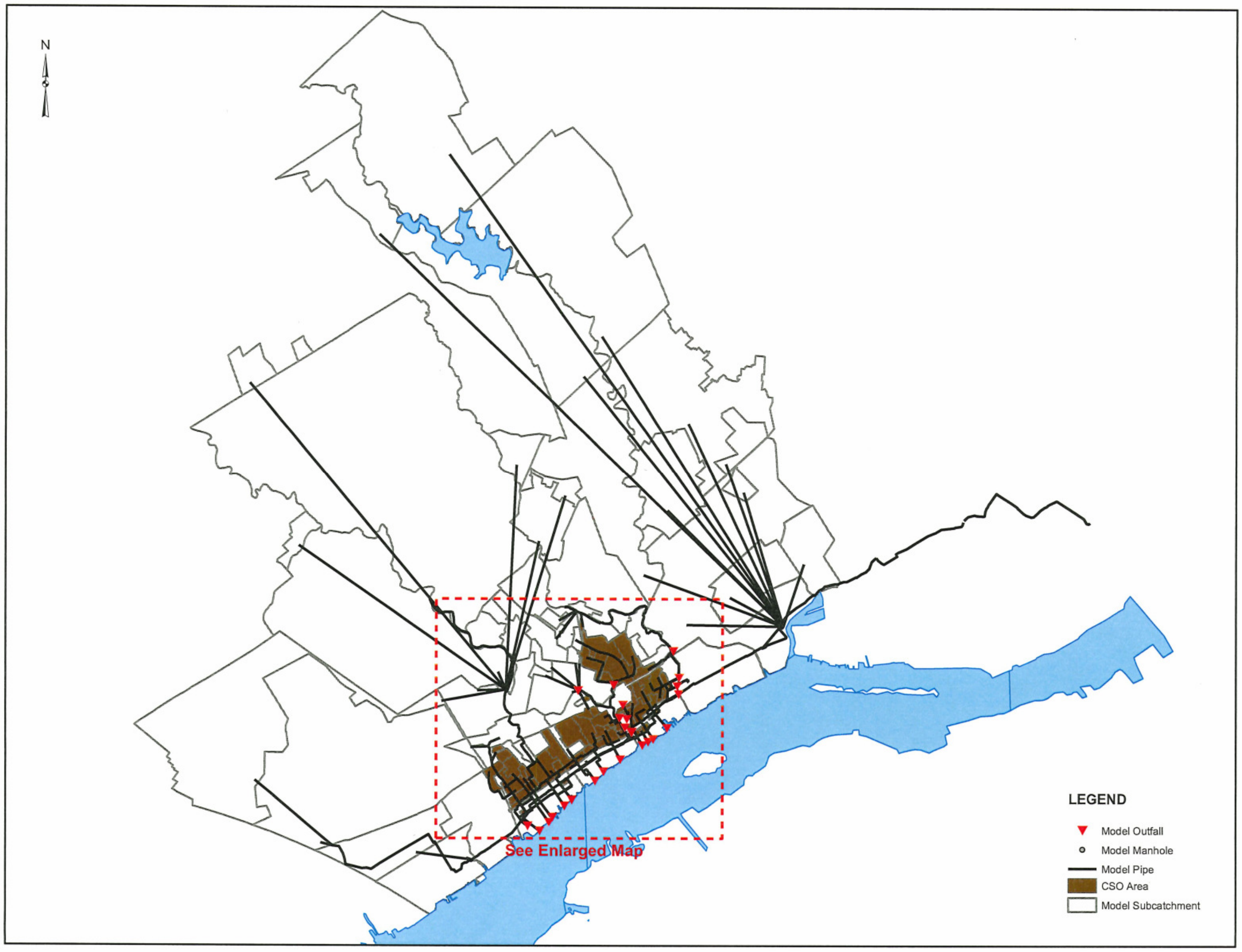
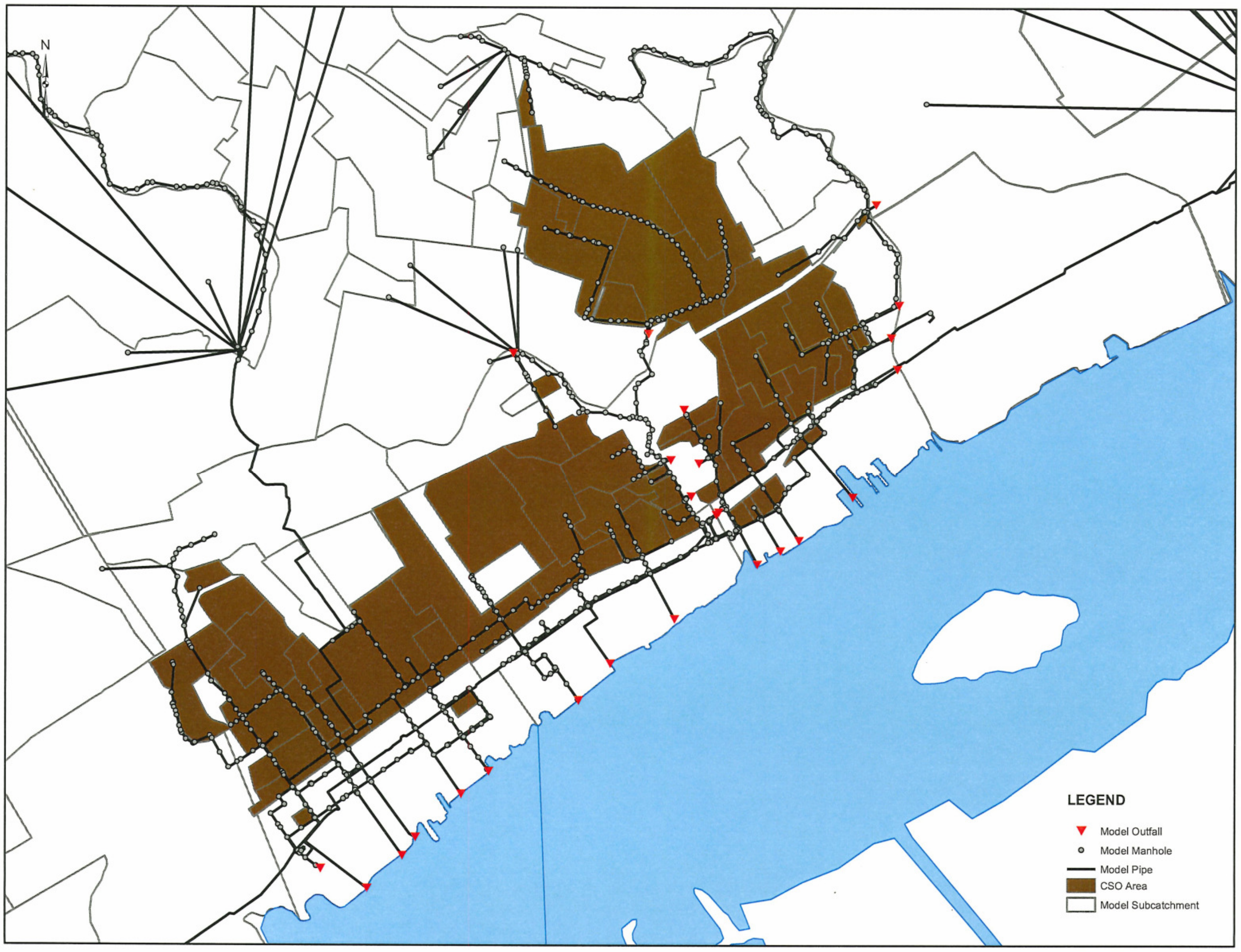


Figure 3-9: Updated H&H Model Layout – CSS Area



Section 4 DELCORA H&H Model Calibration and Validation

4.1 Model Calibration and Validation

Model credibility is developed through model calibration and validation. Model calibration involves application of the model to known external inputs (e.g., rainfall), evaluation of the model's ability to replicate monitored conditions (e.g., flow and volume), and adjustment of key model parameters as needed until an acceptable level of agreement is reached between simulated and monitored conditions.

After the model is satisfactorily calibrated it must be validated by running known storms with known flow results and having the model replicate the known events. Storms used in model validation should be independent from the storms used in the model calibration.

4.1.1 Calibration/Validation Criteria

4.1.1.1 Dry Weather Flow Calibration Criteria

Dry weather flow (DWF) analysis was based on the rainfall and flow monitoring results. DWF distribution in the collection system was based on land use data. Weekday, weekend and monthly diurnal factors from the DWF analysis were applied for each flow meter service area. Upstream meters in the system were calibrated first, then flows through the system to the pumps stations and to the WRTP were balanced. Figure 4-1 shows the arrangement of the meters in the system and meter identification.

DWF calibration will adhere to industry standards and the criteria below:

- The simulated hydrograph should match the general observed hydrograph shape,
- The simulated time of peaks and troughs will be within 1 hour of the observed,
- The simulated peak flow will be within 10% of the observed flow, and
- The simulated flow volume over 24 hours will be within 10% of observed flow.

4.1.1.2 Wet Weather Flow Calibration Criteria

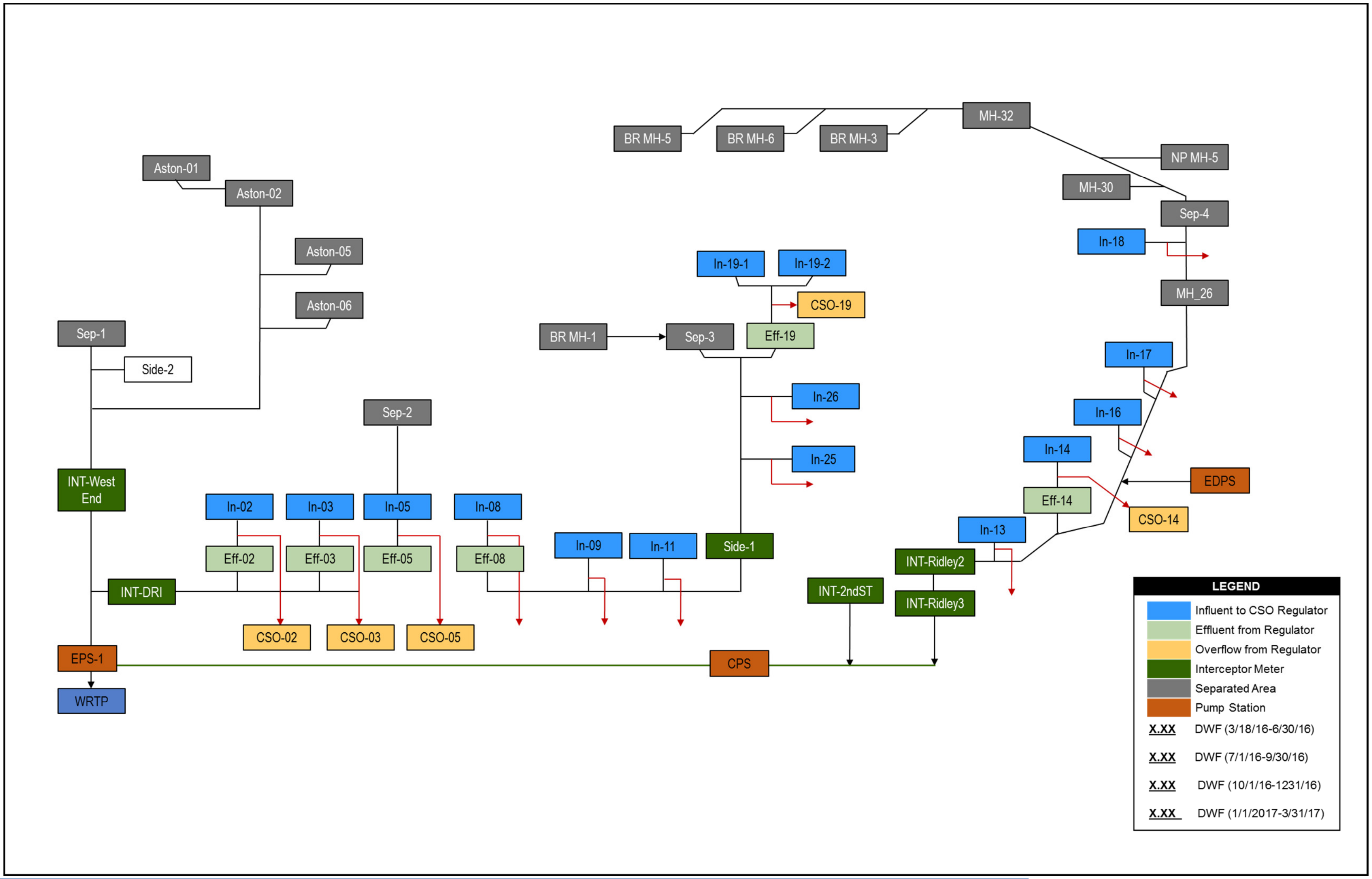
Wet weather flow (WWF) includes surface runoff from the combined area, RDII from the entire service area, and connected rooftops, if any, from the separated area. RDII parameters will be developed based on the separated area, and surface runoff parameters will be adjusted for the combined area to calibrate the system response to the wet weather conditions.

Four (4) wet weather events were selected for wet weather calibration. Final selections include wet weather events with various rainfall intensities and volume.

WWF calibration will adhere to industry standards and the criteria below:

- The simulated hydrograph should match the general observed hydrograph shape,
- The simulated time of peaks and troughs will be similar having regard to the duration of the event,

Figure 4-1: Flow Meter Schematic



- The simulated peak flow for significant peaks will be within the range of -15% to +25%,
- The simulated flow volume will be within the range of -10% to +20%,
- The depth of surcharge will be in the range of -0.1 m to +0.5 m, and
- At key points such as CSOs, the unsurcharged depth will be within ± 100 mm (± 0.33 ft.)

4.1.2 Model Calibration Approach

The runoff calibration for the combined sewer area is achieved by primarily adjusting width and percent imperviousness. The RDII calibration for separated areas was achieved by adjusting RTK values. The calibration of hydraulic control structures (weirs and orifices) is achieved by adjustment the discharge coefficients. The conduit hydraulics calibration is achieved by adjusting Manning's n and head loss coefficients. Flow depth, as well as flow rate, is checked while calibrating the hydraulic model.

After calibration, a different set of flow monitoring data was used to validate the model calibration. Model calibration and validation is an iterative process.

Percent Imperviousness

The percent imperviousness for combined sewer subcatchment is the key parameter to be adjusted to calibrate runoff to the observed wet weather flow volumes. If runoff from a large portion of the impervious surface could not be captured by the combined sewers due to a limited number and size of storm inlets, the percent imperviousness will need to be reduced significantly from its initial value calculated based on impervious land cover. This is done to represent a more reasonable "effectively connected area" and to achieve a satisfactory calibration for runoff volume.

Width

The width for the combined sewer sub catchments, in conjunction with percent imperviousness, will be adjusted to calibrate to the observed wet weather flow peaks.

Depression Storage

The depression storage is another hydrologic parameter for wet weather volume calibration. It can also be adjusted to achieve a satisfactory calibration for the wet weather flow start timing.

RDII Parameters

RDII parameters are to be adjusted to calibrate to the observed wet weather volumes and flow hydrograph shape for the separate sewer areas. Then, the runoff parameters will be adjusted to calibrate to the observed data.

Pipe Roughness

Pipe roughness was adjusted to calibrate to the observed flow depths and velocities at the meter locations.

Orifice and Weir

Orifice and weir parameters discharge coefficients were adjusted to calibrate to the observed overflows at the outfall meter locations.

Minor Loss

Minor loss values were applied in the model where necessary to refine observed flow/depth relationships at the meter locations.

4.1.3 Model Calibration Results

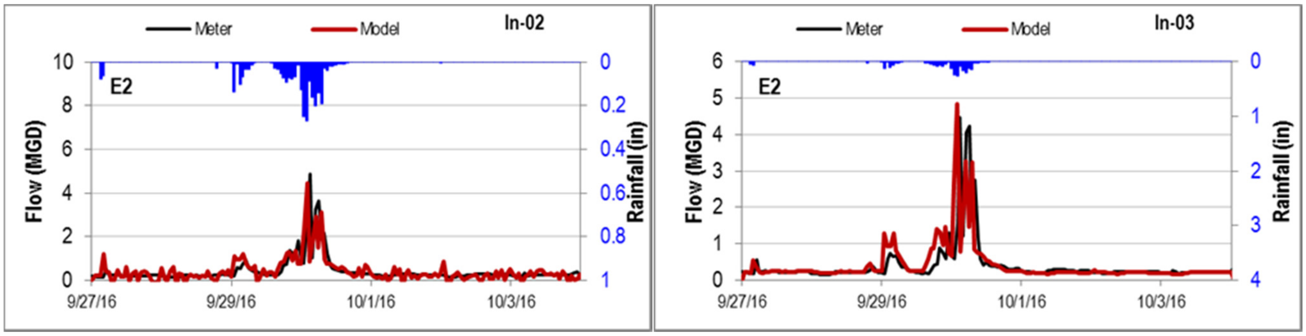
Successful calibration is indicated by satisfying agreements between the model prediction and the flow monitoring data in terms of shape of hydrograph, wet weather volume and peak flow. The calibration was performed and evaluated for various sizes of storms and different antecedent conditions so that the calibrated model can be reasonably applied for various hydrologic conditions. Wet weather events used for model calibration and validation are summarized in listed in Table 4-1. The larger storm events will have more weighting factor in the calibration process because the large events are the ones that dominate the total overflow volume.

Table 4-1: Wet Weather Events for Model Calibration and Validation

Event ID	Start Time	Stop Time	Rainfall Depth* (inches)	Used in Calibration	Used in Validation
E1	5/29/16 19:00	5/30/16 5:00	1.82	C	
E2	9/28/16 12:00	9/30/16 10:00	2.36	C	
E3	11/29/16 7:00	11/29/16 20:00	1.08	C	
E5	5/21/16 11:00	5/22/16 21:00	1.71		V
E6	7/28/16 15:00	7/29/16 9:00	1.26	C	
*At Chester PS rain gauge					

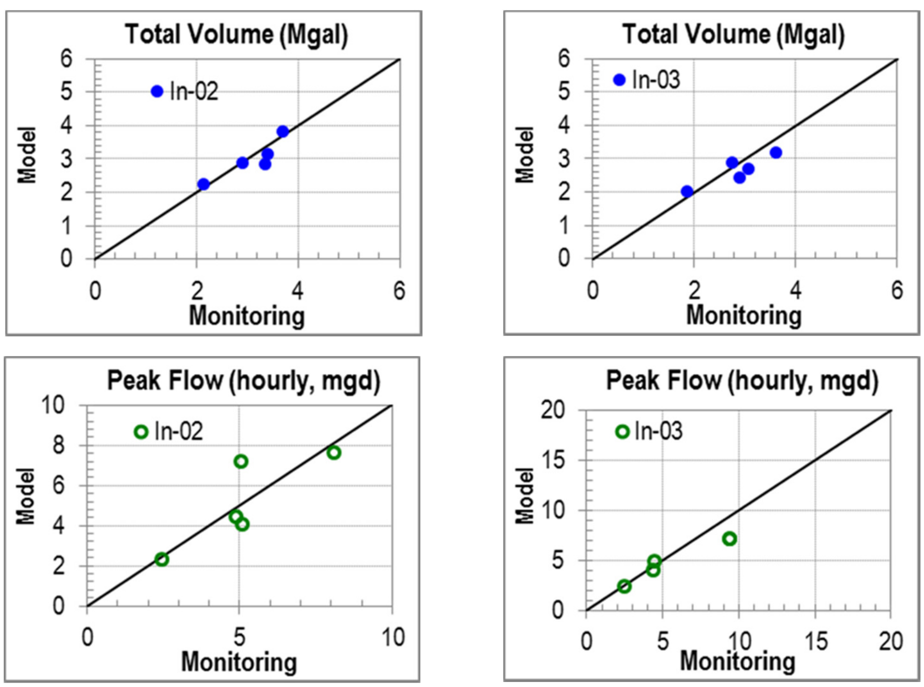
Examples of model calibration results are shown in Figure 4-2. Additional figures for all meters installed at different locations, including meters installed at major trunk interceptor, overflow pipes, influent pipe to overflow control structure, intercepting pipes, previous CSO areas, separate sewer areas and boundaries can be found in Appendix C.

Figure 4-2: Model Calibration Hydrograph (Example Plot)



Comparisons of the predicted total volume against the monitoring total volume and predicted peak flow against monitoring peak flow were analyzed and shown in 1:1 ratio plots for all calibrated meters. This is to evaluate the overall calibration and validation from all the events. The event points in Figure 4-3 are distributed close to the 1:1 ratio line, which means that the model predicted peak flow and wet weather event volume are in good agreement with the metered data. Additional figures for all model calibration plots can be found in Appendix C.

Figure 4-3: Model Calibration Hydrograph (Example Plot)



Section 5 Conclusion

The H&H model from the 2012 DELCORA LTCP Update was reviewed and updated. Data from the rainfall and flow monitoring program was used to calibrate and validate the updated H&H model. The calibrated H&H model will be used to assist DELCORA throughout the remaining steps in the CSO LTCP update process.

In a previous report (Greeley and Hansen, 2016), a typical hydrologic period was selected to represent the average conditions in terms of rainfalls, river flows and combined sewer system response across the DELCORA service area. Subsequent reports will apply the selected typical hydrologic period to the calibrated H&H model to evaluate existing CSO discharge frequency and volume and to evaluate the impacts of proposed LTCP control alternatives on CSO discharges.

Section 6 References

Chesapeake Conservancy. (2017). *Land Cover Data Project*. Retrieved April 10, 2017, from Chesapeak Conservancy Innovation Center: http://chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/land-cover-data-project/

Greeley and Hansen. (2015). *Hydrologic and Hydraulic Model Update and Calibration Plan.* Report prepared for Delaware County Regional Water Quality Control Authority (DELCORA).

Greeley and Hansen. (2016). *Typical Hydrologic Period Report.* Report prepared for Delaware County Regional Water Quality Control Authority (DELCORA).

Muleta, M., & Boulos, P. (2008). Analysis and Calibration of RDII and Design of Sewer Collection Systems. *ASCE Conference Proceedings 316* (p. 642). American Society of Civil Engineers.

NOAA. (2017). *Tides and Currents*. Retrieved May 05, 2017, from National Oceanic and Atmospheric Administration: https://tidesandcurrents.noaa.gov/

USACE. (1996). *Hydrologic Aspects of Flood Warning - Preparedness Programs, Technical Letter 1110-2-540.* Washington, DC: United States Army Corps of Engineers.

USDA. (2017). *Soil Survey*. Retrieved May 05, 2017, from United States Department of Agriculture Natural Resources Conservation Service Soils: https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/

USDA. (2017a). *Web Soil Survey*. Retrieved June 13, 2017, from United States Department of Agriculture Natural Resources Conservation Service: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

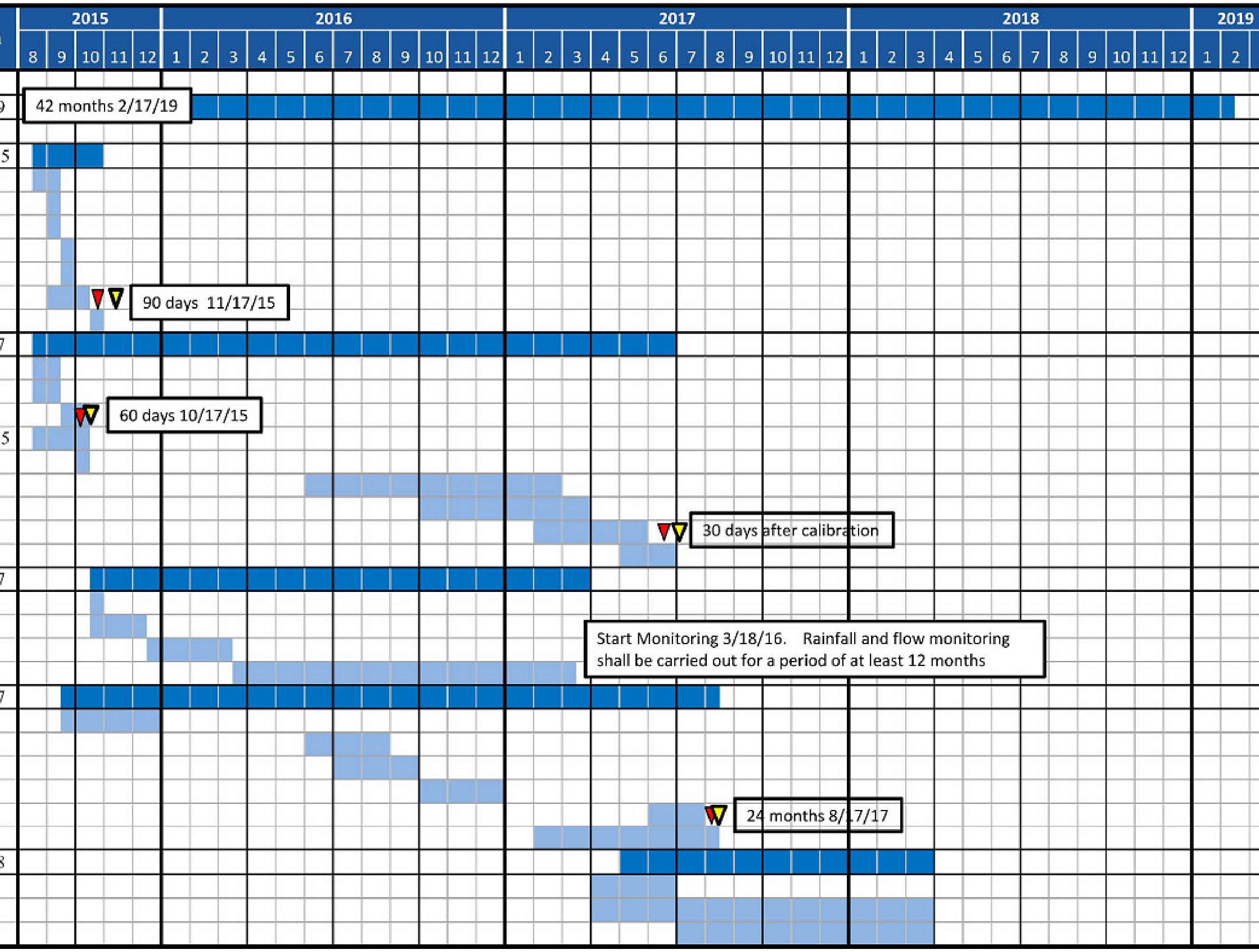
WaPUG. (2002). *Code of Practice for the Hydraulic Modelling of Sewer Systems.* Wastewater Users Planning Group.

Weston. (2012). *Long-Term Control Plan, City of Chester Combined Sewer System.* Report prepared for DELCORA (Revised April 2012).

Appendix A H&H Model Update and Calibration Schedule

Figure 6-1 Schedule for H&H Model Development and Implementation (Updated July 28, 2016)

	Tasks of DELCORA H&H Model Development and Implementation	Start	Finish
Lodging date of Consent Decree (8/17/15)			
DELCORA Long Term Control Plan Update		8/17/15	2/14/19
TASK 3 - Typical Year Rainfall Record (90 days)		8/18/15	10/31/15
1	Develop criteria for determination of typical hydrologic period		
2	Review available historic rainfall and flow data		
3	Obtain rainfall data from the Philadelphia National Airport.		
4	Review with DELCORA		
5	Select the typical hydrologic period and document the selection process		
6	Draft Report		
7	Final Report		
TASK 5 - Hydrologic & Hydraulic Model		8/18/15	8/17/17
1	Initial assessment of GIS Model		
2	Initial assessment of H&H Model		
3	Report summarizing Initial Assessment		
4	Develop an H&H Model Update and Calibration Plan (60 days)	8/18/15	10/14/15
5	Develop Schedule for Model Development and implementation		
6	H&H Model Update		
7	Flow Monitoring Data Analysis		
8	H&H Model Calibration		
9	H&H Model Report		
TASK 6 - Rainfall and Flow Monitoring		10/15/15	3/31/17
1	Prepare Rainfall and Flow Monitoring Work Plan (from Task 5)		
2	Procure Flow Metering and Rain Gauge Services		
3	Install and Calibrate Rain Gauge and Flow Meters for Official Data Gathering		
4	Conduct Rainfall and Flow Monitoring		
TASK 7 - Existing Service Area Characterization		9/15/15	8/17/17
1	GIS Mapping Review and Update		
2	Refine Service Area Delineation (Combined and Separated)		
3	Investigate Existing CSO Facilities		
4	Investigate Service Agreements		
5	Perform H&H Modeling of Existing System		
6	Documentation		
Evaluation of CSO Alternatives (Part of Task 11)		5/1/17	3/31/18
1	Develop Future DWF and Service Area		
2	Develop CSO Alternatives		
3	Evaluate CSO Alternatives using H&H Model		



NOTES:
- Consent Order Deadline
- Draft and Final submittals

Appendix B Description of Hydrologic Soil Groups

Hydrologic Soil Groups (USDA, 2017a)

Hydrologic soil groups are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms.

The soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). The groups are defined as follows:

Group A. Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.

Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.

Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.

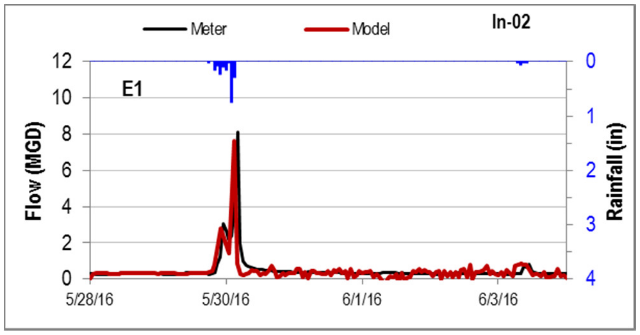
Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

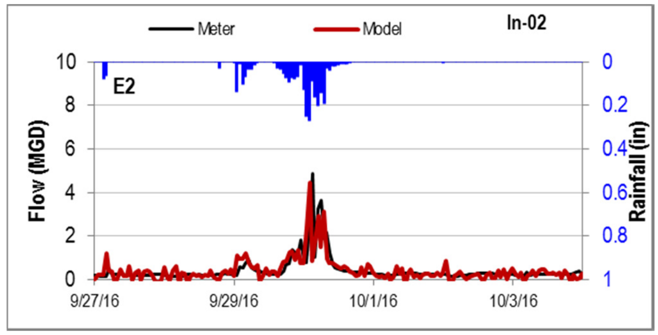
If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes.

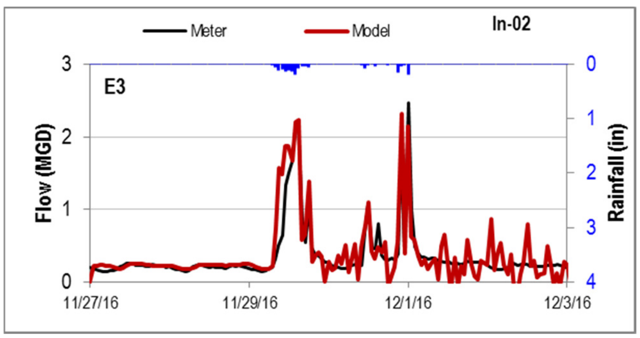
Appendix C Model Calibration and Validation Results

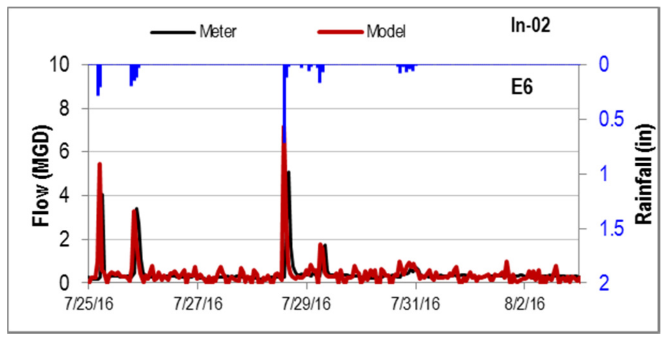
FLOW METER IN-02 MODEL CALIBRATION AND VALIDATION RESULTS

In-02 Model Calibration Results (Metered and Modeled Flow)

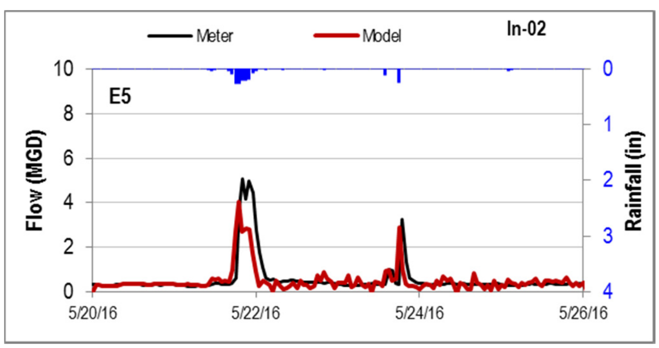




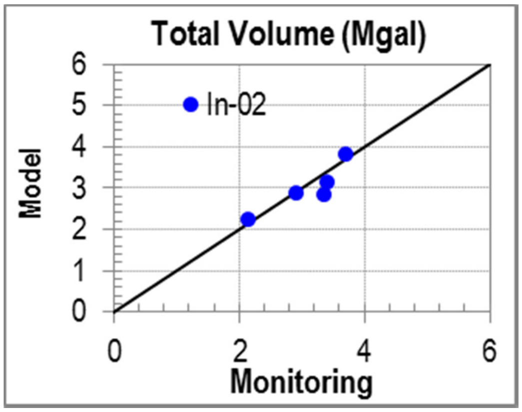


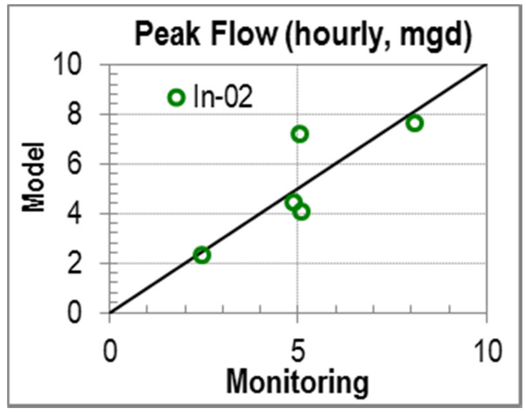


In-02 Model Validation Results (Metered and Modeled Flow)



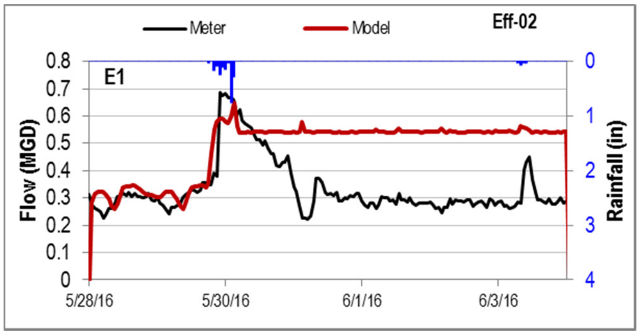
In-02 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

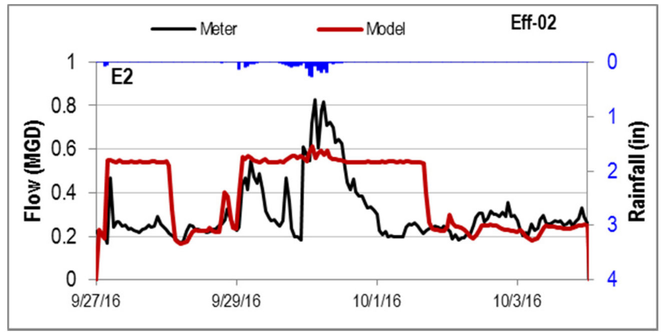


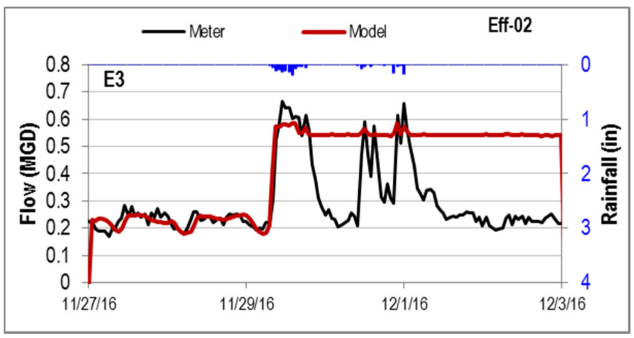


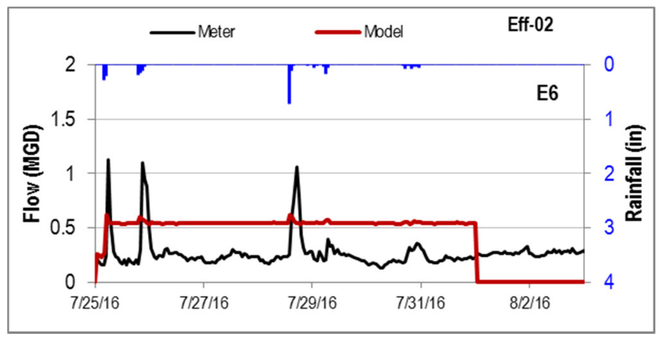
FLOW METER EFF-02 MODEL CALIBRATION AND VALIDATION RESULTS

EFF-02 Model Calibration Results (Metered and Modeled Flow)

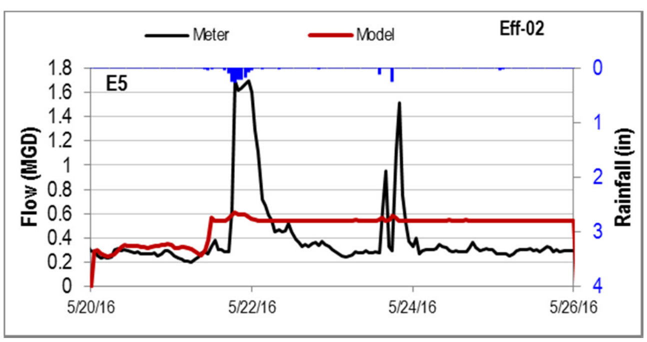




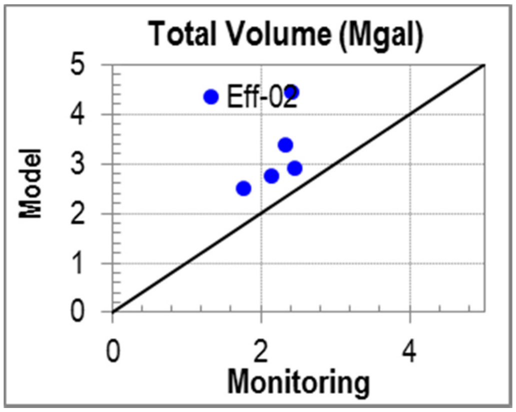


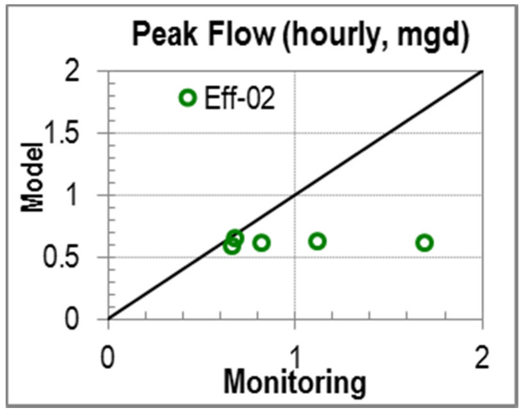


EFF-02 Model Validation Results (Metered and Modeled Flow)



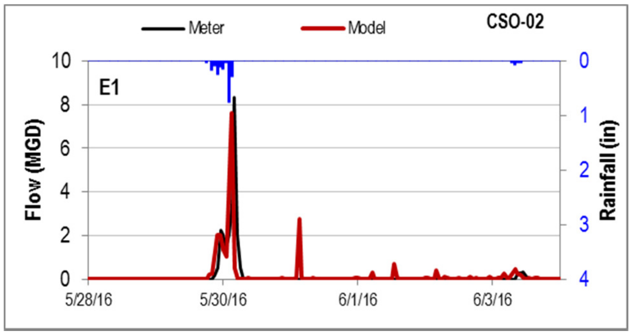
EFF-02 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

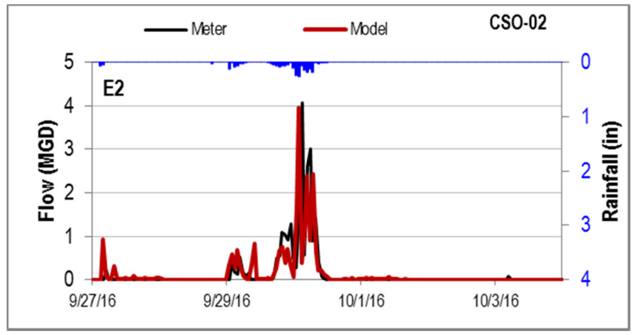


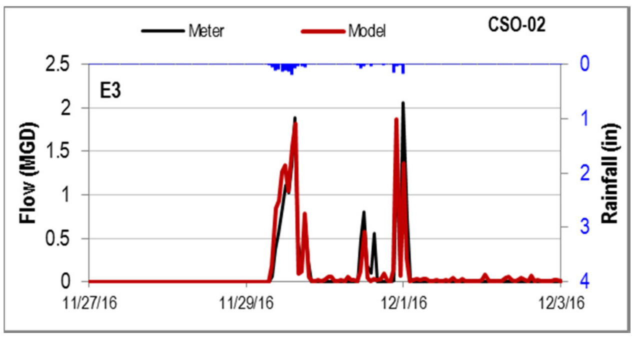


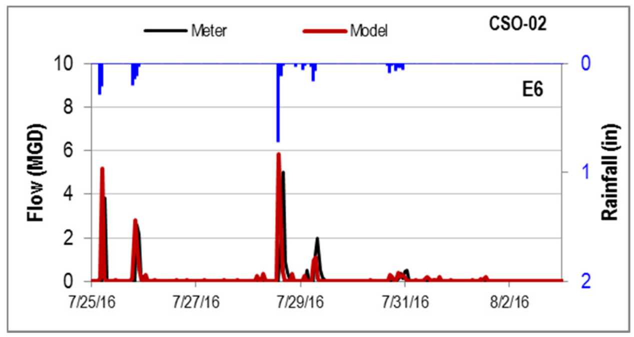
FLOW METER CSO-02 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-02 Model Calibration Results (Metered and Modeled Flow)

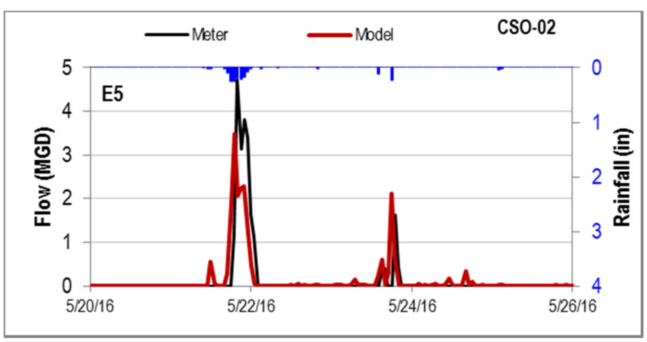




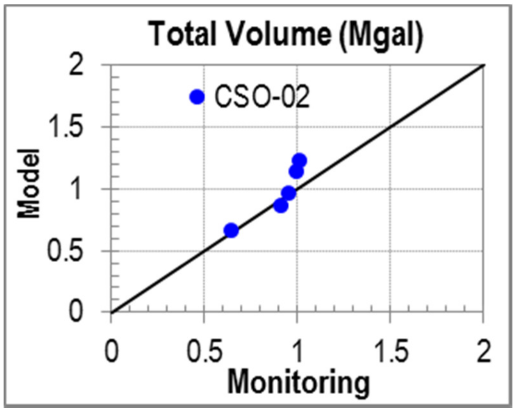


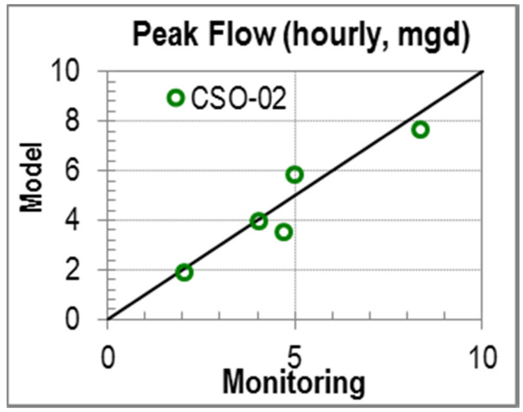


CSO-02 Model Validation Results (Metered and Modeled Flow)



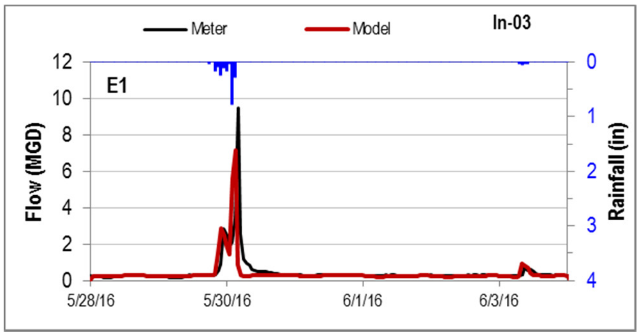
CSO-02 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

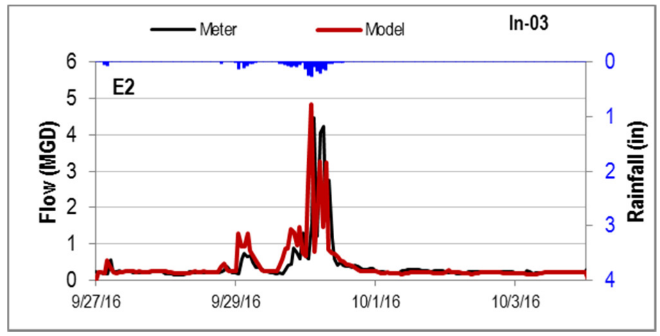


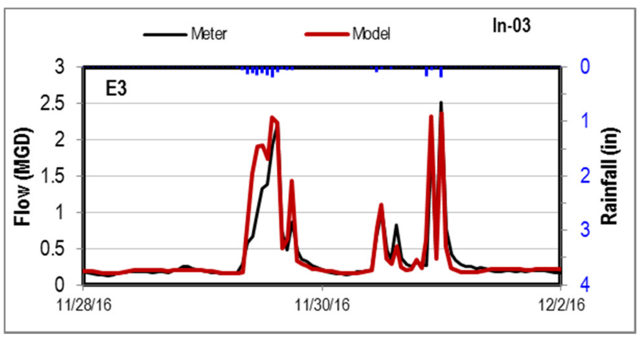


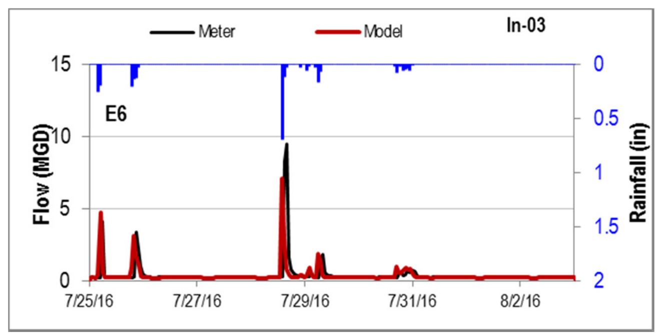
FLOW METER IN-03 MODEL CALIBRATION AND VALIDATION RESULTS

In-03 Model Calibration Results (Metered and Modeled Flow)

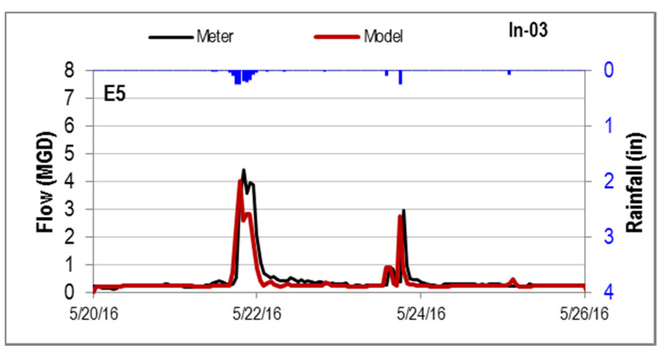




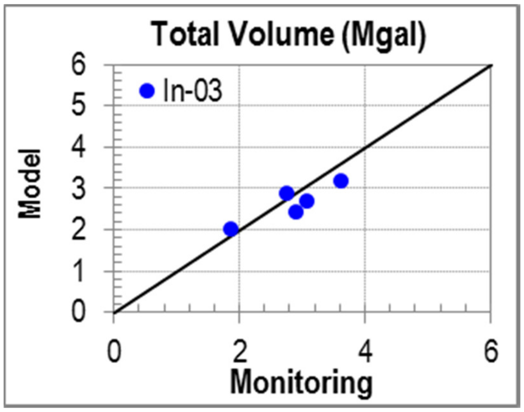


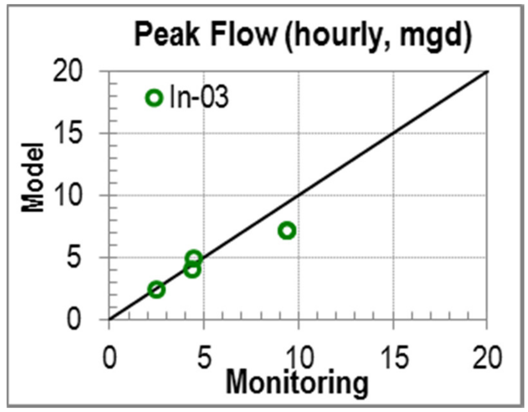


In-03 Model Validation Results (Metered and Modeled Flow)



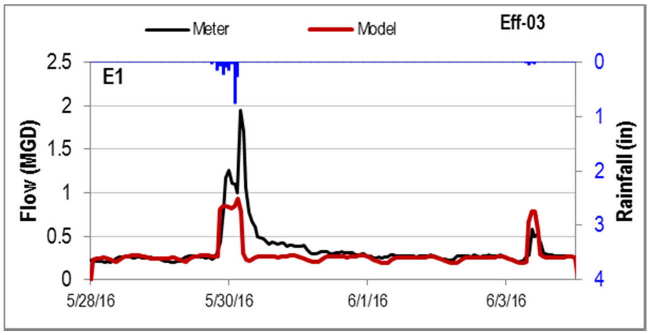
In-03 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

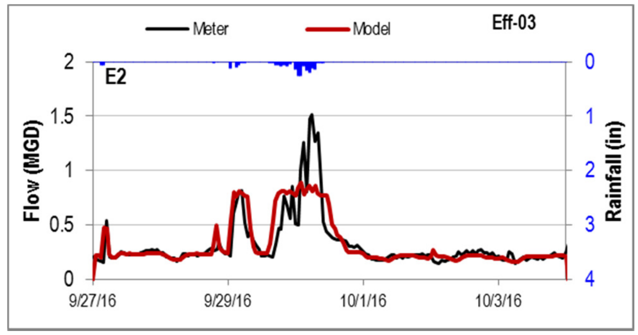


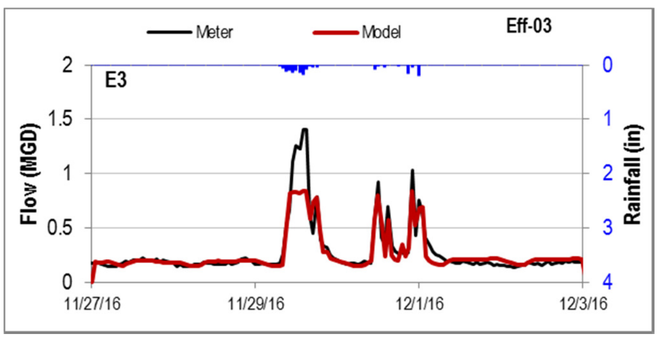


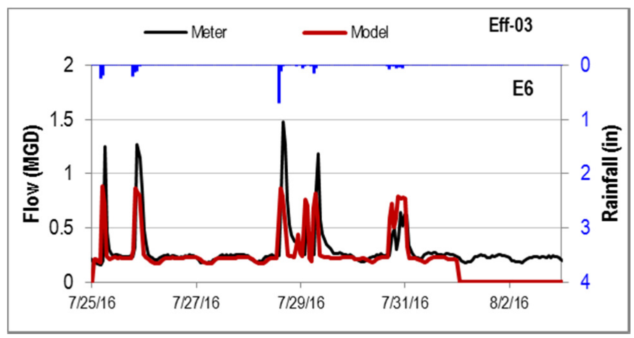
FLOW METER Eff-03 MODEL CALIBRATION AND VALIDATION RESULTS

Eff-03 Model Calibration Results (Metered and Modeled Flow)

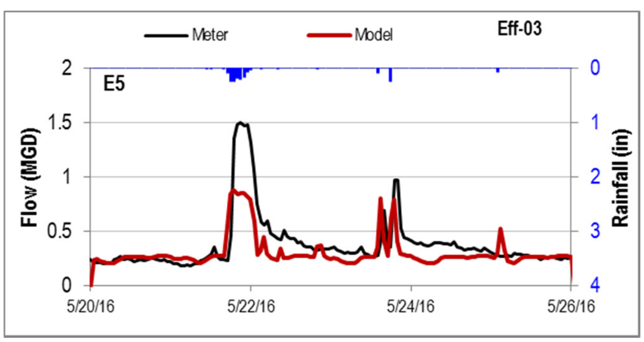




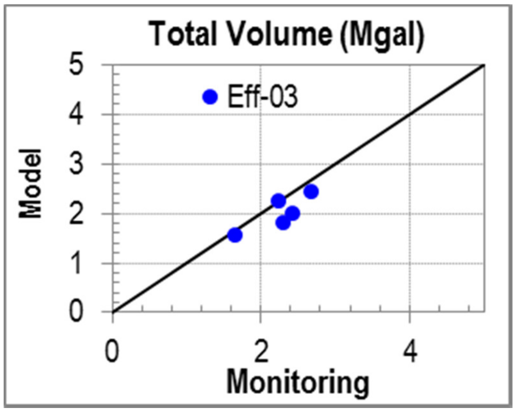


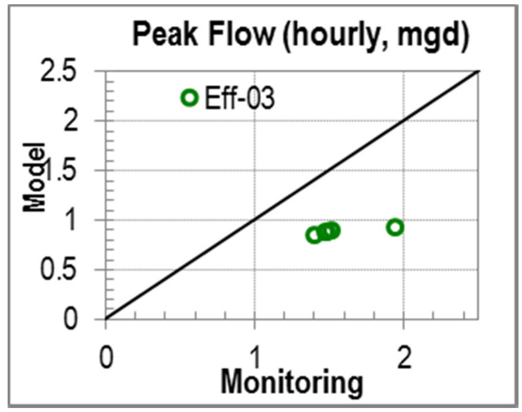


Eff-03 Model Validation Results (Metered and Modeled Flow)



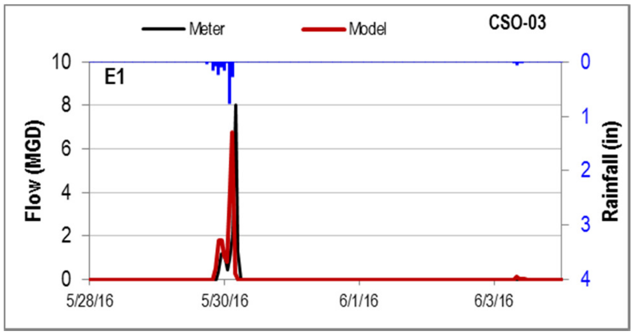
Eff-03 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

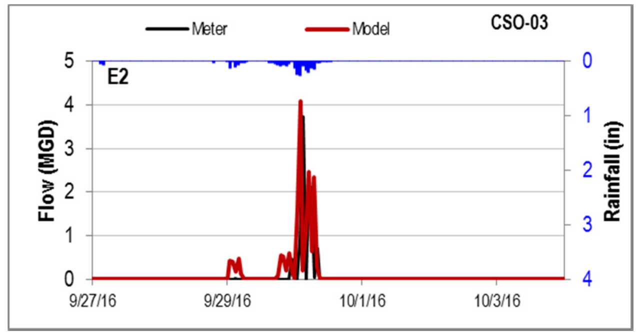


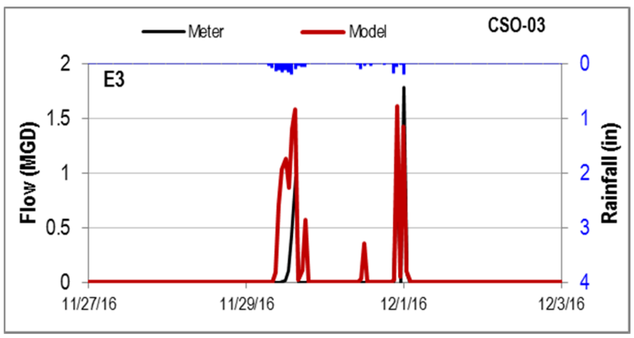


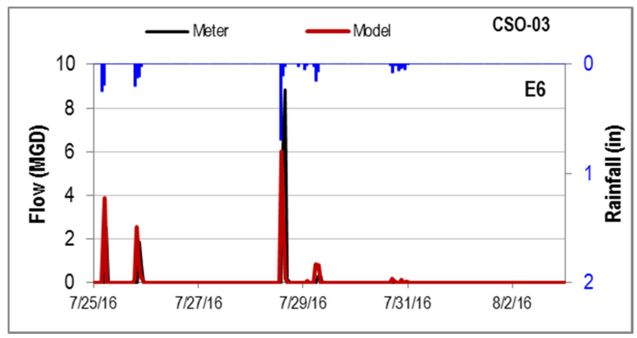
FLOW METER CSO-03 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-03 Model Calibration Results (Metered and Modeled Flow)

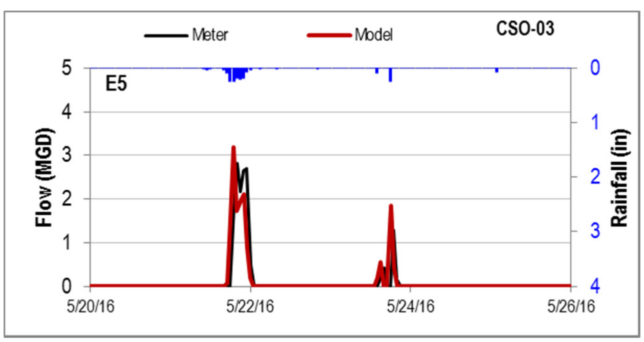




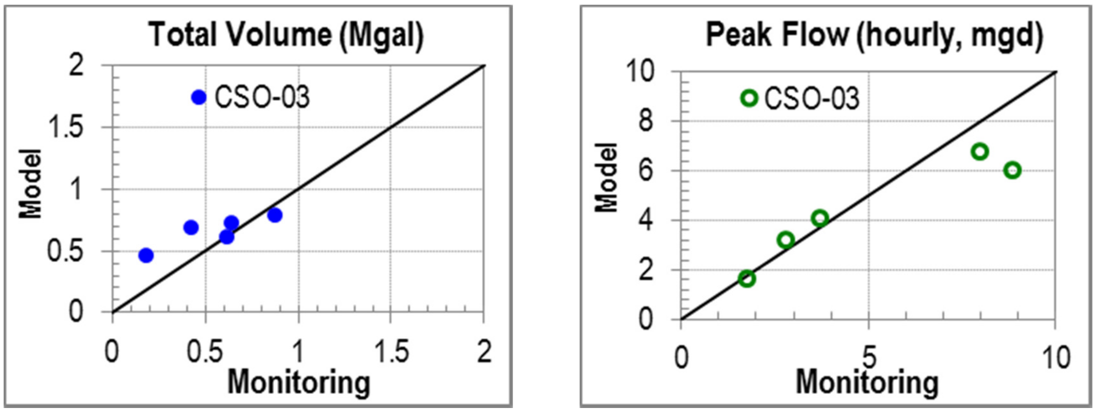




CSO-03 Model Validation Results (Metered and Modeled Flow)

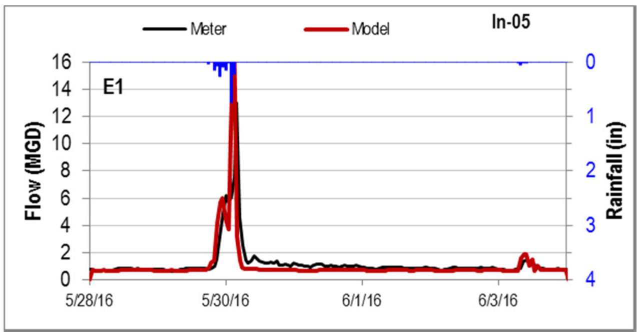


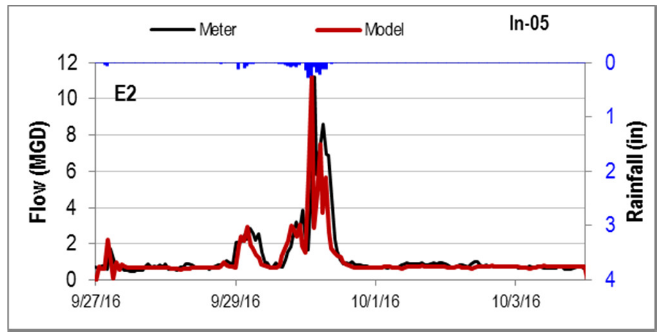
CSO-03 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

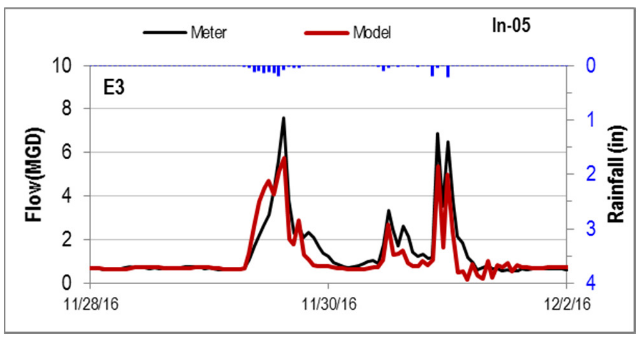


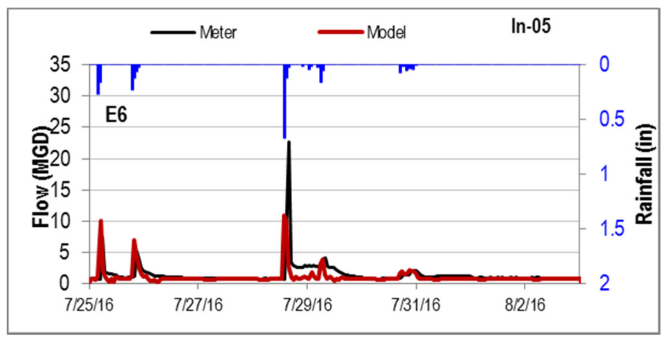
FLOW METER IN-05 MODEL CALIBRATION AND VALIDATION RESULTS

In-05 Model Calibration Results (Metered and Modeled Flow)

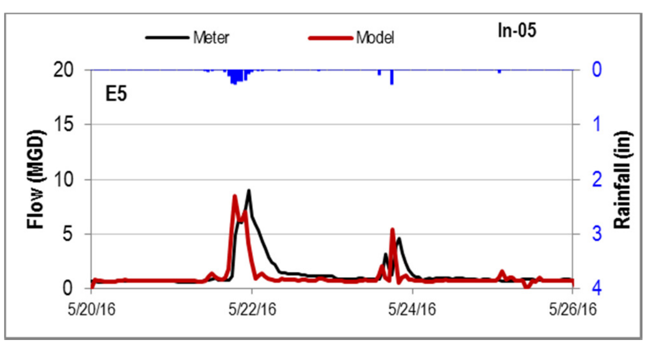




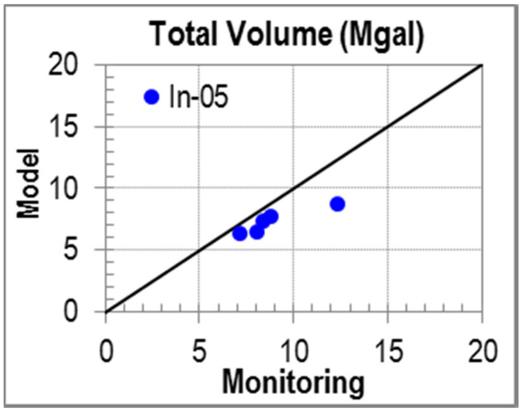


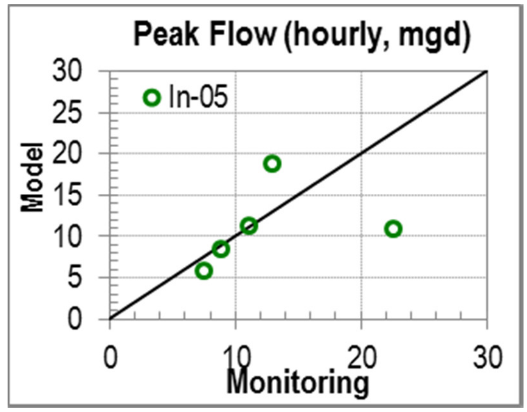


In-05 Model Validation Results (Metered and Modeled Flow)



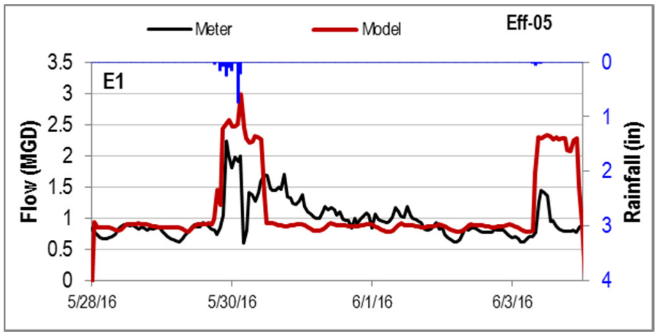
In-05 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

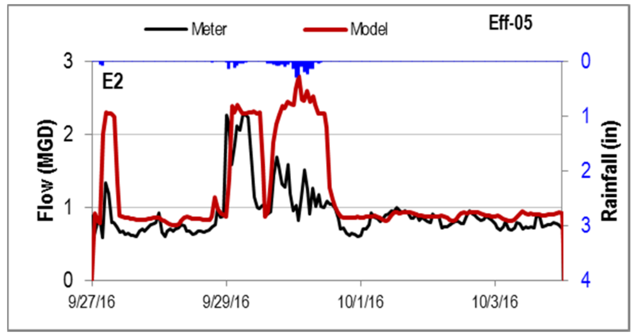


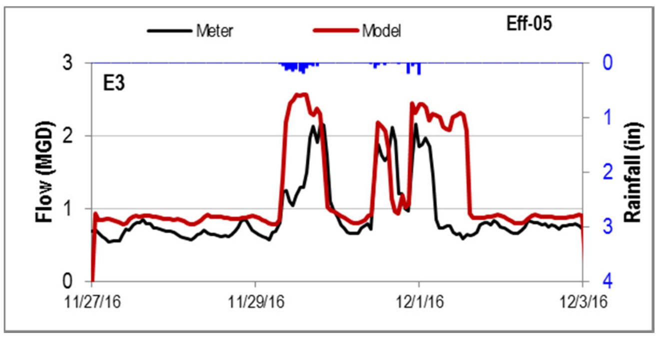


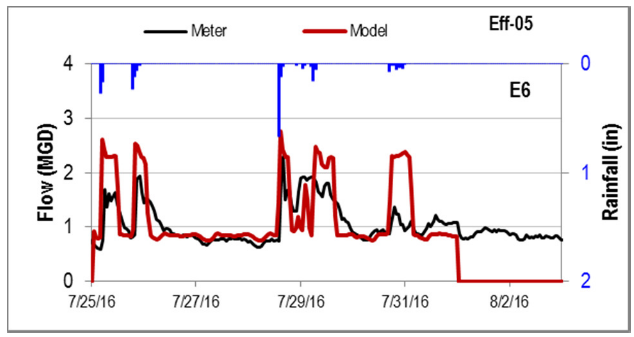
FLOW METER eFF-05 MODEL CALIBRATION AND VALIDATION RESULTS

Eff-05 Model Calibration Results (Metered and Modeled Flow)

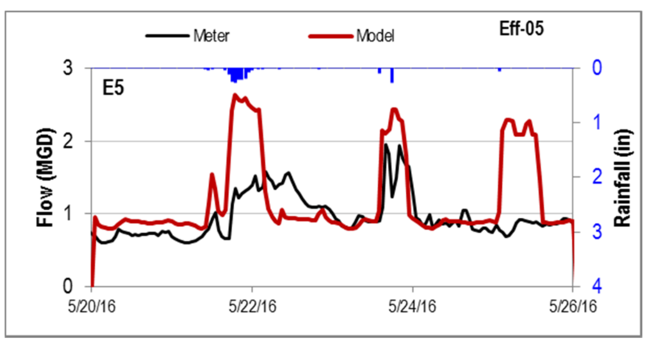




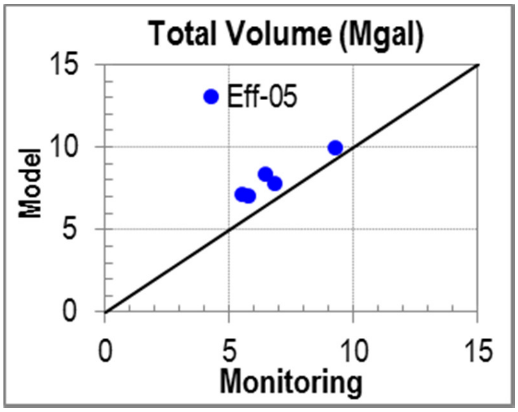


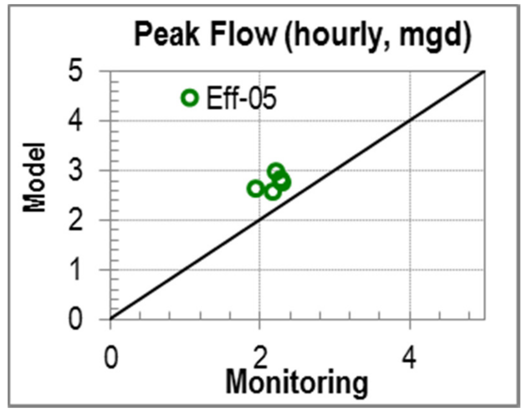


Eff-05 Model Validation Results (Metered and Modeled Flow)



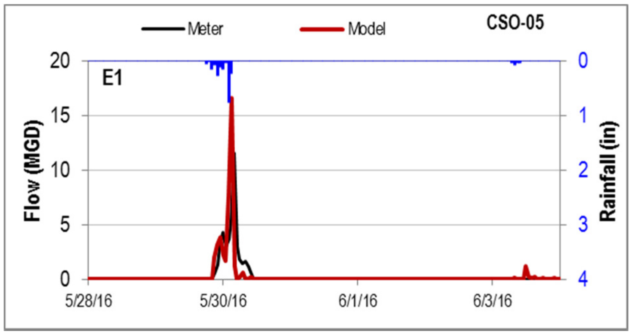
Eff-05 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

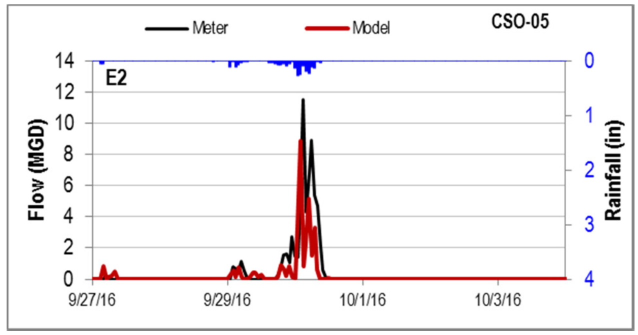


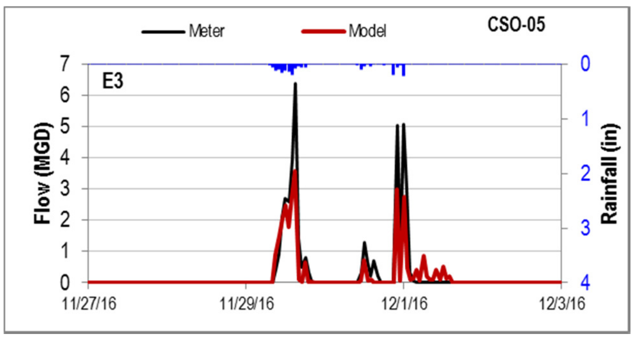


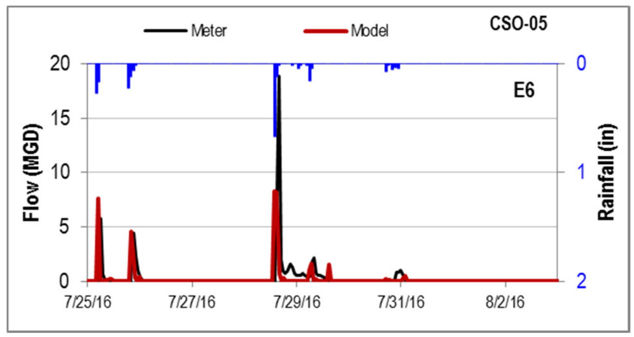
FLOW METER CSO-05 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-05 Model Calibration Results (Metered and Modeled Flow)

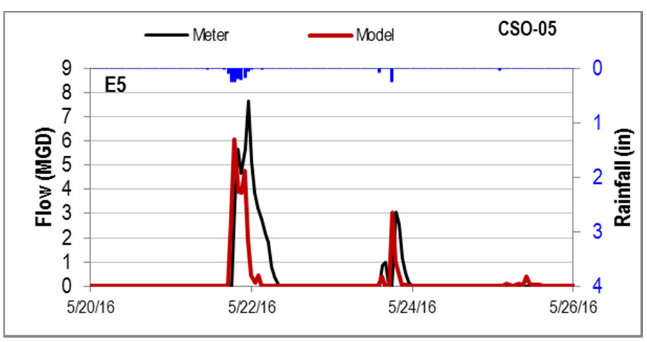




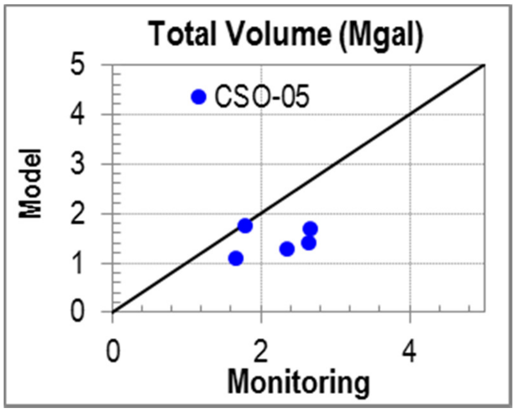


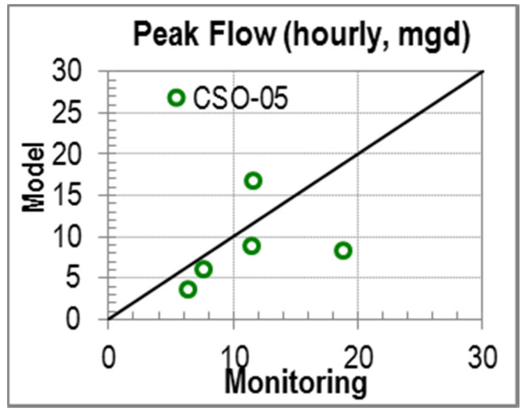


CSO-05 Model Validation Results (Metered and Modeled Flow)



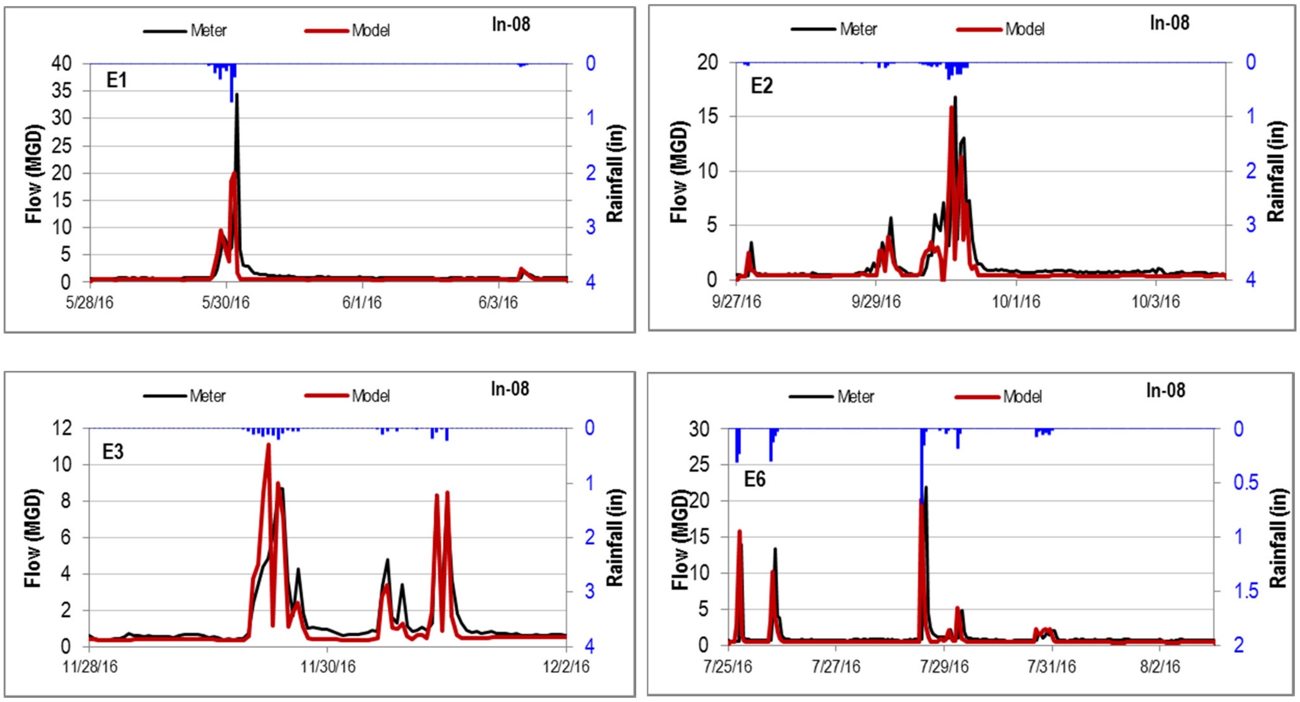
CSO-05 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



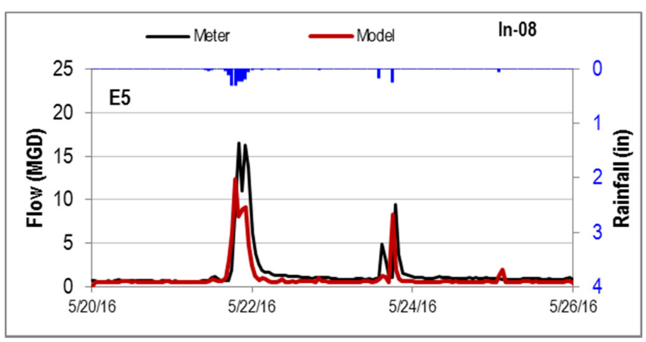


FLOW METER IN-08 MODEL CALIBRATION AND VALIDATION RESULTS

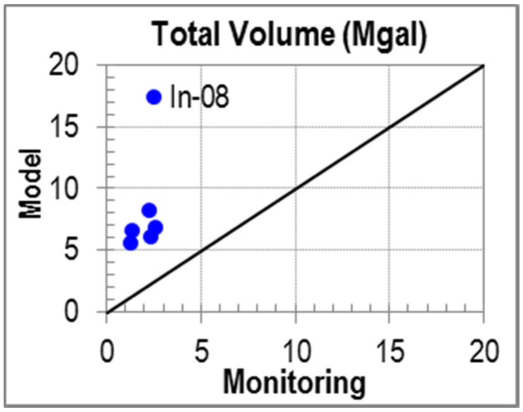
In-08 Model Calibration Results (Metered and Modeled Flow)

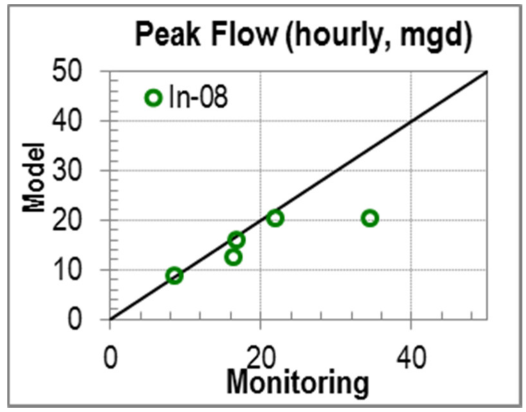


In-08 Model Validation Results (Metered and Modeled Flow)



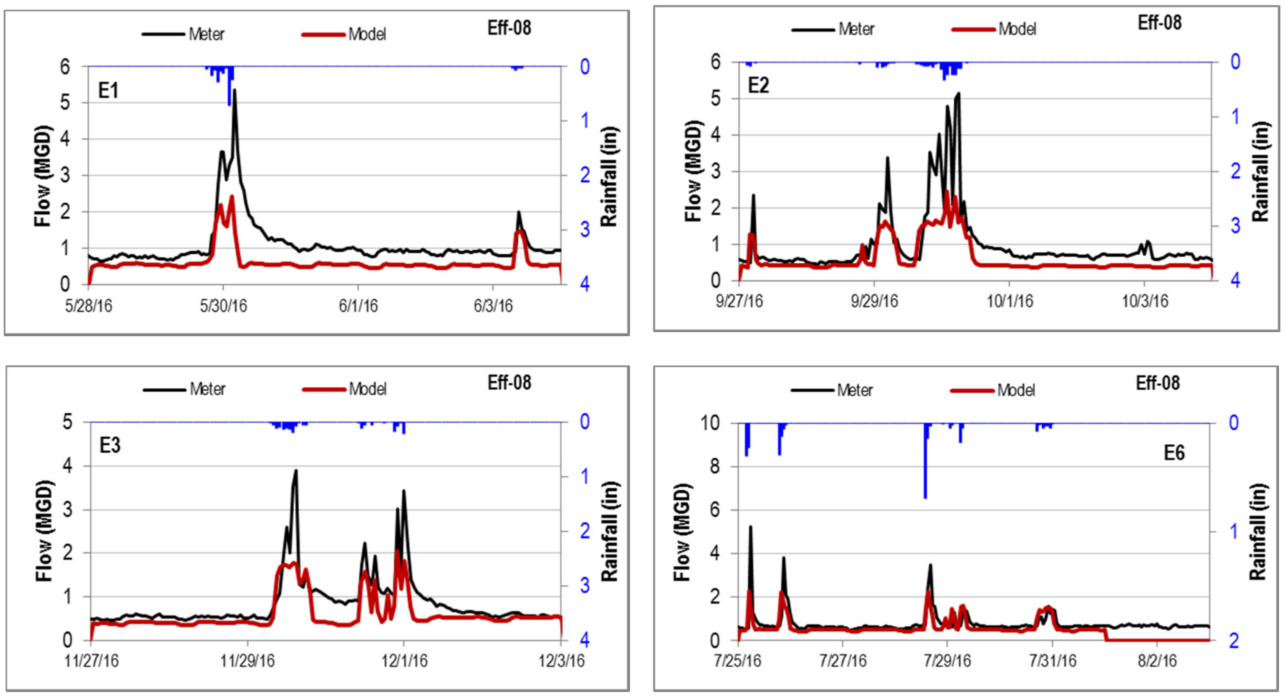
In-08 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



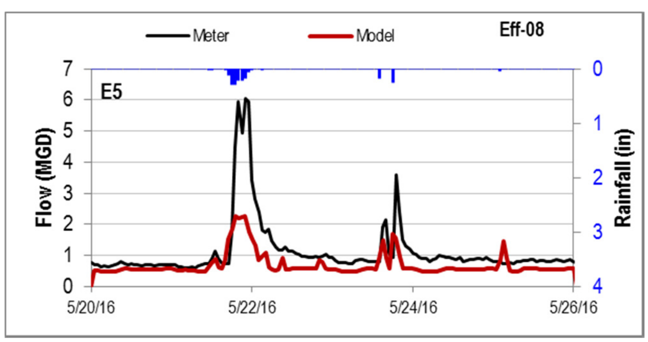


FLOW METER Eff-08 MODEL CALIBRATION AND VALIDATION RESULTS

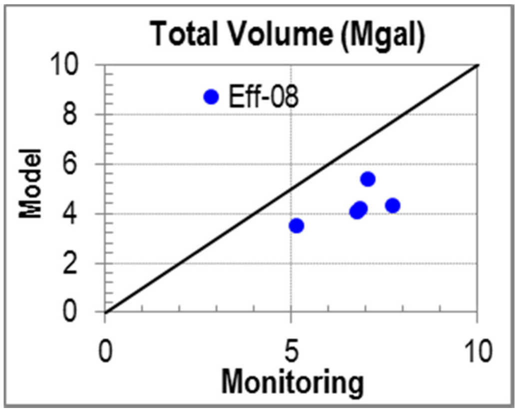
Eff-08 Model Calibration Results (Metered and Modeled Flow)

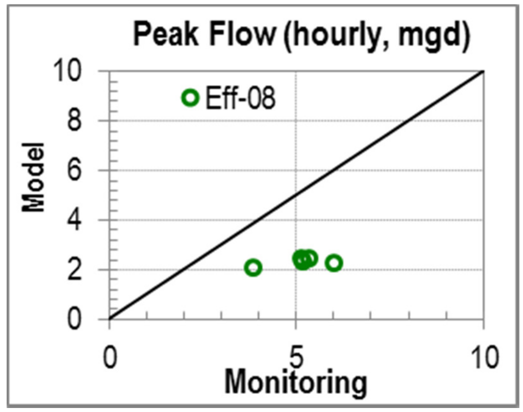


Eff-08 Model Validation Results (Metered and Modeled Flow)



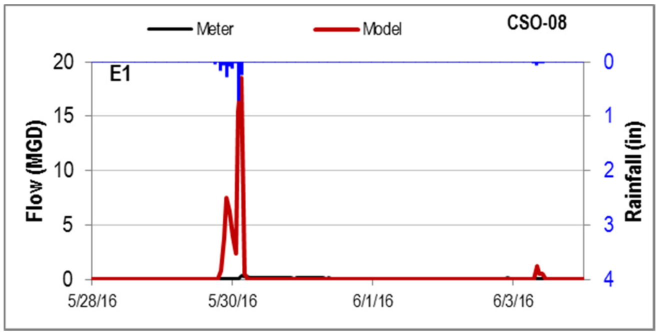
Eff-08 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

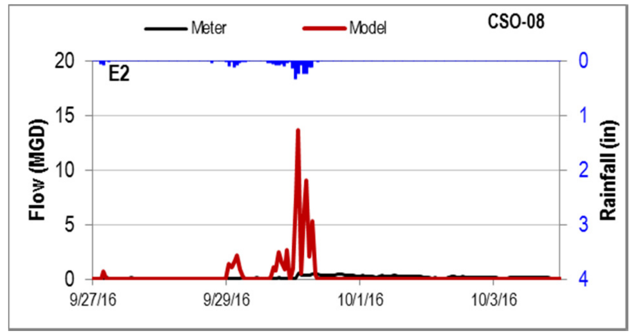


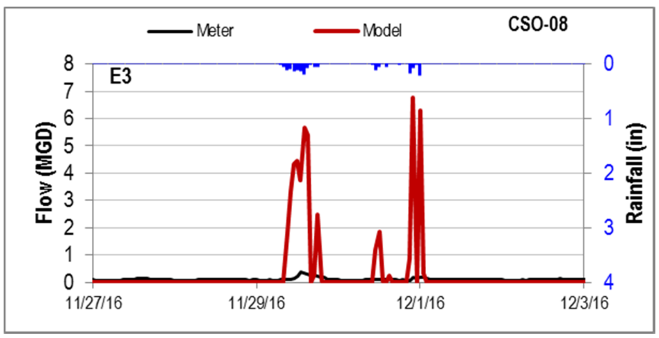


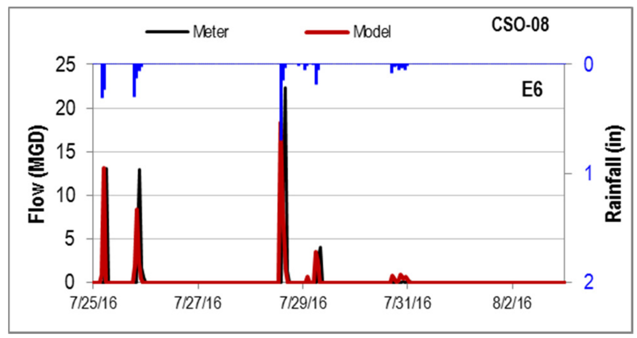
FLOW METER CSO-08 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-08 Model Calibration Results (Metered and Modeled Flow)

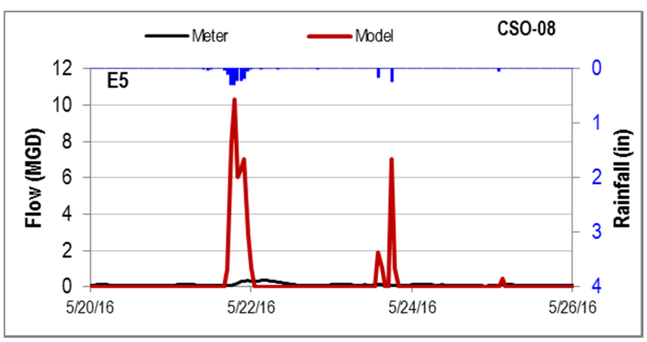




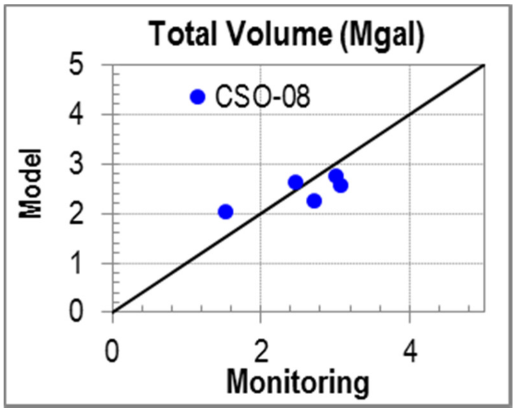


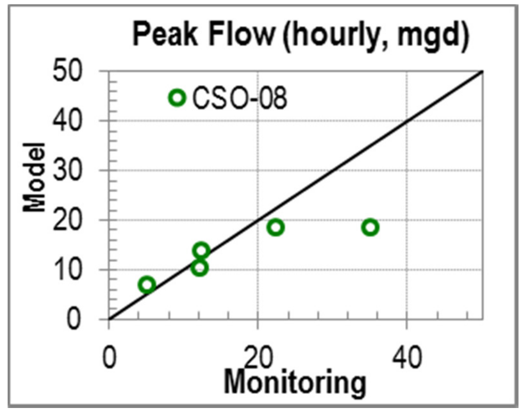


CSO-08 Model Validation Results (Metered and Modeled Flow)



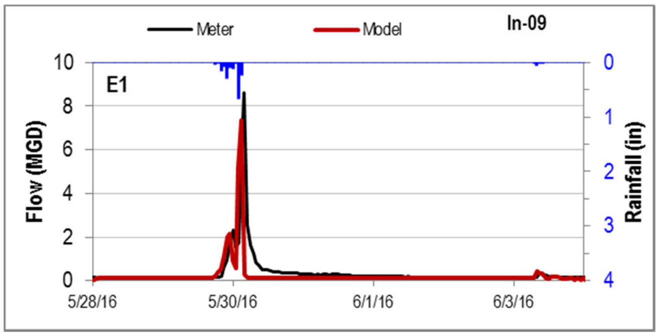
CSO-08 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

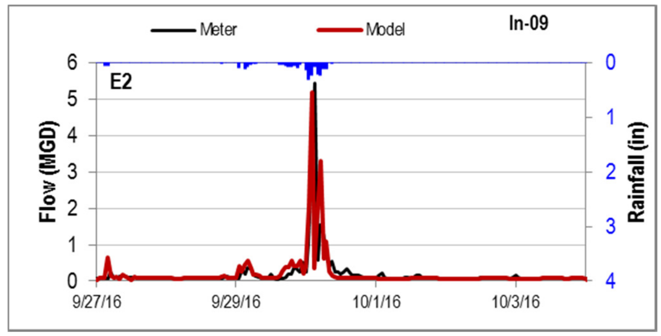


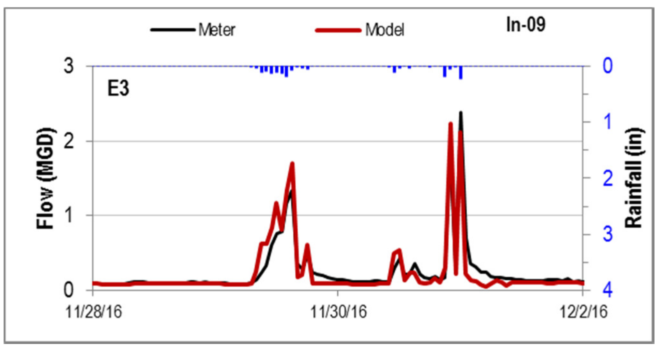


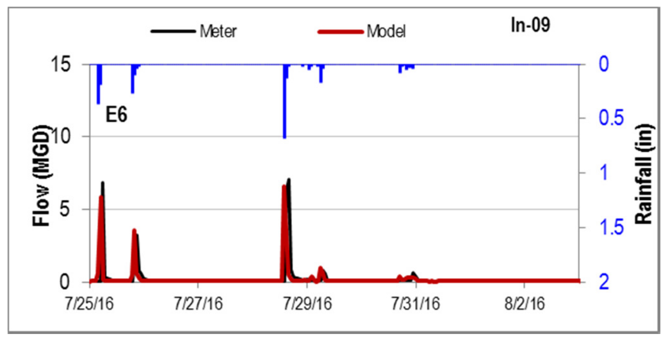
FLOW METER IN-09 MODEL CALIBRATION AND VALIDATION RESULTS

In-09 Model Calibration Results (Metered and Modeled Flow)

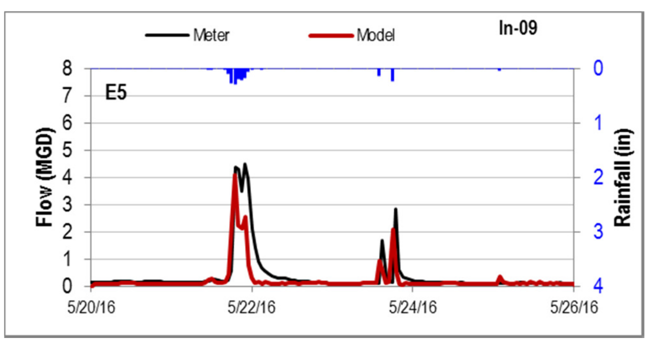




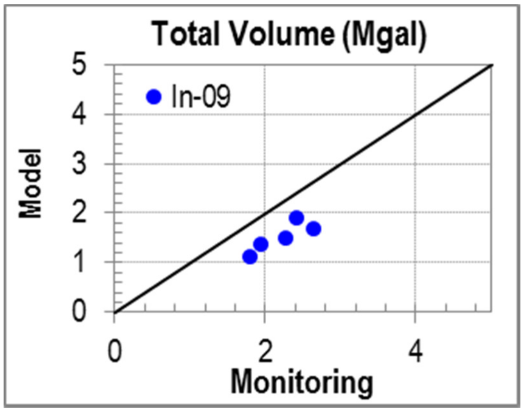


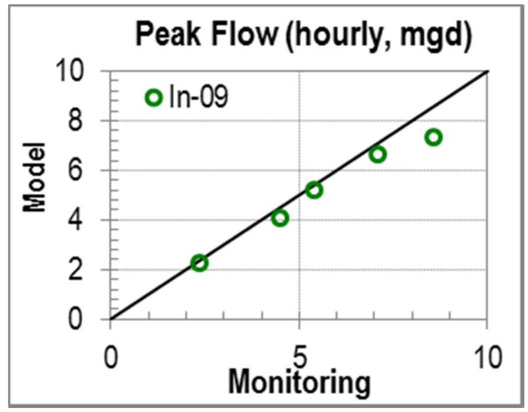


In-09 Model Validation Results (Metered and Modeled Flow)



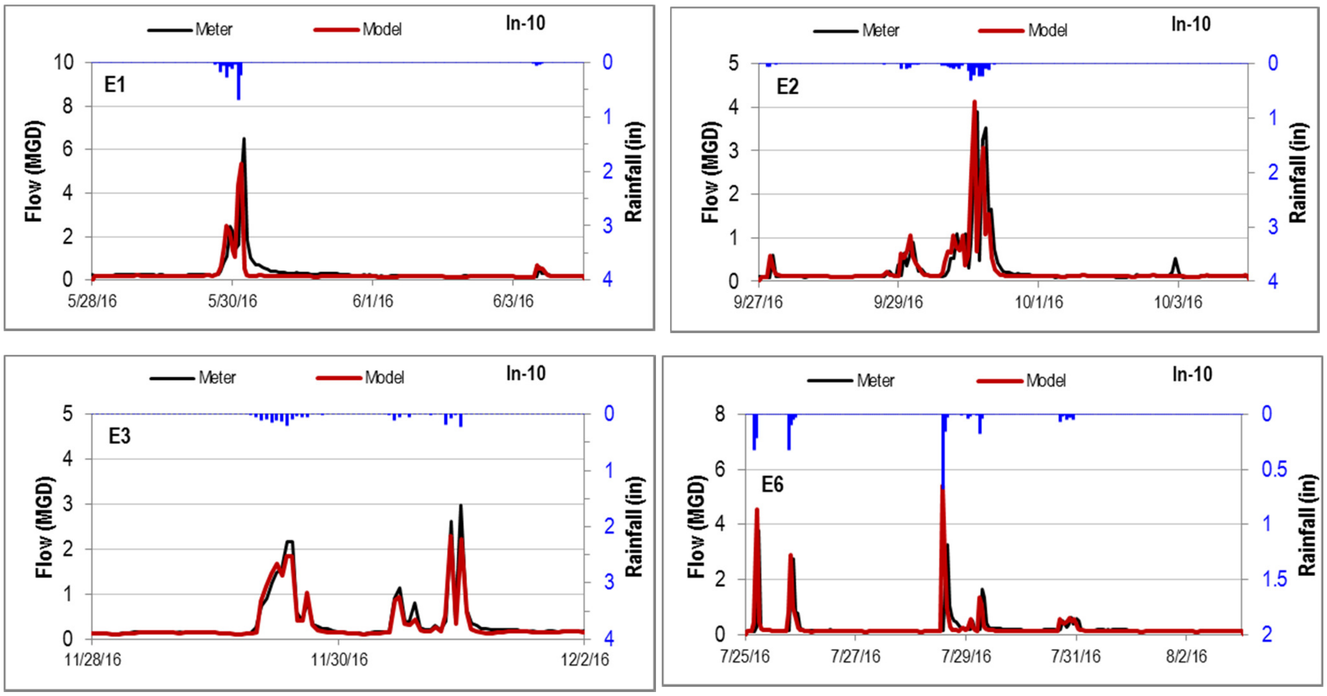
In-09 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



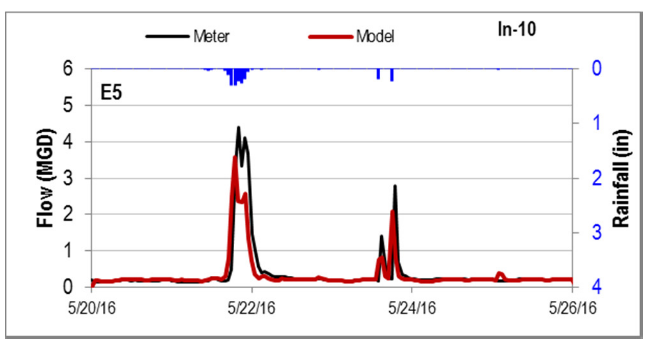


FLOW METER IN-10 MODEL CALIBRATION AND VALIDATION RESULTS

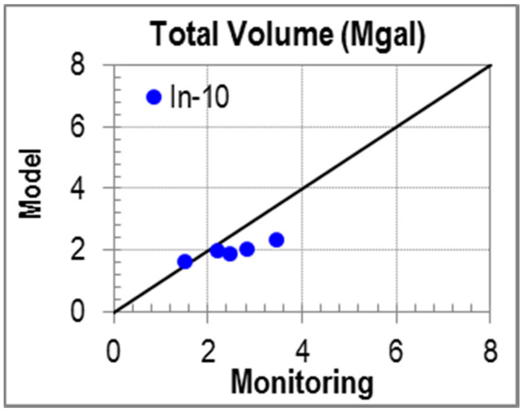
In-10 Model Calibration Results (Metered and Modeled Flow)

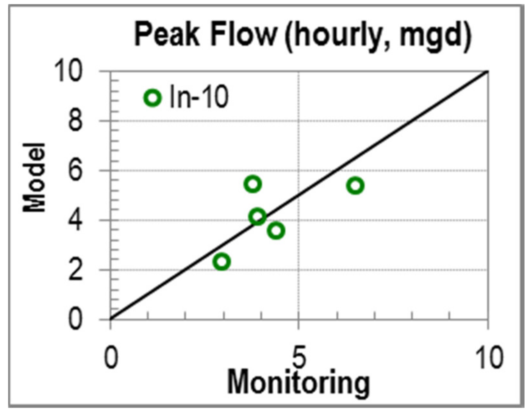


In-10 Model Validation Results (Metered and Modeled Flow)



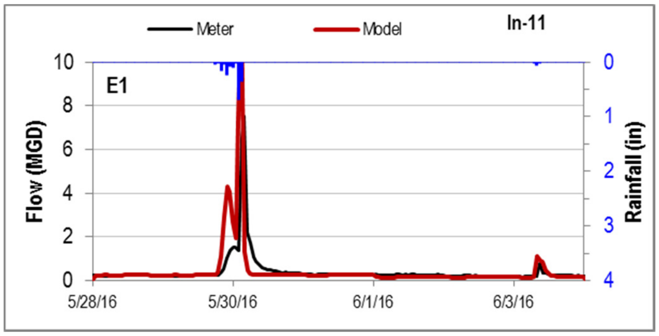
In-10 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

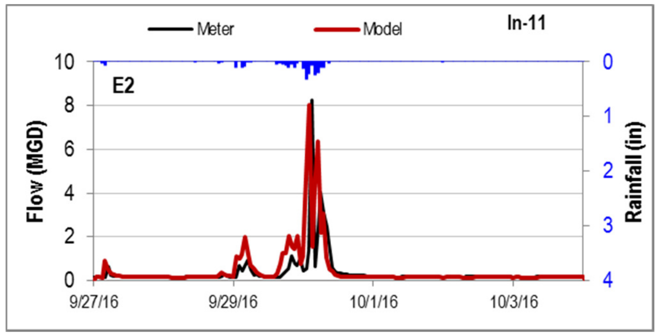


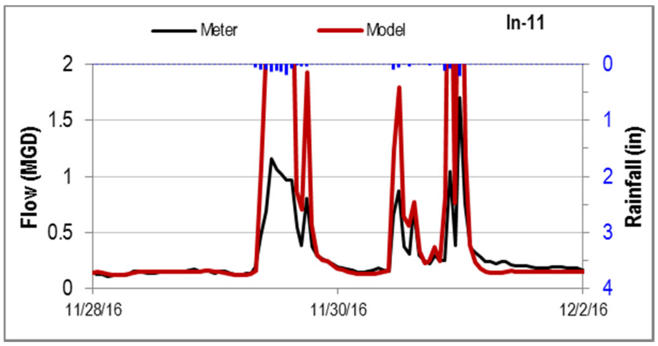


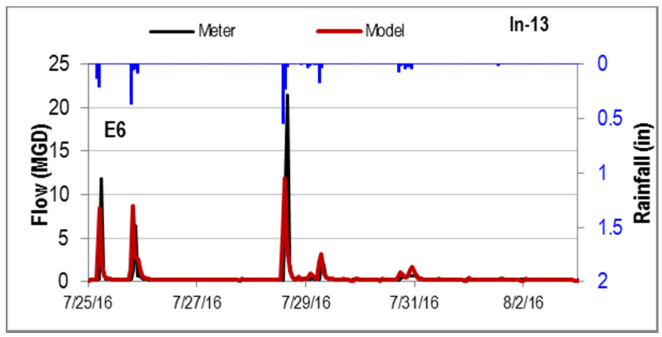
FLOW METER IN-11 MODEL CALIBRATION AND VALIDATION RESULTS

In-11 Model Calibration Results (Metered and Modeled Flow)

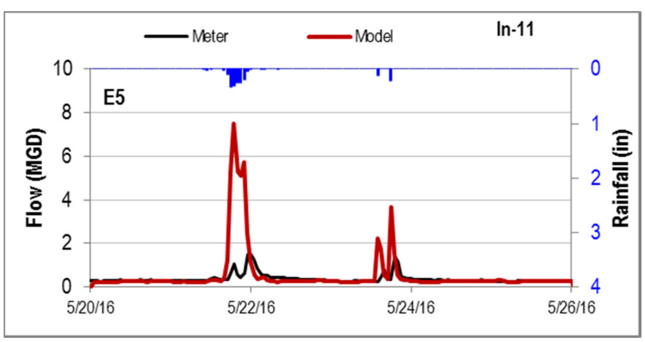




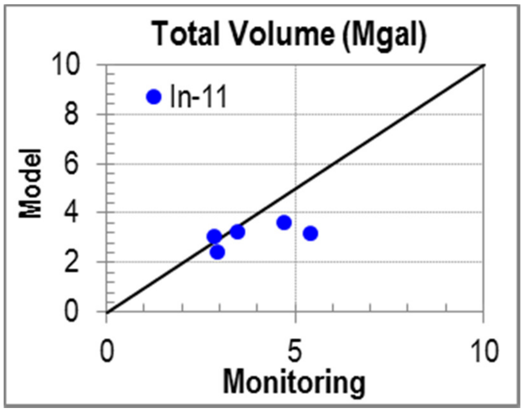


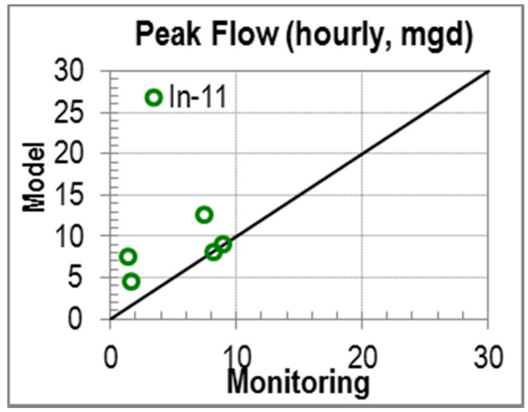


In-11 Model Validation Results (Metered and Modeled Flow)



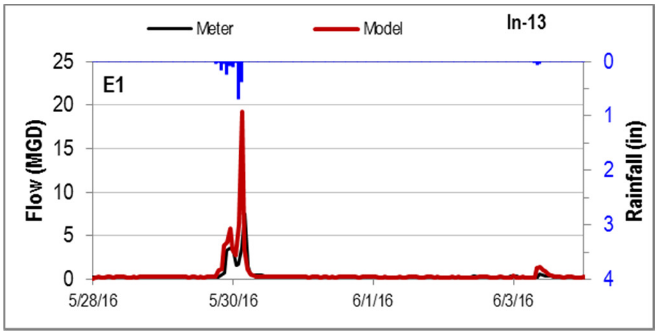
In-11 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

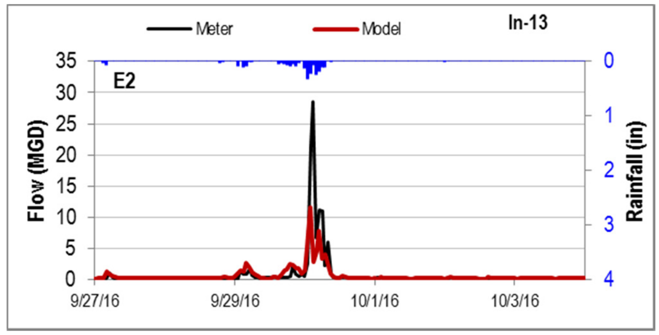


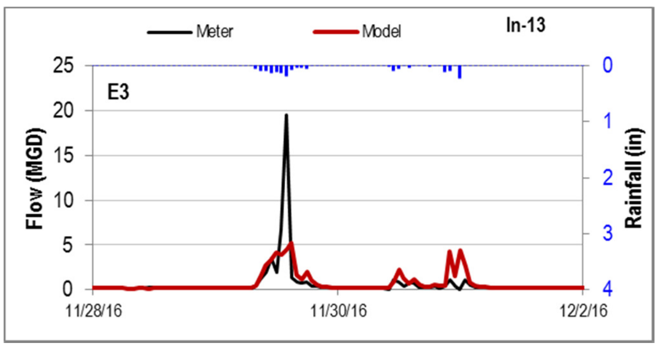


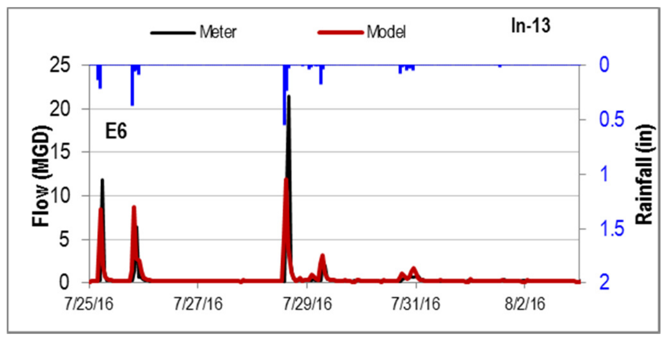
FLOW METER IN-13 MODEL CALIBRATION AND VALIDATION RESULTS

In-13 Model Calibration Results (Metered and Modeled Flow)

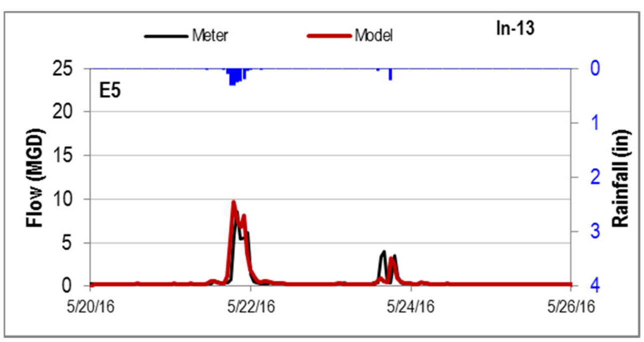




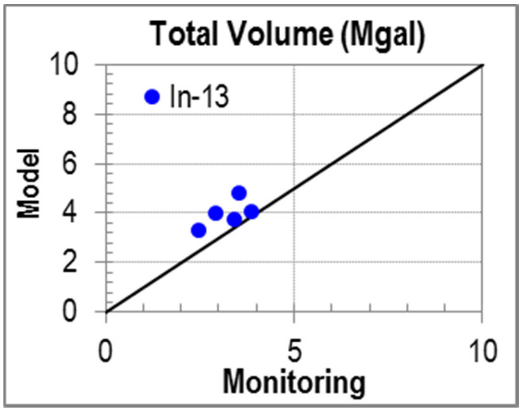


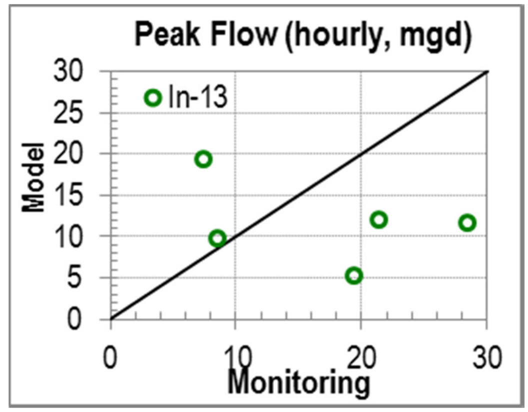


In-13 Model Validation Results (Metered and Modeled Flow)



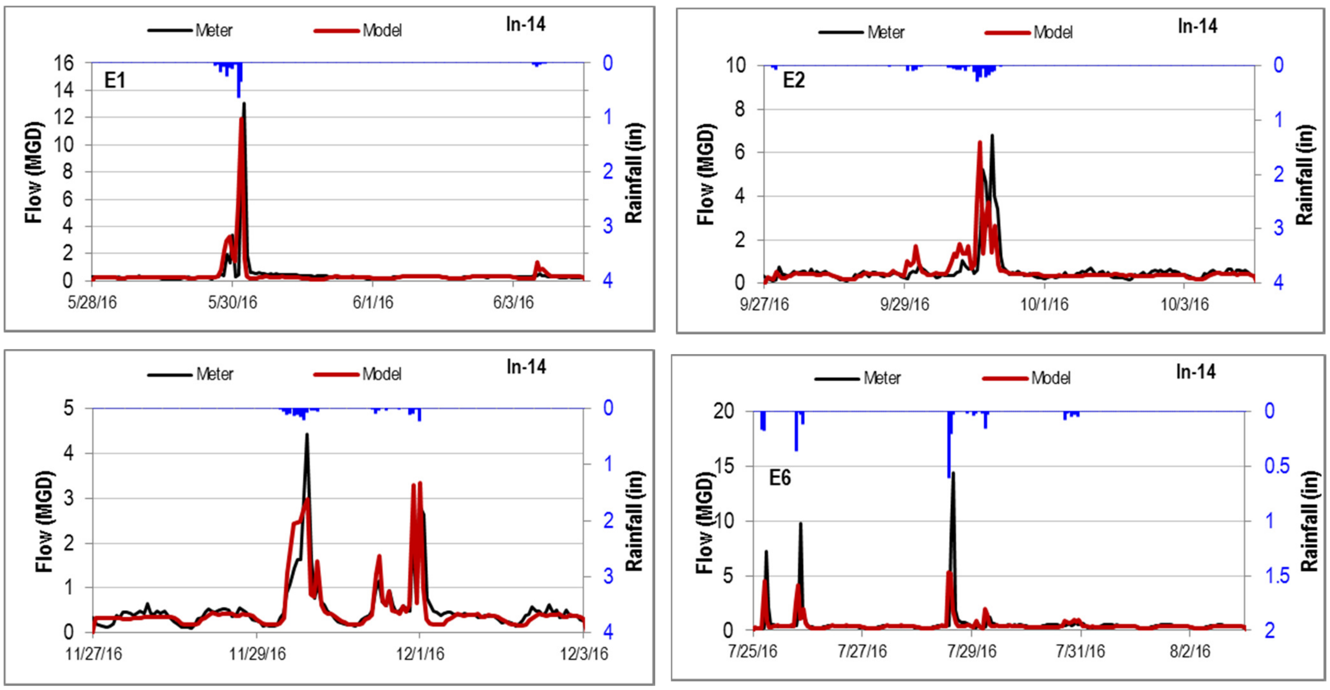
In-13 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



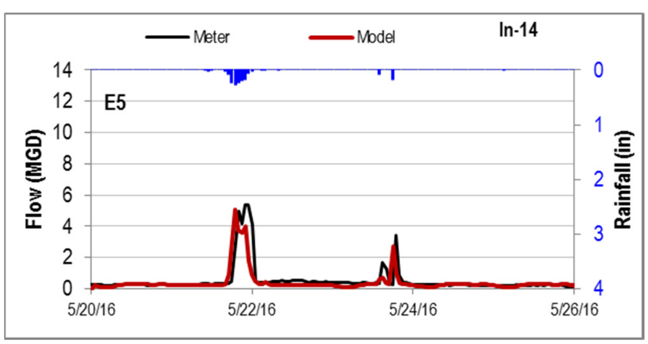


FLOW METER IN-14 MODEL CALIBRATION AND VALIDATION RESULTS

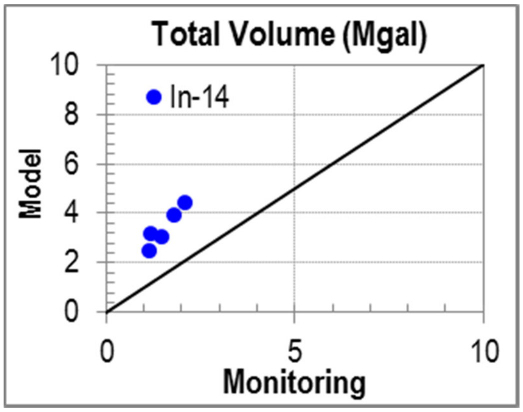
In-14 Model Calibration Results (Metered and Modeled Flow)

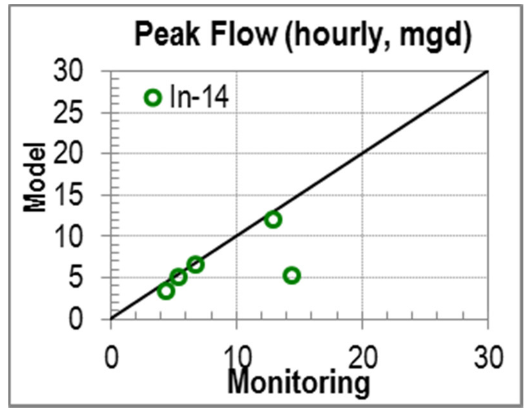


In-14 Model Validation Results (Metered and Modeled Flow)



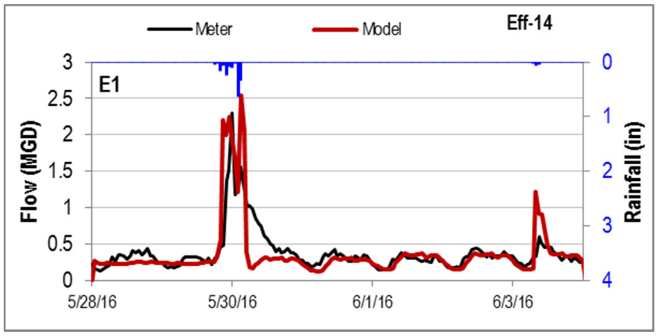
In-14 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

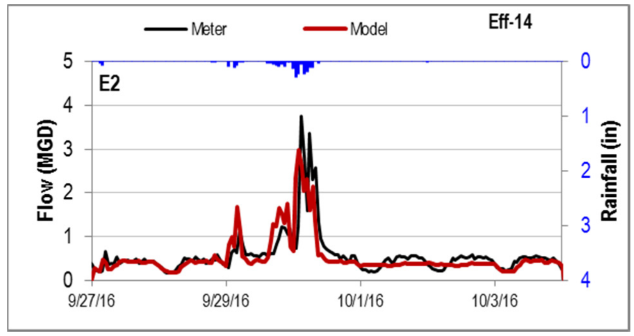


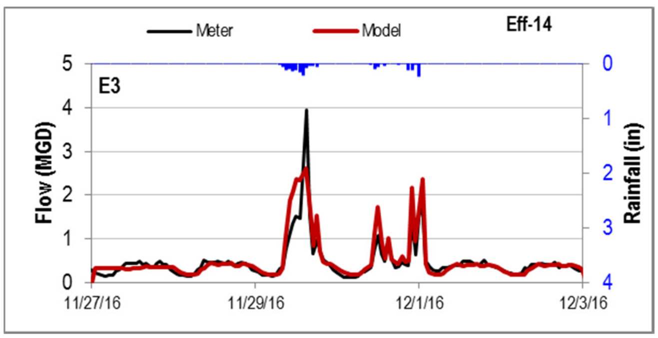


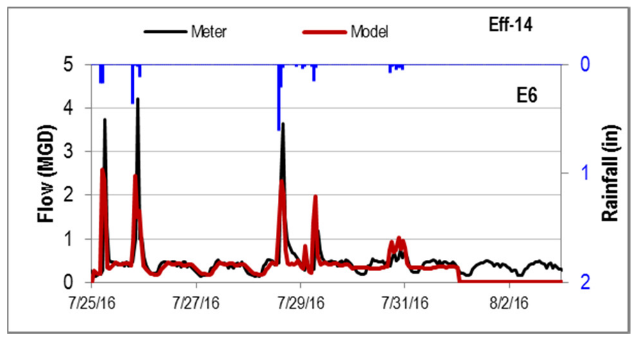
FLOW METER Eff-14 MODEL CALIBRATION AND VALIDATION RESULTS

Eff-14 Model Calibration Results (Metered and Modeled Flow)

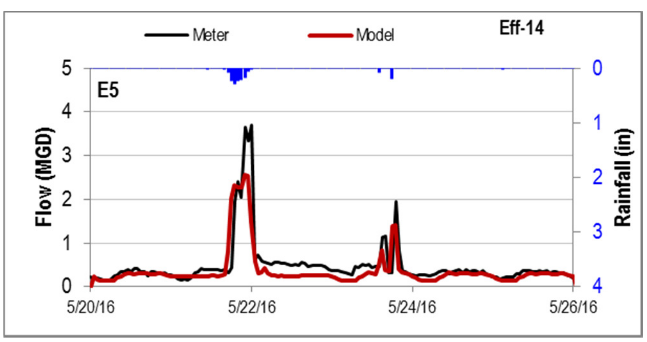




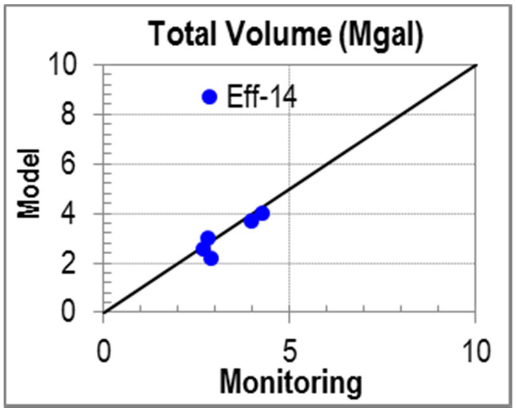


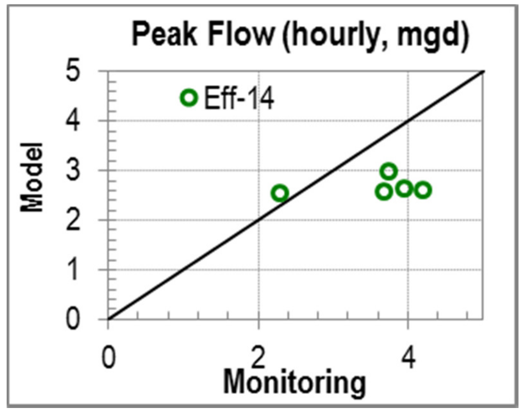


Eff-14 Model Validation Results (Metered and Modeled Flow)



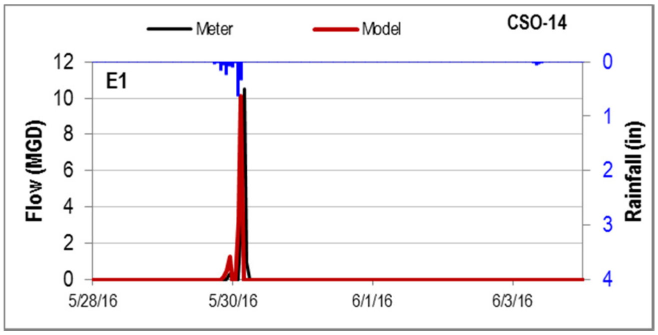
Eff-14 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

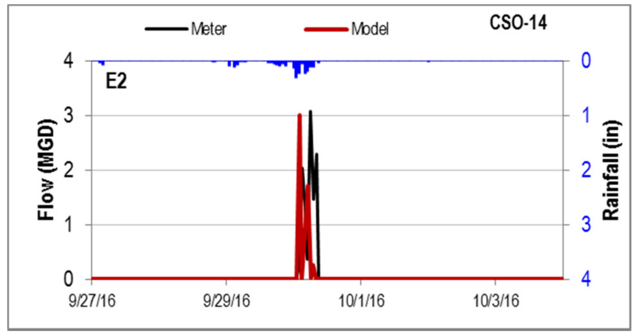


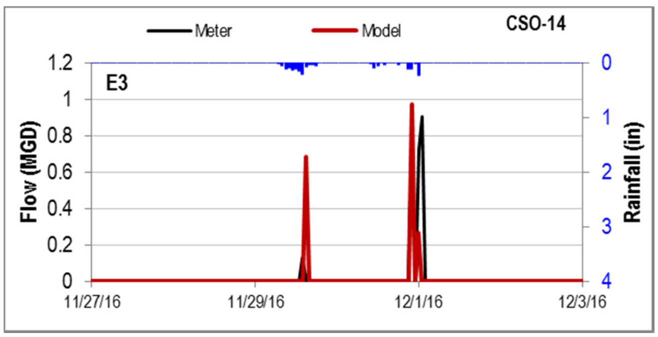


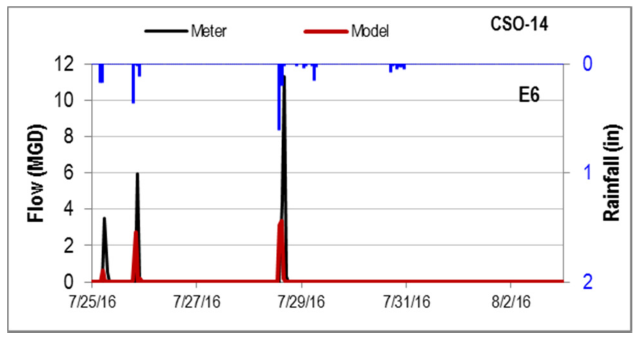
FLOW METER CSO-14 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-14 Model Calibration Results (Metered and Modeled Flow)

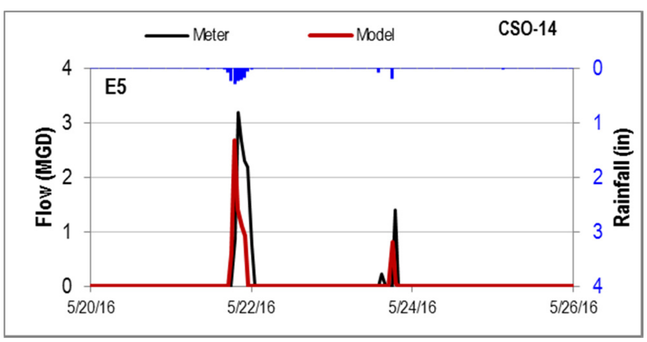




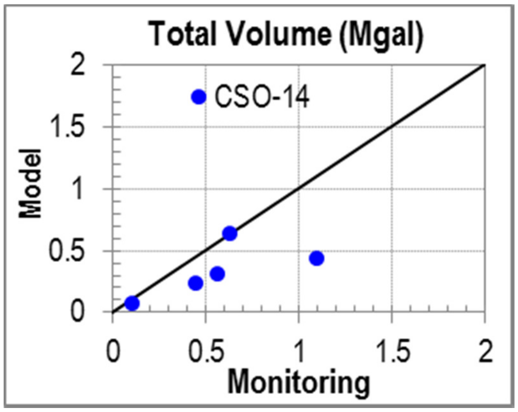


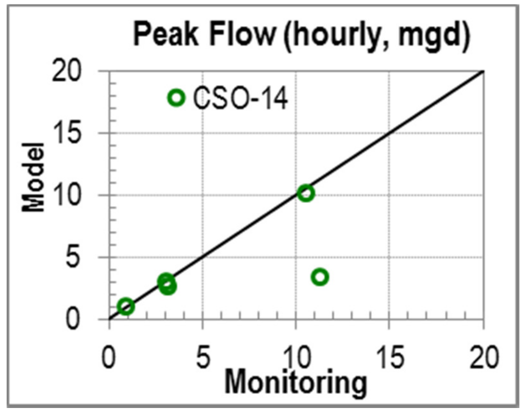


CSO-14 Model Validation Results (Metered and Modeled Flow)



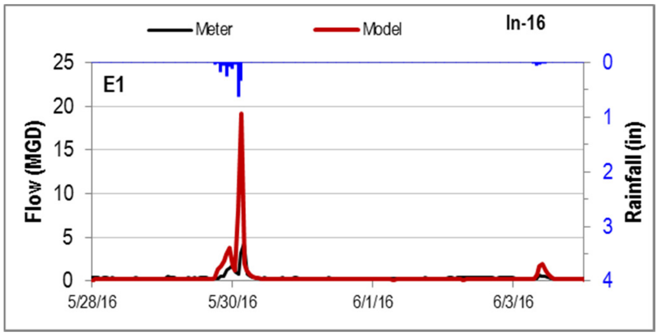
CSO-14 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

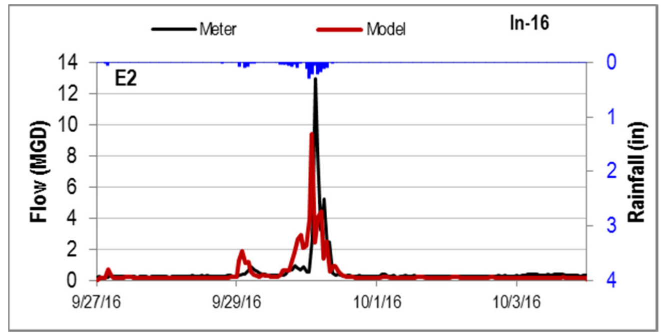


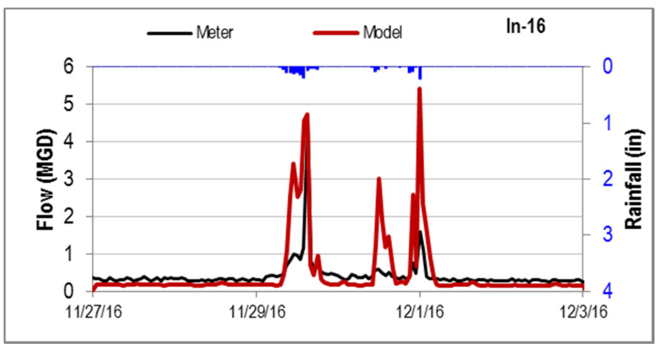


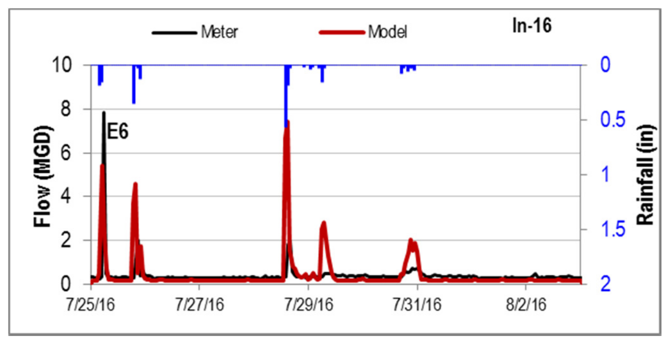
FLOW METER IN-16 MODEL CALIBRATION AND VALIDATION RESULTS

In-16 Model Calibration Results (Metered and Modeled Flow)

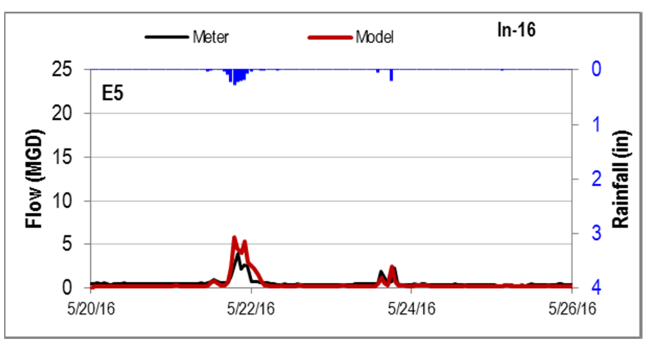




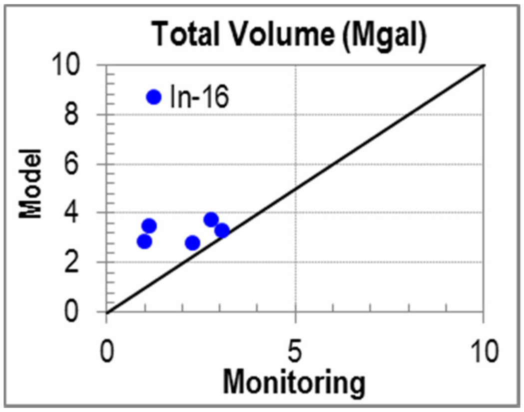


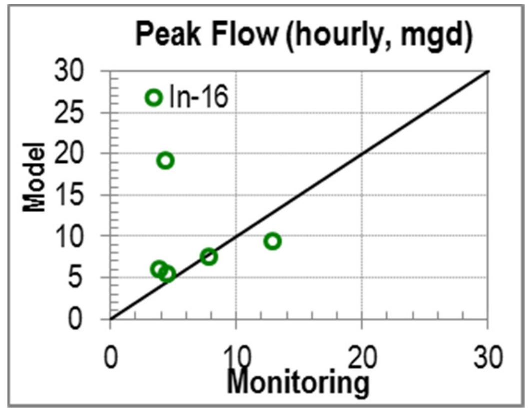


In-16 Model Validation Results (Metered and Modeled Flow)



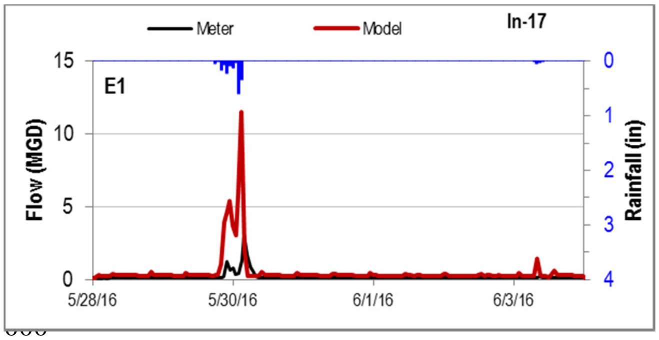
In-16 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

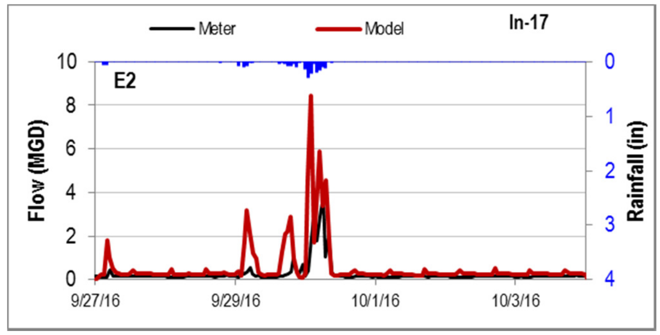


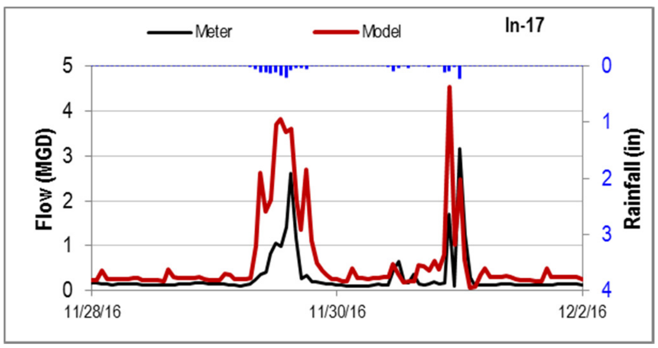


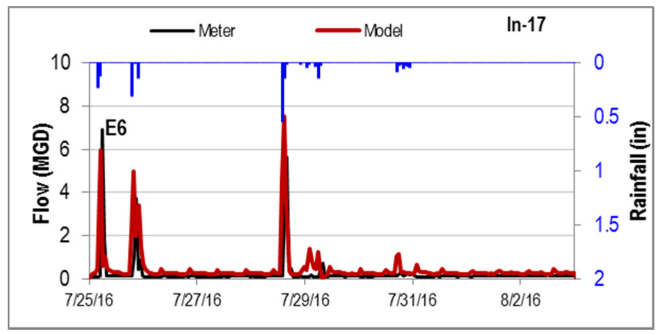
FLOW METER IN-17 MODEL CALIBRATION AND VALIDATION RESULTS

In-17 Model Calibration Results (Metered and Modeled Flow)

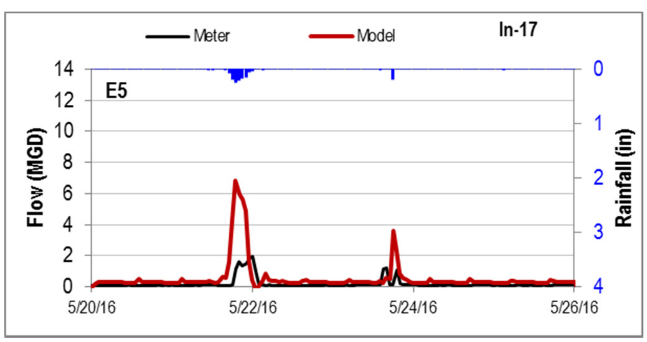




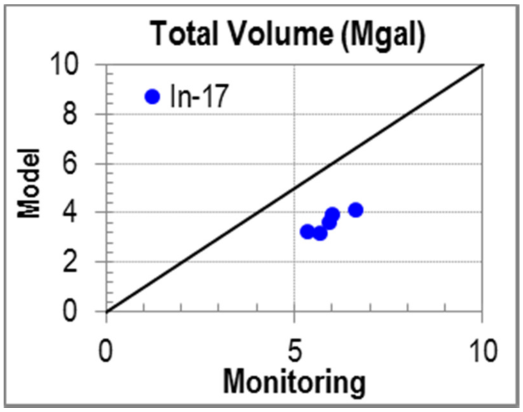


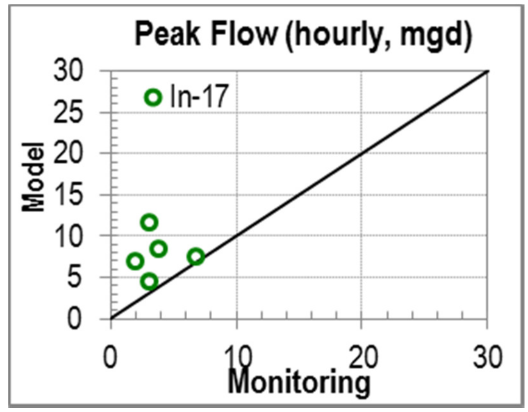


In-17 Model Validation Results (Metered and Modeled Flow)



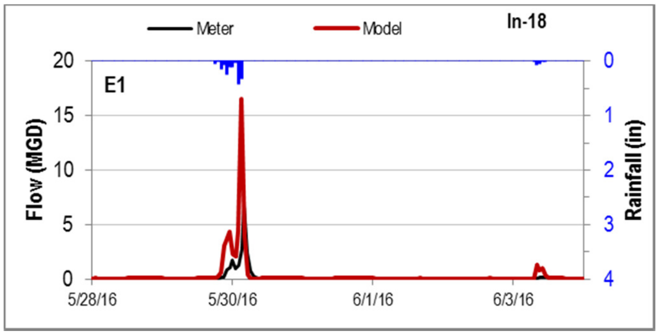
In-17 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

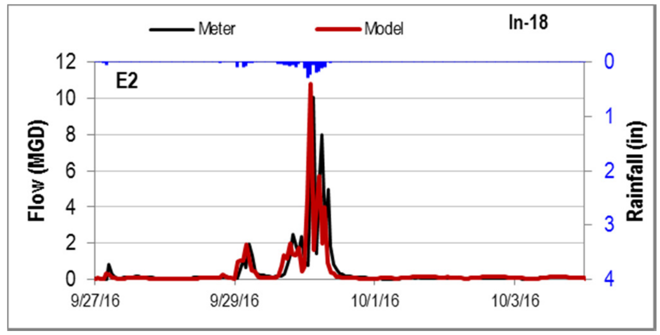


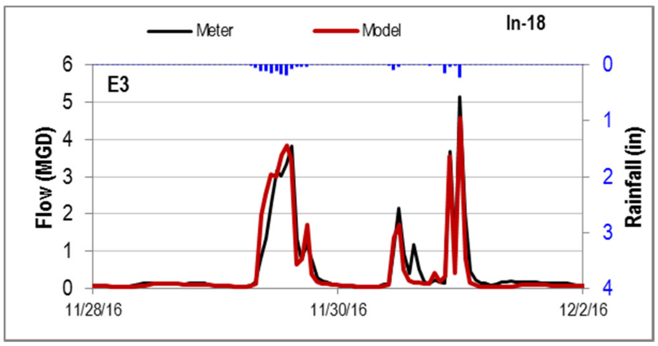


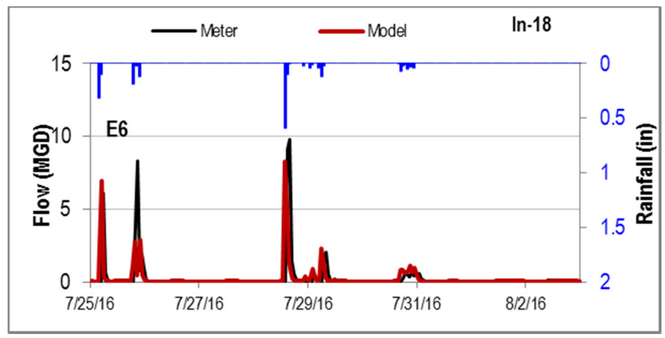
FLOW METER IN-18 MODEL CALIBRATION AND VALIDATION RESULTS

In-18 Model Calibration Results (Metered and Modeled Flow)

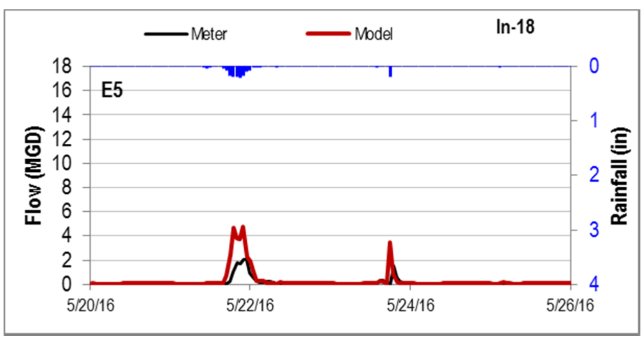




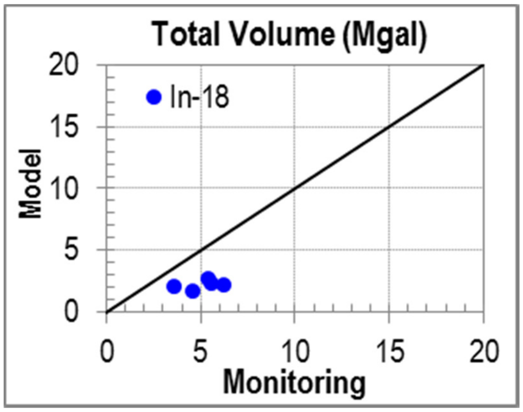


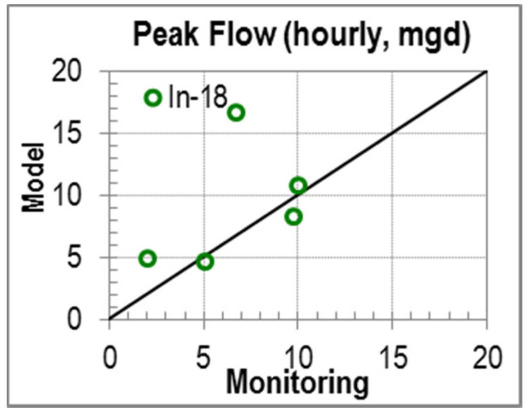


In-18 Model Validation Results (Metered and Modeled Flow)



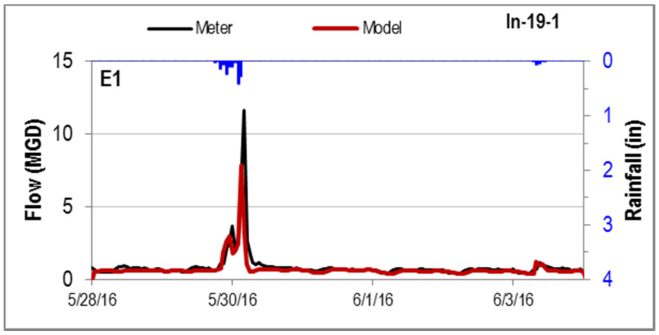
In-18 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

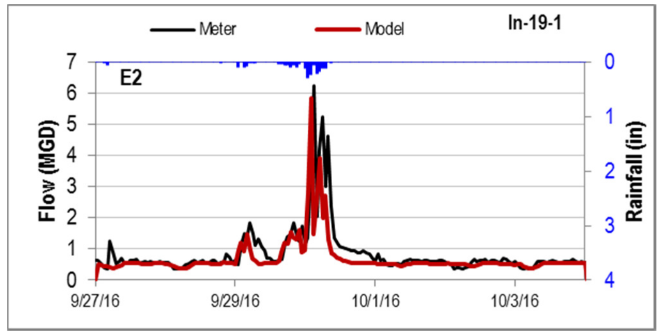


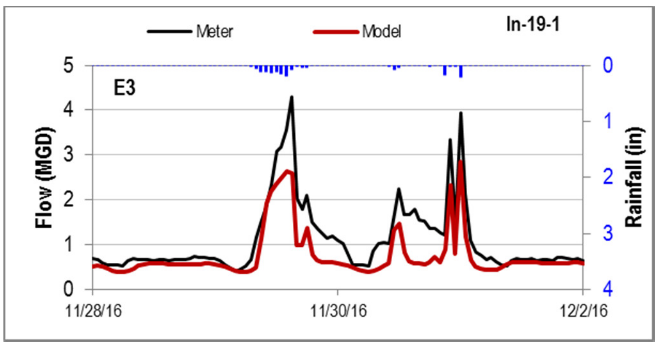


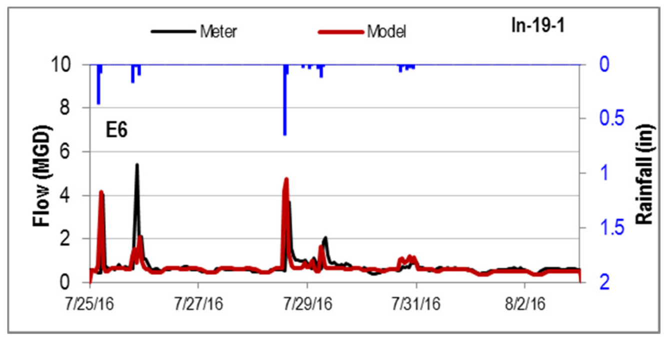
FLOW METER IN-19-1 MODEL CALIBRATION AND VALIDATION RESULTS

In-19-1 Model Calibration Results (Metered and Modeled Flow)

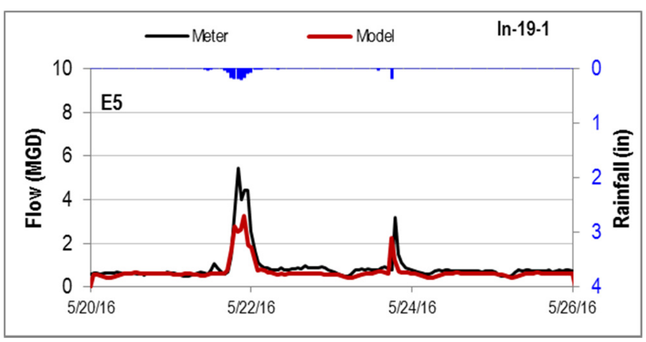




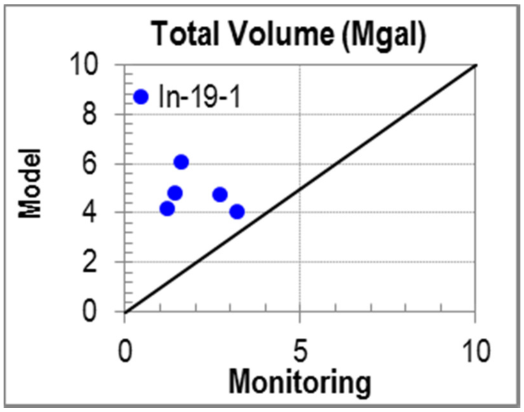


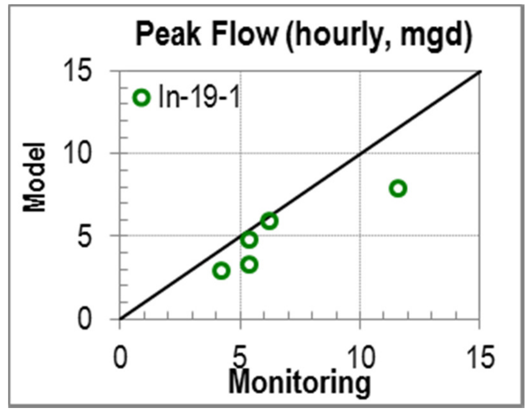


In-19-1 Model Validation Results (Metered and Modeled Flow)



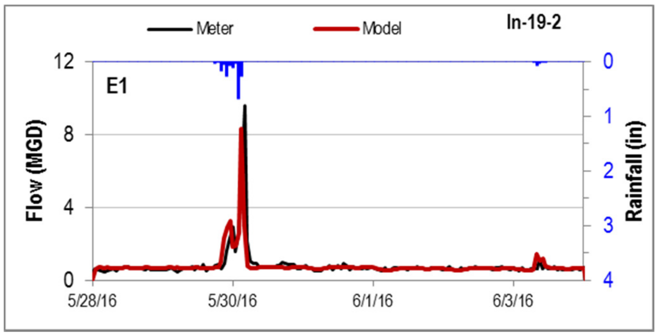
In-19-1 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

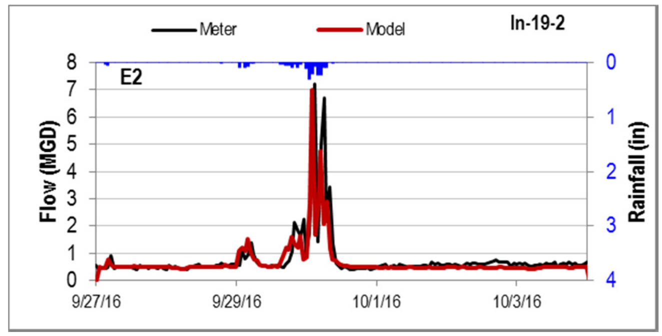


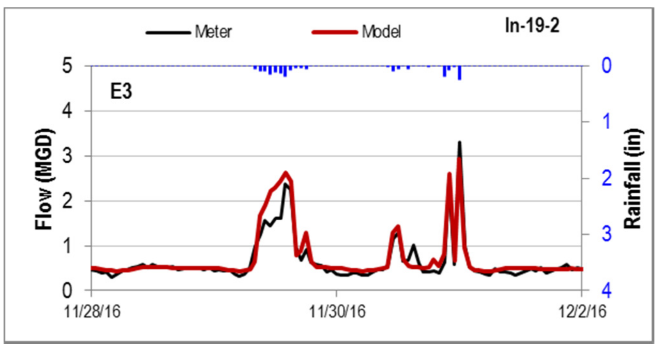


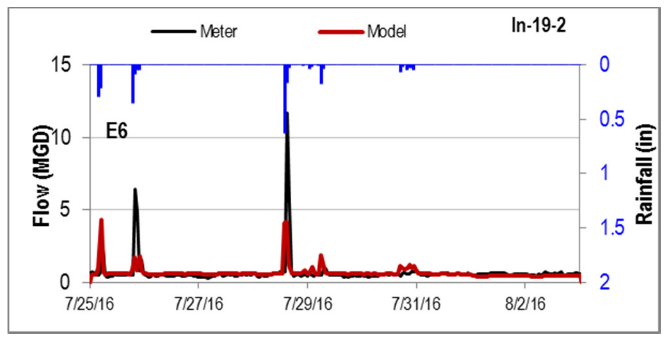
FLOW METER IN-19-2 MODEL CALIBRATION AND VALIDATION RESULTS

In-19-2 Model Calibration Results (Metered and Modeled Flow)

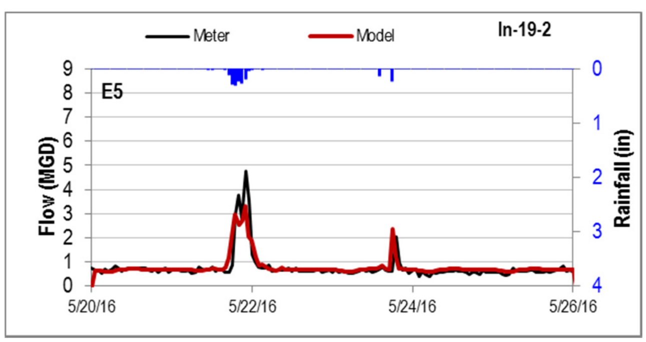




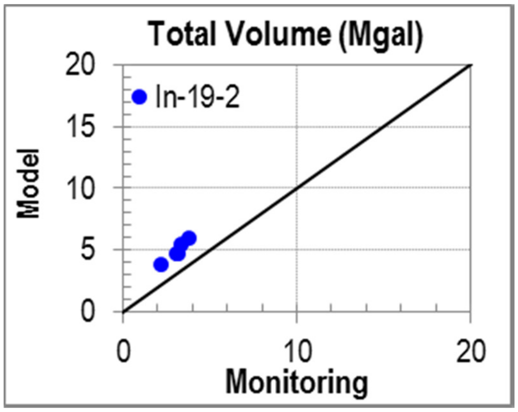


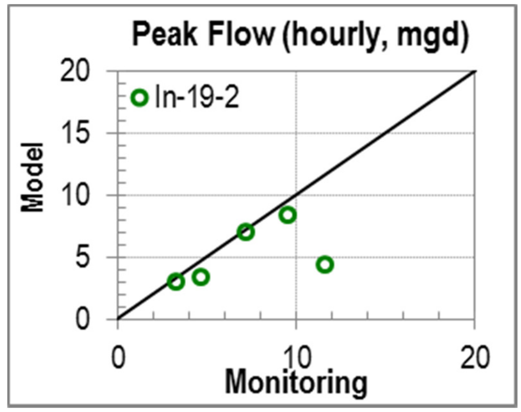


In-19-2 Model Validation Results (Metered and Modeled Flow)



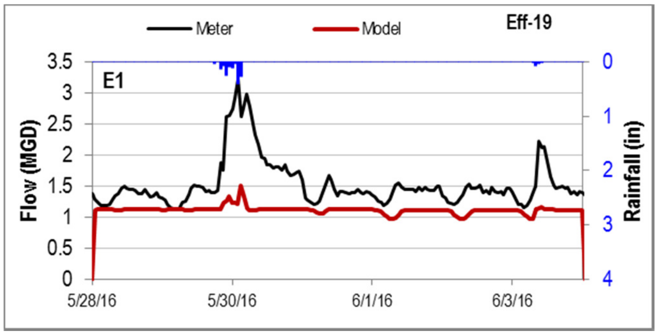
In-19-2 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

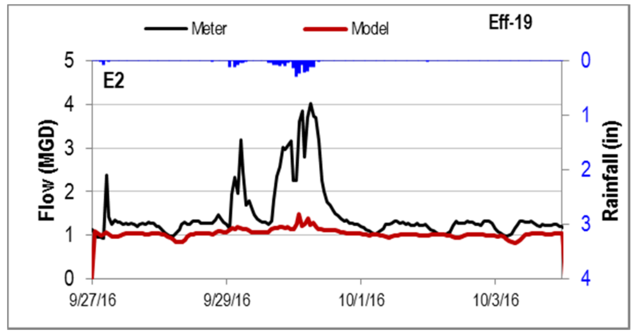


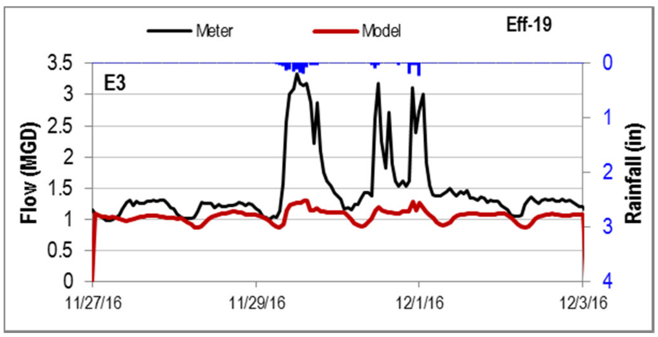


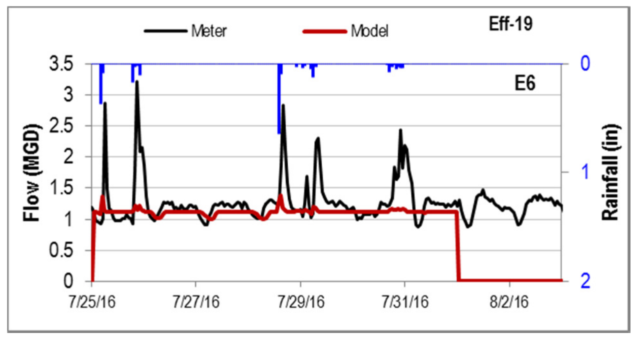
FLOW METER Eff-19 MODEL CALIBRATION AND VALIDATION RESULTS

Eff-19 Model Calibration Results (Metered and Modeled Flow)

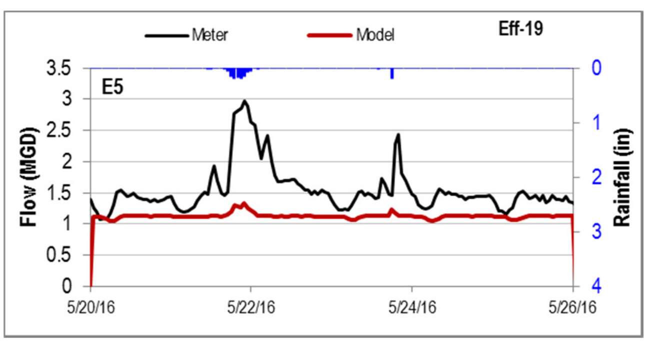




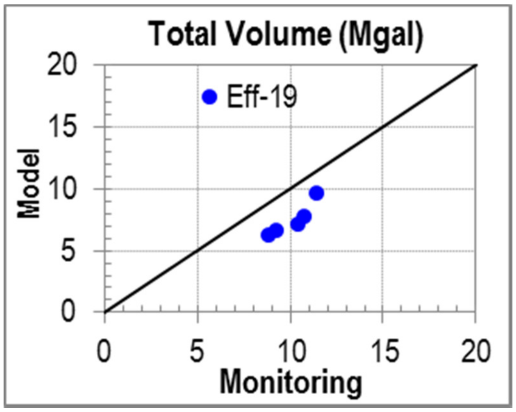


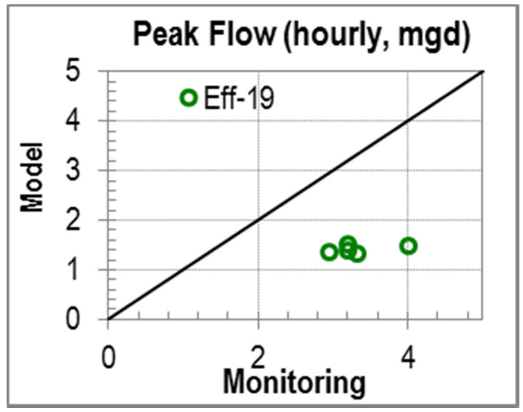


Eff-19 Model Validation Results (Metered and Modeled Flow)



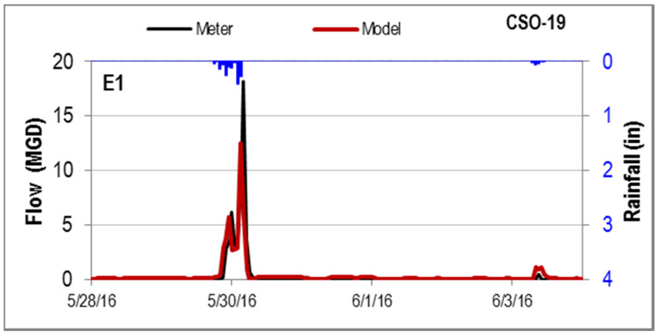
Eff-19 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

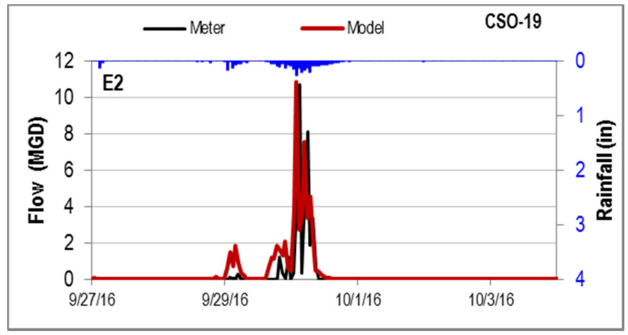


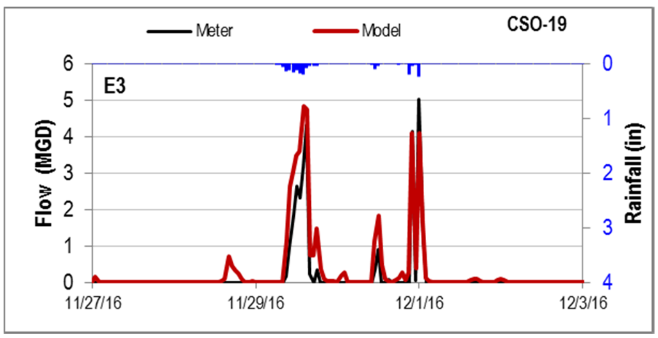


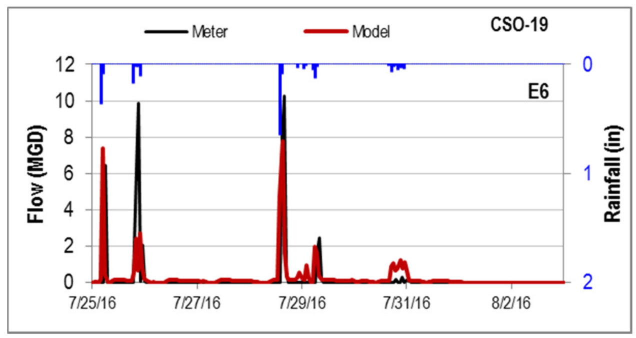
FLOW METER CSO-19 MODEL CALIBRATION AND VALIDATION RESULTS

CSO-19 Model Calibration Results (Metered and Modeled Flow)

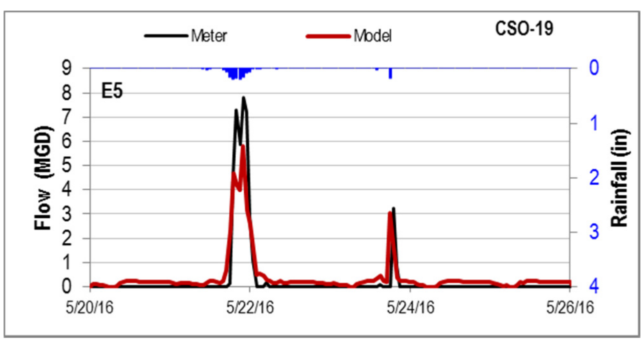




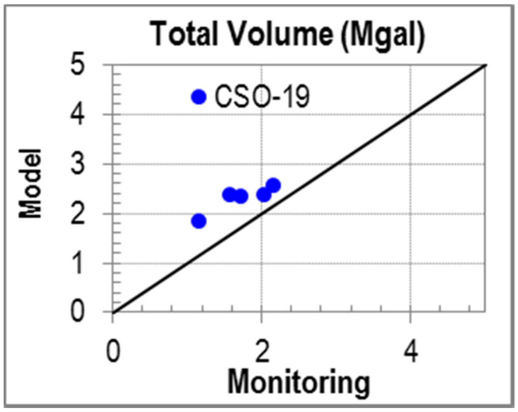


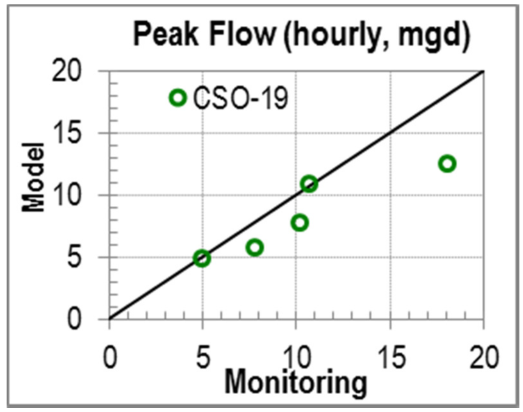


CSO-19 Model Validation Results (Metered and Modeled Flow)



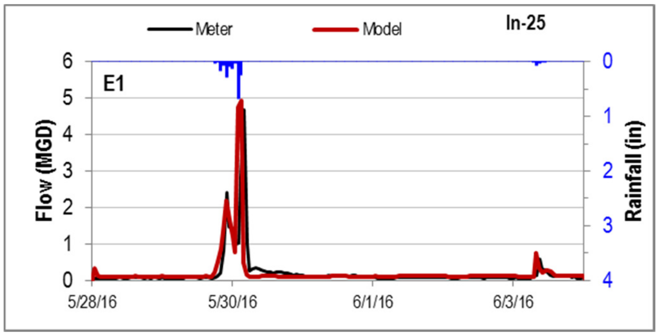
CSO-19 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

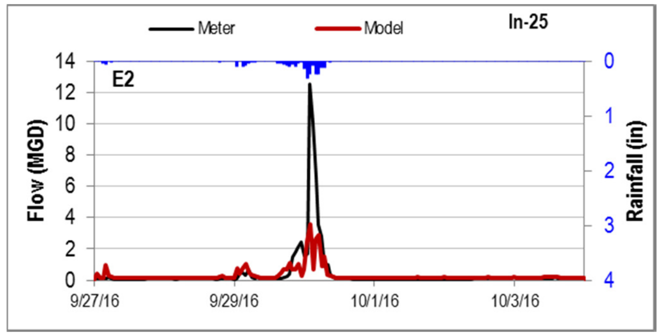


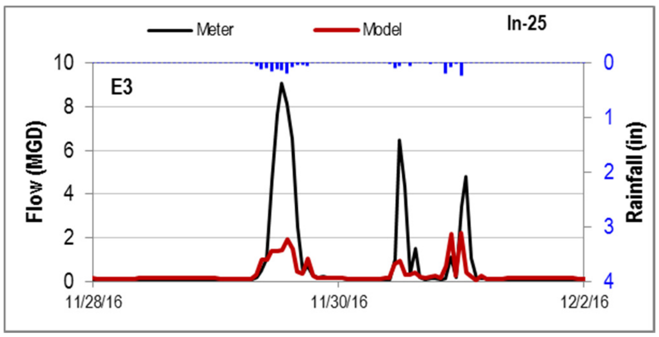


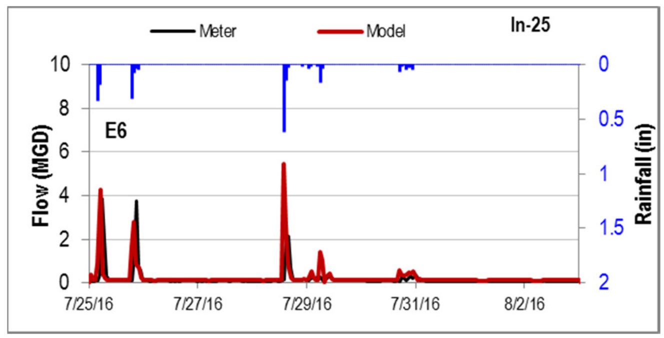
FLOW METER IN-25 MODEL CALIBRATION AND VALIDATION RESULTS

In-25 Model Calibration Results (Metered and Modeled Flow)

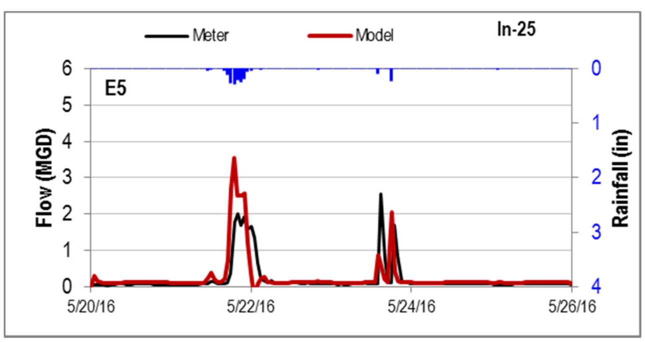




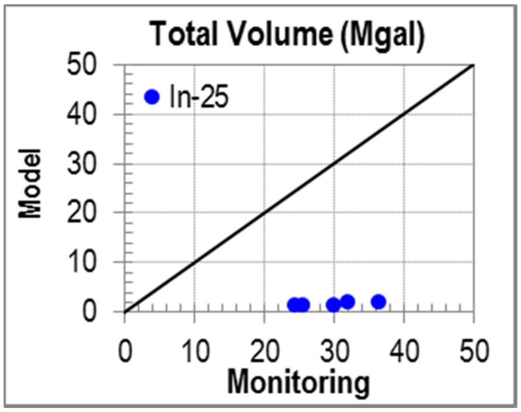


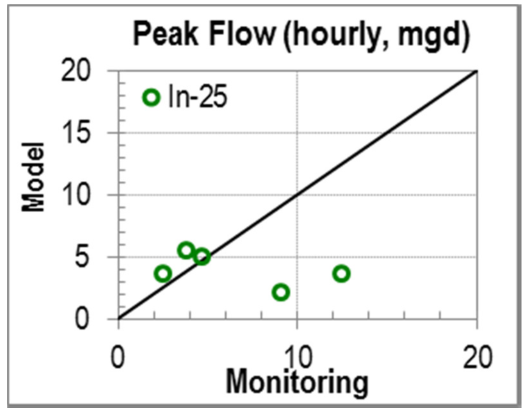


In-25 Model Validation Results (Metered and Modeled Flow)



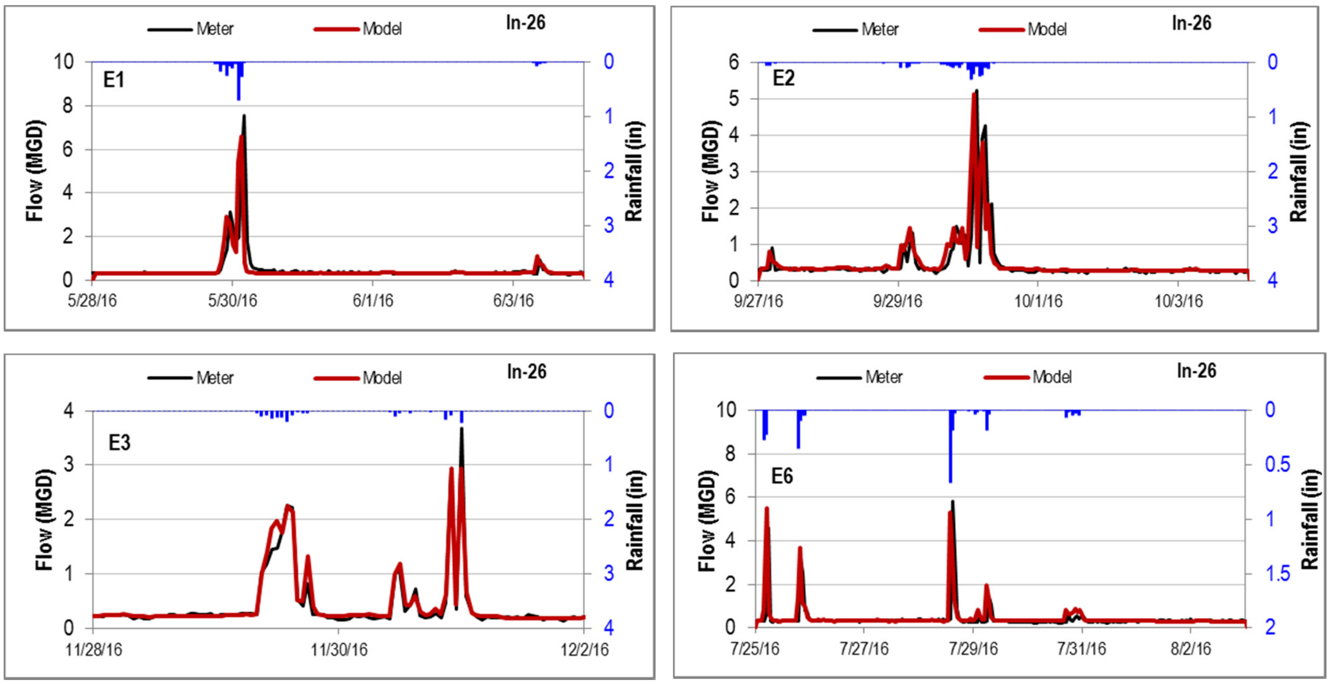
In-25 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



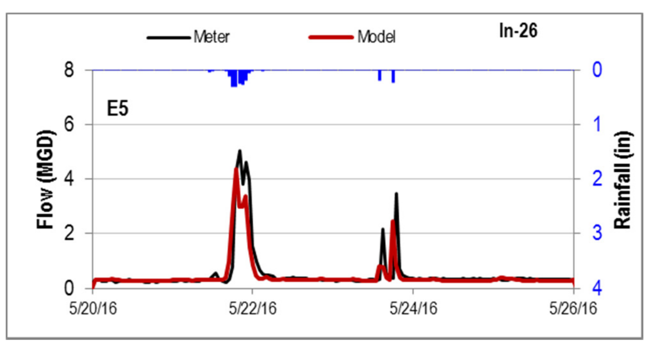


FLOW METER IN-26 MODEL CALIBRATION AND VALIDATION RESULTS

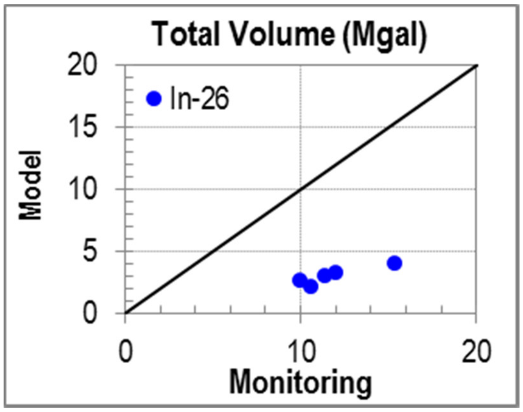
In-26 Model Calibration Results (Metered and Modeled Flow)

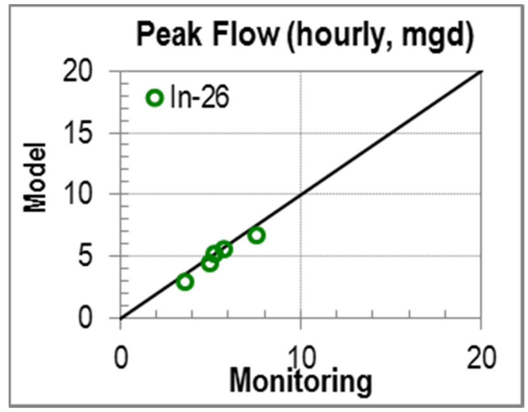


In-26 Model Validation Results (Metered and Modeled Flow)



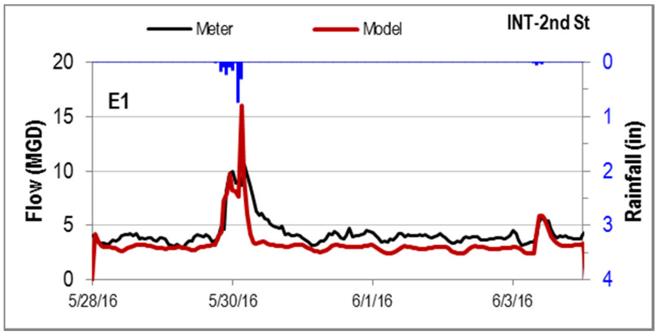
In-26 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

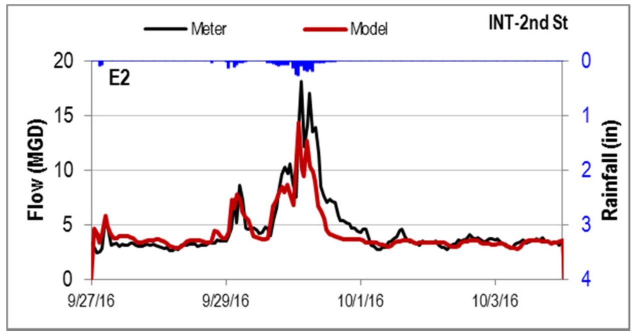


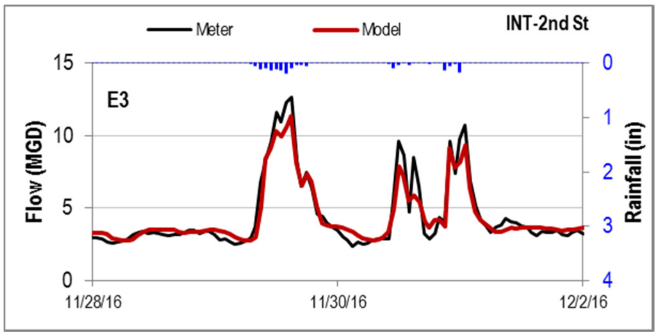


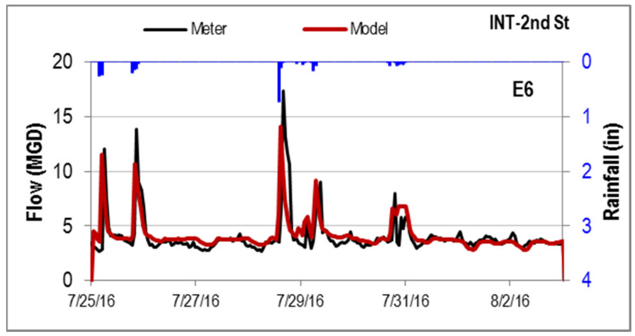
FLOW METER INT-2nd St MODEL CALIBRATION AND VALIDATION RESULTS

INT-2nd St Model Calibration Results (Metered and Modeled Flow)

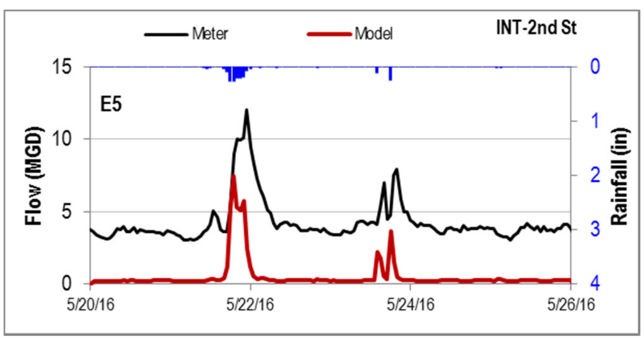




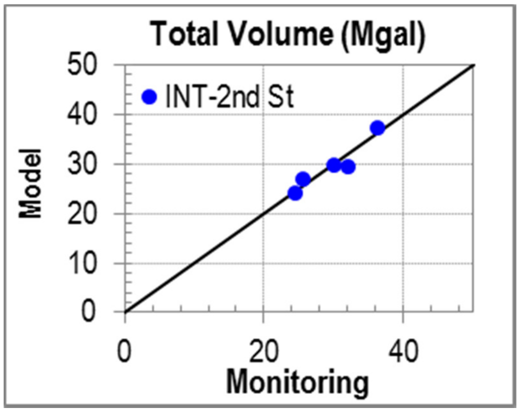


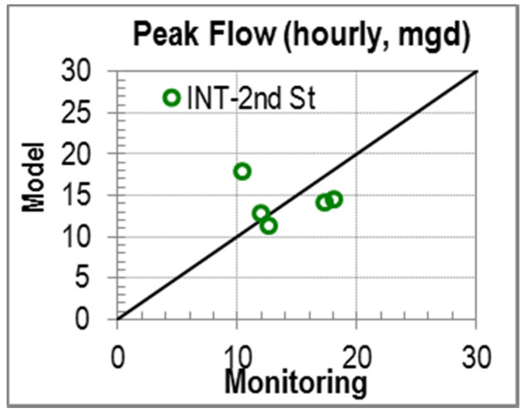


INT-2nd St Model Validation Results (Metered and Modeled Flow)



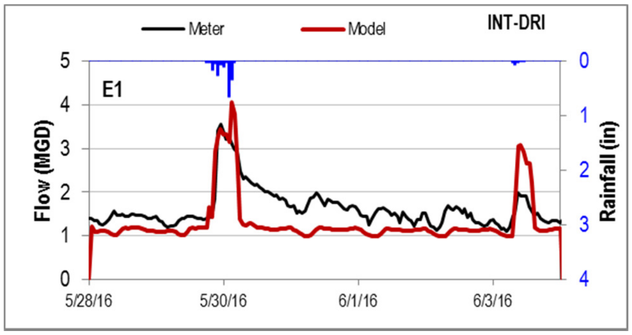
INT-2nd St Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

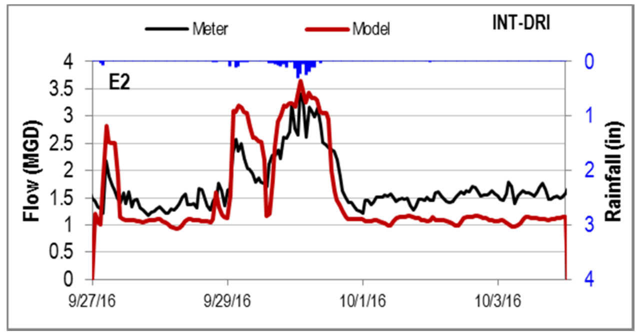


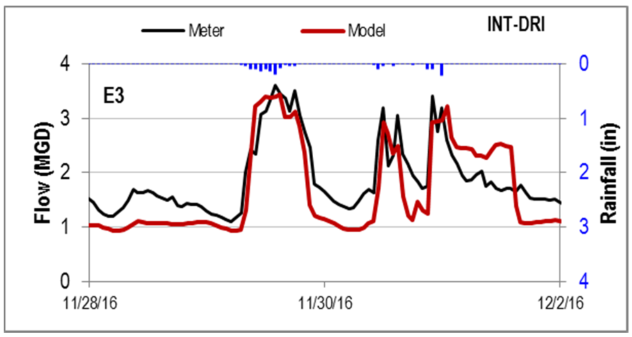


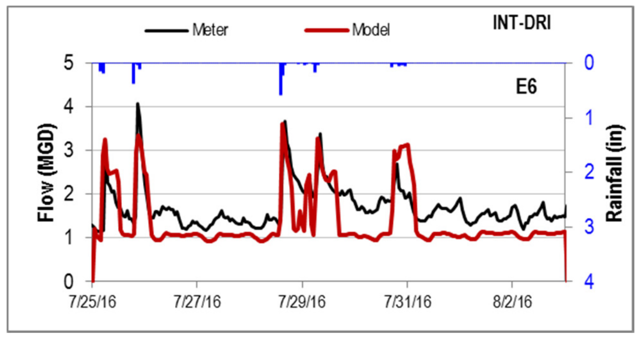
FLOW METER INT-DRI MODEL CALIBRATION AND VALIDATION RESULTS

INT-DRI Model Calibration Results (Metered and Modeled Flow)

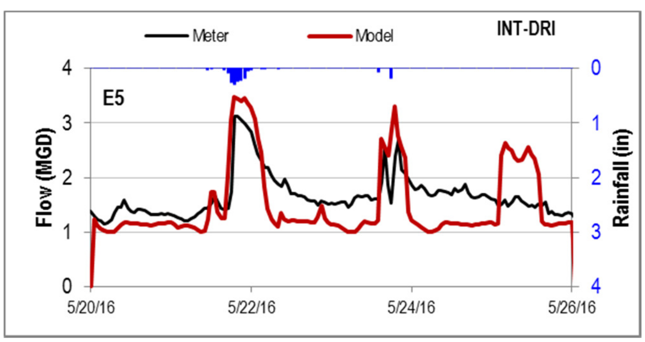




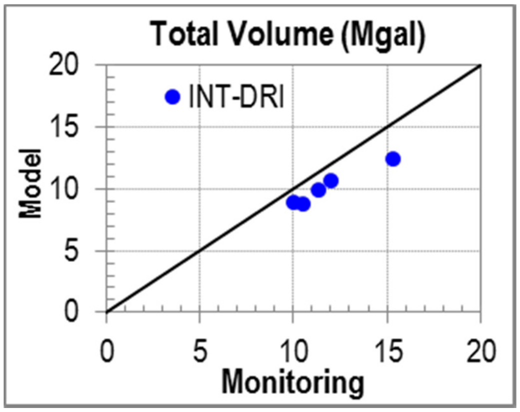


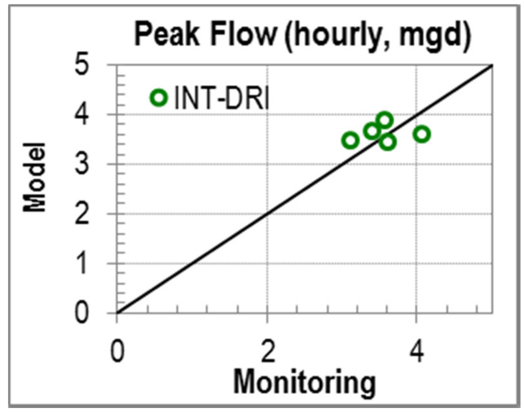


INT-DRI Model Validation Results (Metered and Modeled Flow)



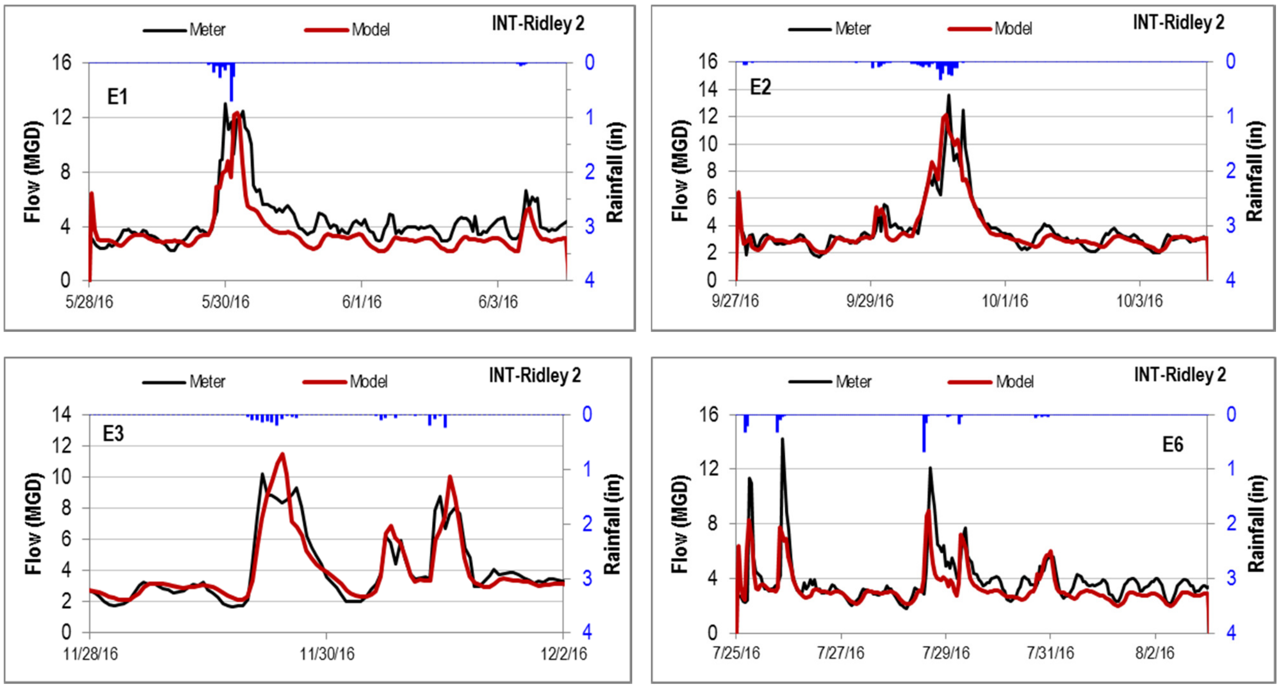
INT-DRI Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



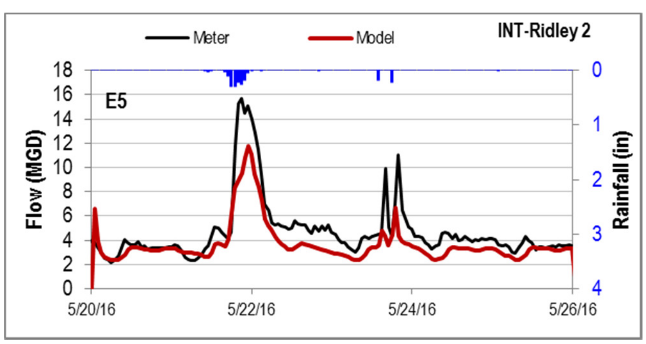


FLOW METER INT-Ridley 2 MODEL CALIBRATION AND VALIDATION RESULTS

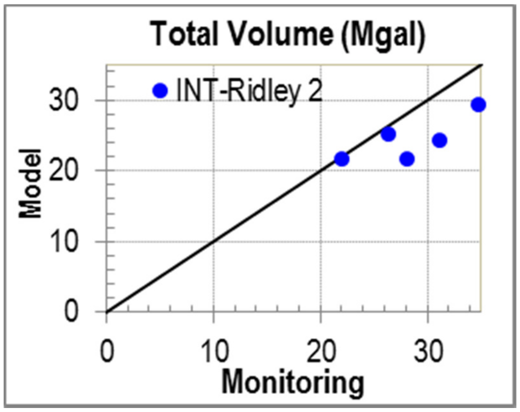
INT-Ridley 2 Model Calibration Results (Metered and Modeled Flow)

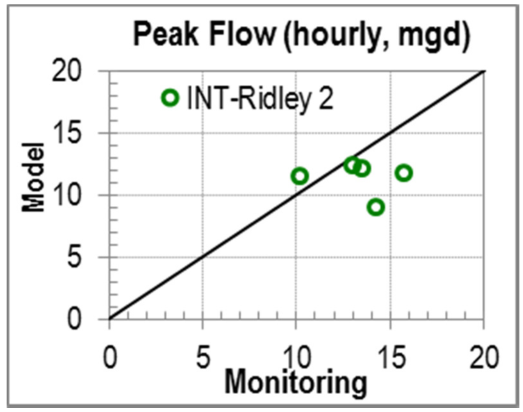


INT-Ridley 2 Model Validation Results (Metered and Modeled Flow)



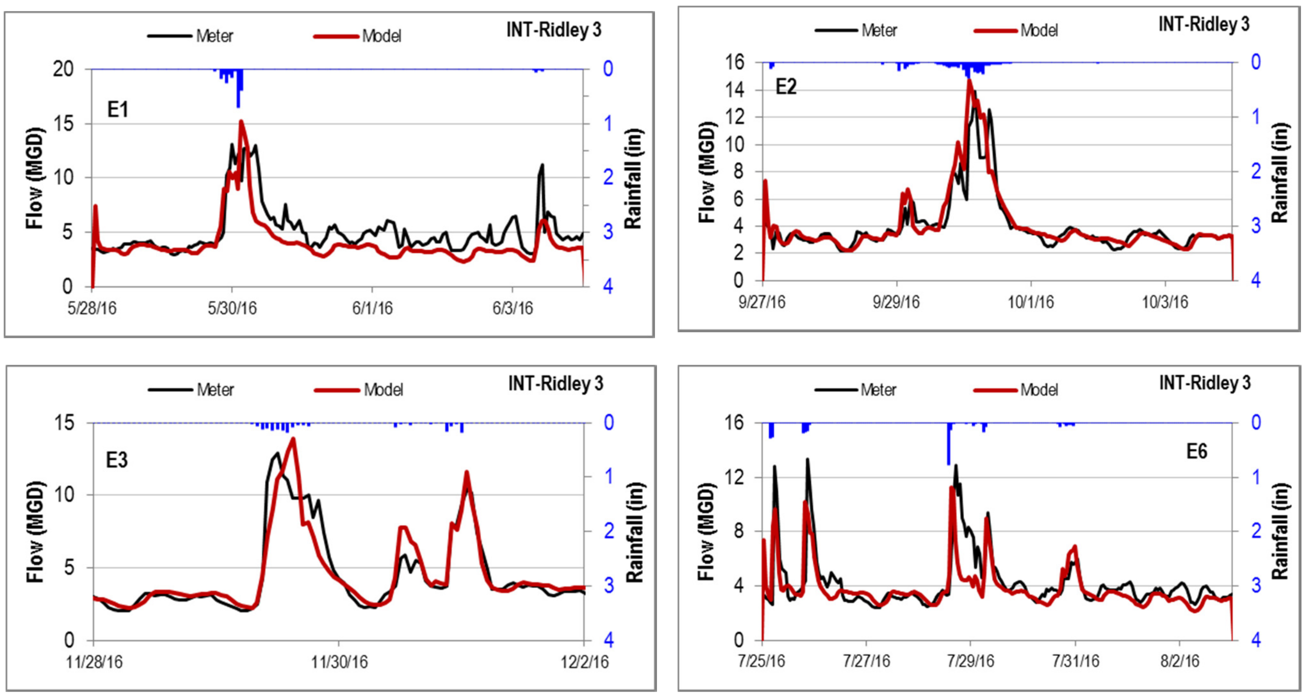
INT-Ridley-2 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



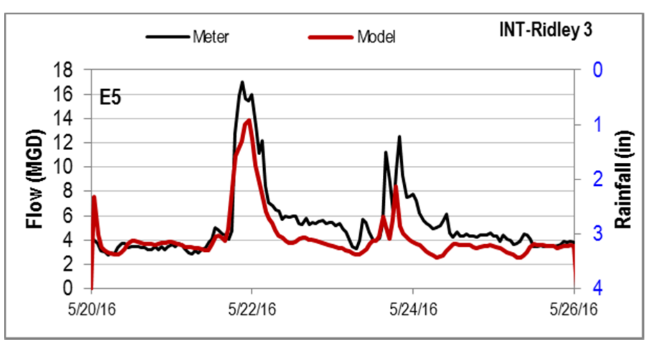


FLOW METER INT-Ridley 3 MODEL CALIBRATION AND VALIDATION RESULTS

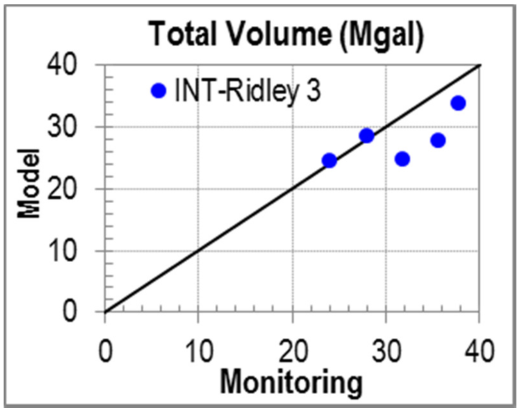
INT-Ridley 3 Model Calibration Results (Metered and Modeled Flow)

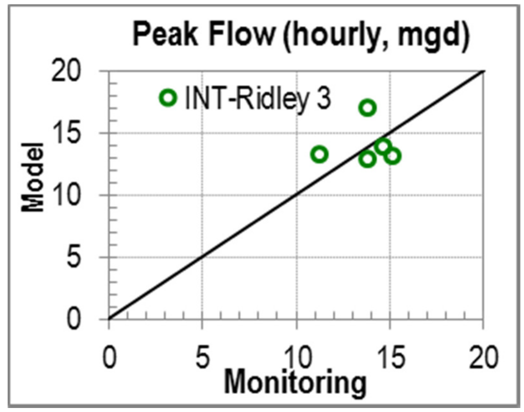


INT-Ridley 3 Model Validation Results (Metered and Modeled Flow)



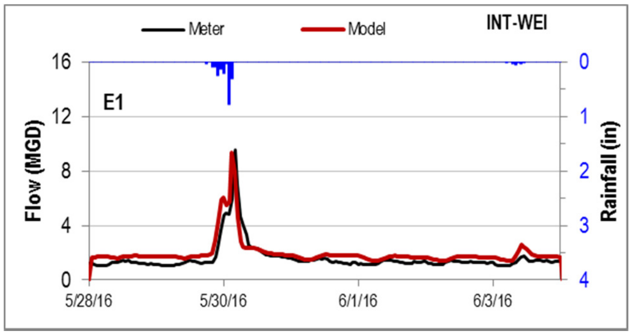
INT-Ridley 3 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

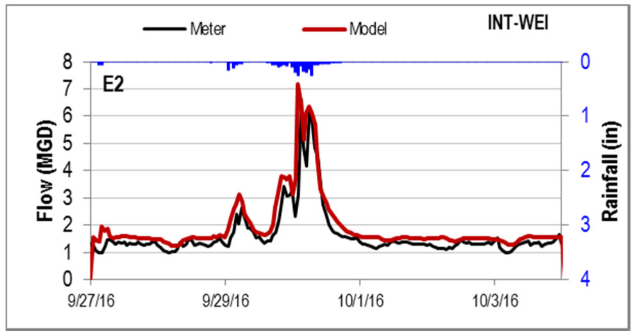


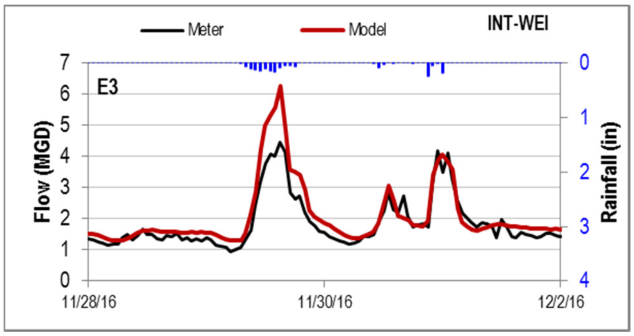


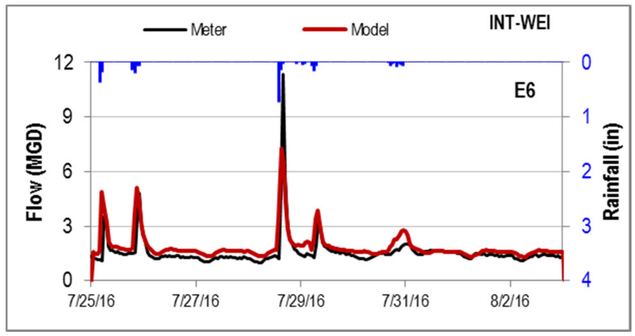
FLOW METER INT-WEI MODEL CALIBRATION AND VALIDATION RESULTS

INT-WEI Model Calibration Results (Metered and Modeled Flow)

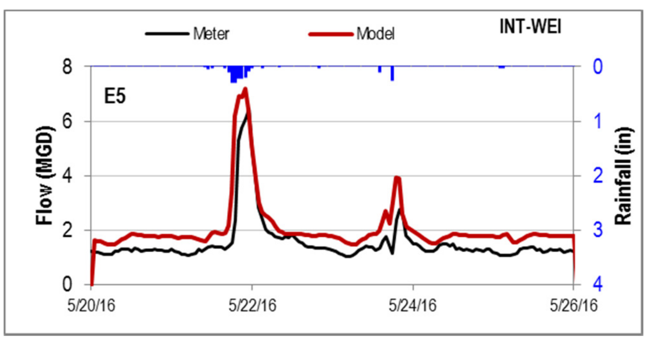




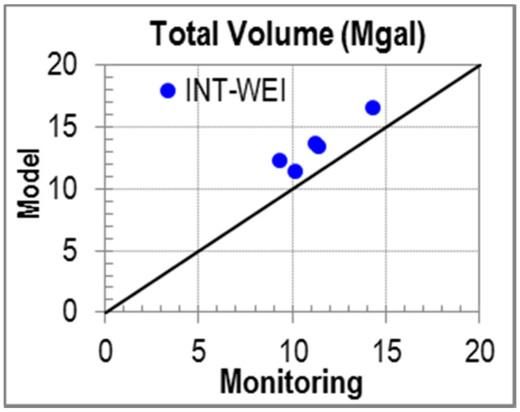


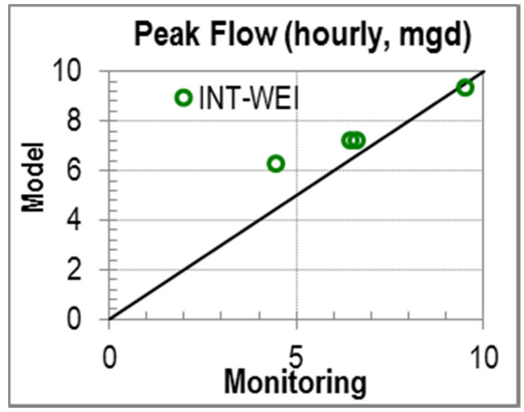


INT-WEI Model Validation Results (Metered and Modeled Flow)



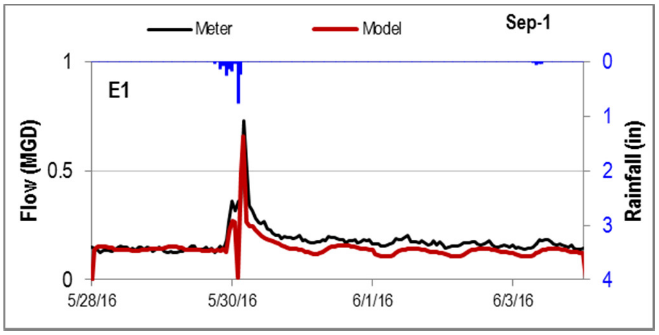
INT-WEI Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

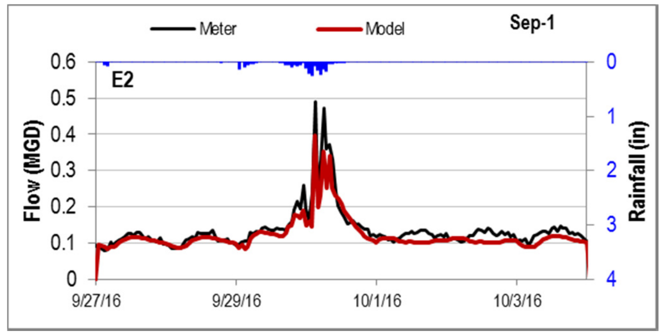


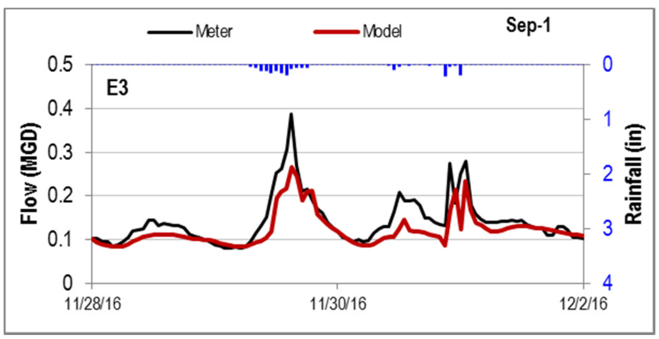


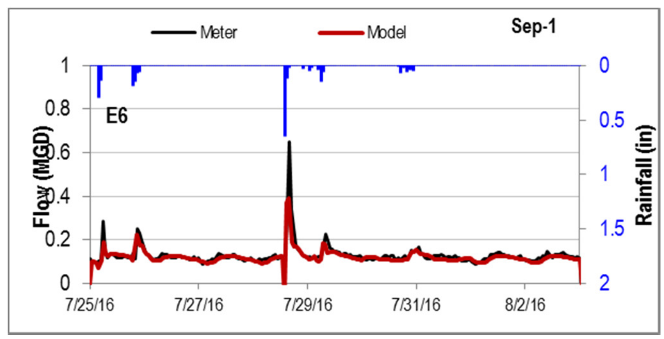
FLOW METER Sep-1 MODEL CALIBRATION AND VALIDATION RESULTS

Sep-1 Model Calibration Results (Metered and Modeled Flow)

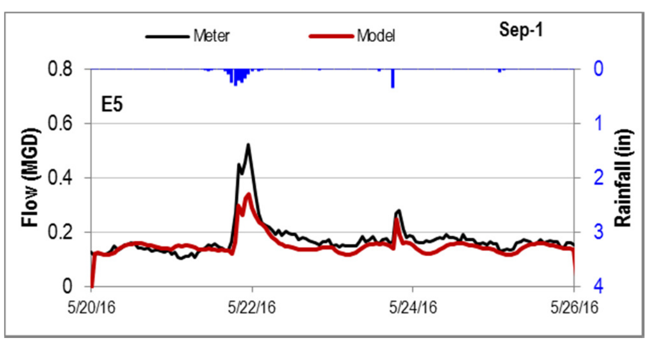




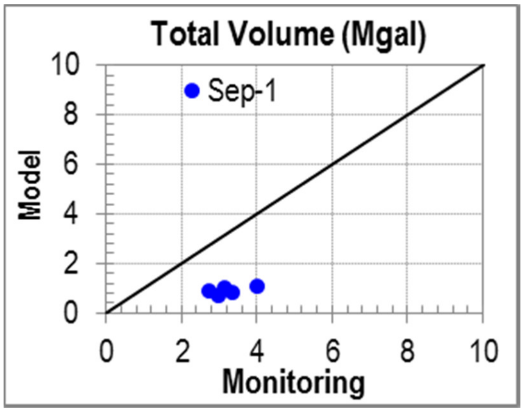


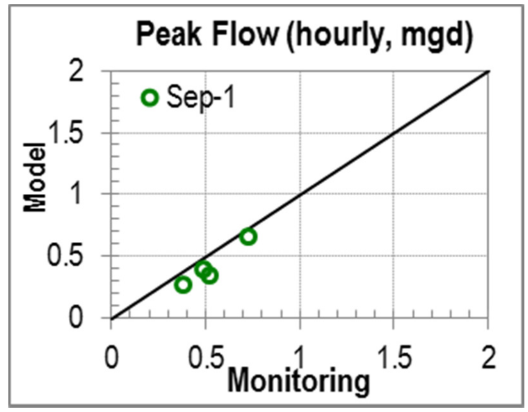


Sep-1 Model Validation Results (Metered and Modeled Flow)



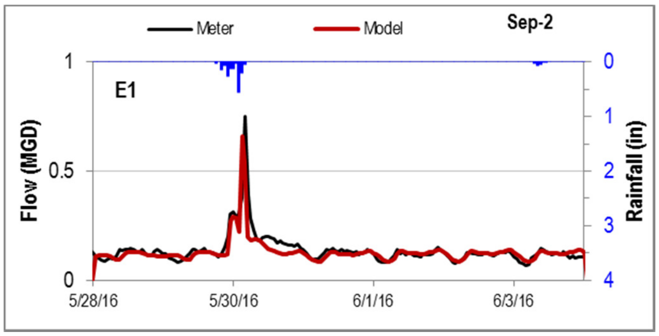
Sep-1 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

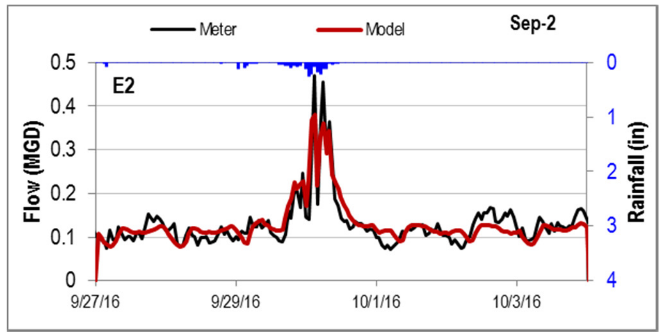


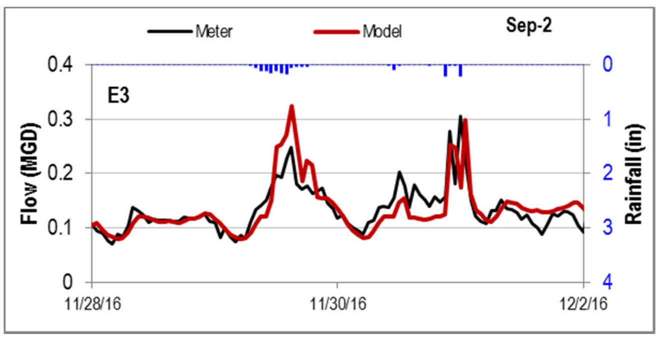


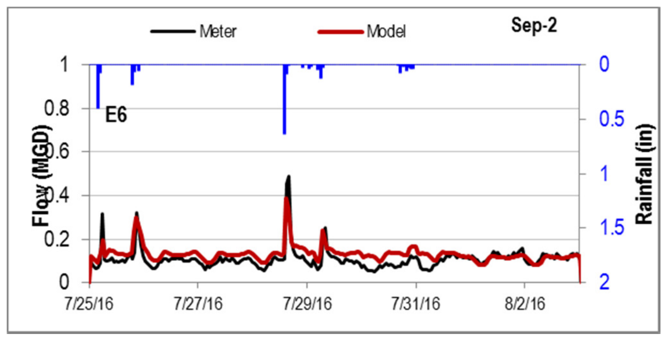
FLOW METER Sep-2 MODEL CALIBRATION AND VALIDATION RESULTS

Sep-2 Model Calibration Results (Metered and Modeled Flow)

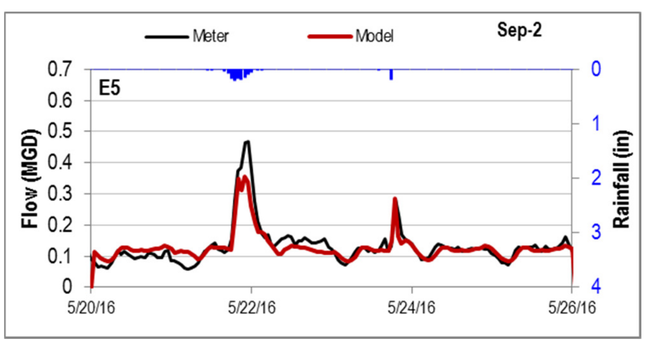




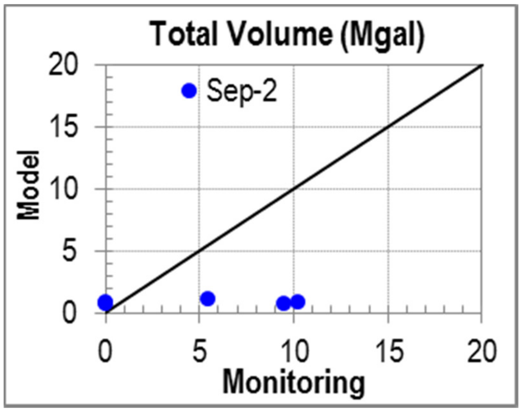


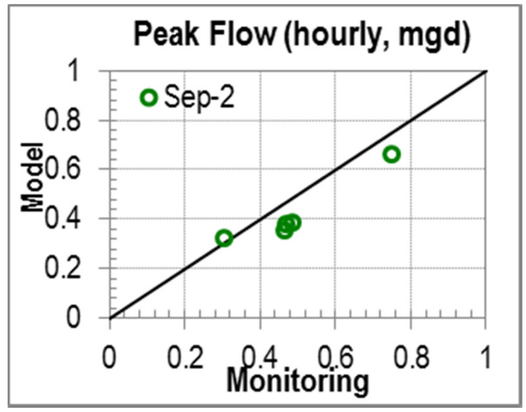


Sep-2 Model Validation Results (Metered and Modeled Flow)



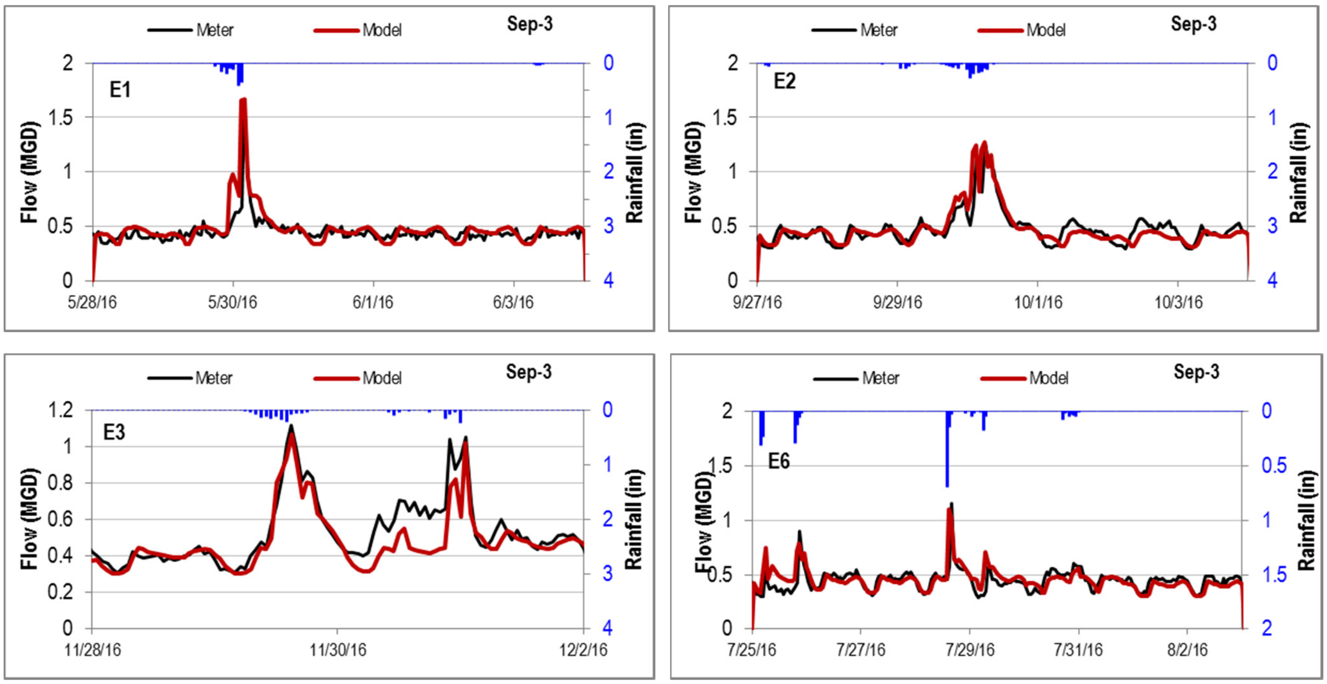
Sep-2 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



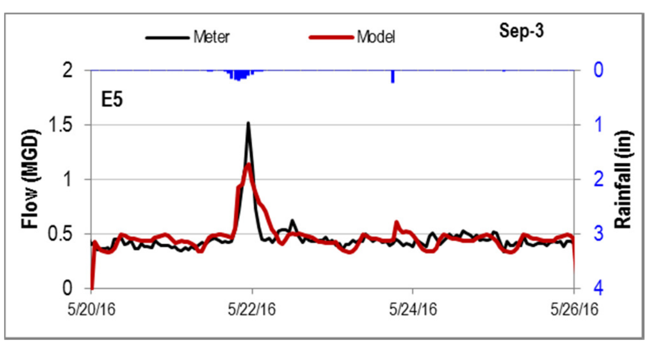


FLOW METER Sep-3 MODEL CALIBRATION AND VALIDATION RESULTS

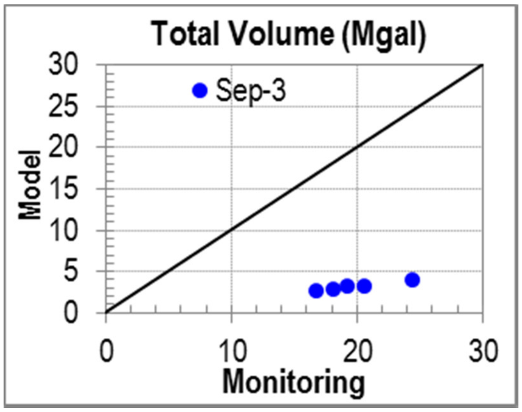
Sep-3 Model Calibration Results (Metered and Modeled Flow)

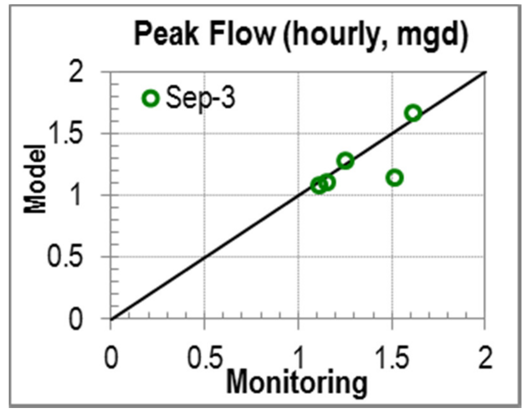


Sep-3 Model Validation Results (Metered and Modeled Flow)



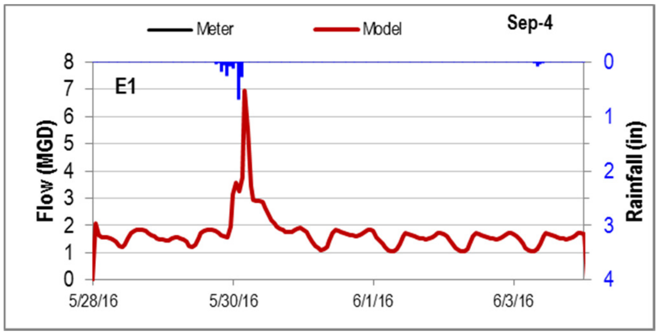
Sep-3 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

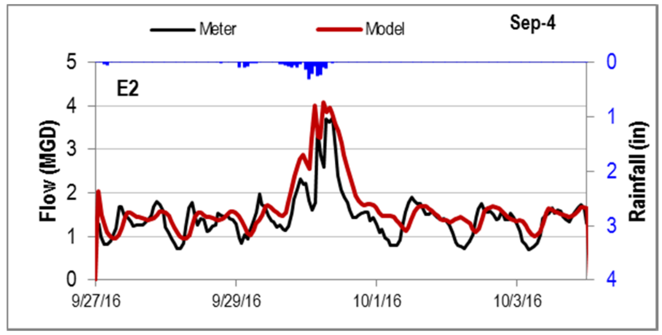


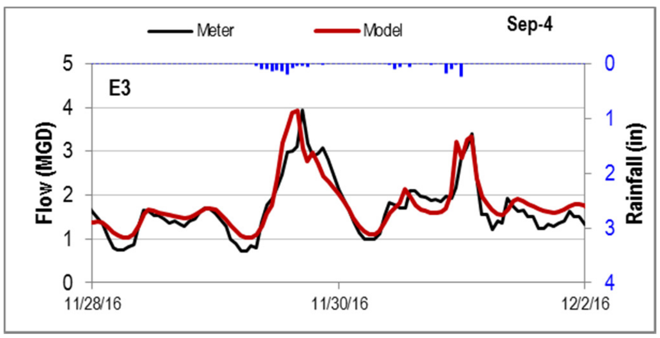


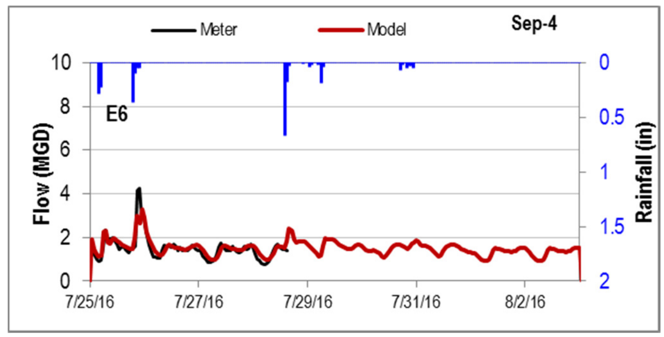
FLOW METER Sep-4 MODEL CALIBRATION AND VALIDATION RESULTS

Sep-4 Model Calibration Results (Metered and Modeled Flow)

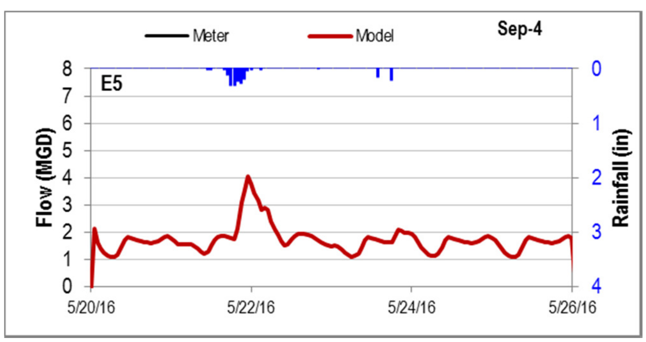




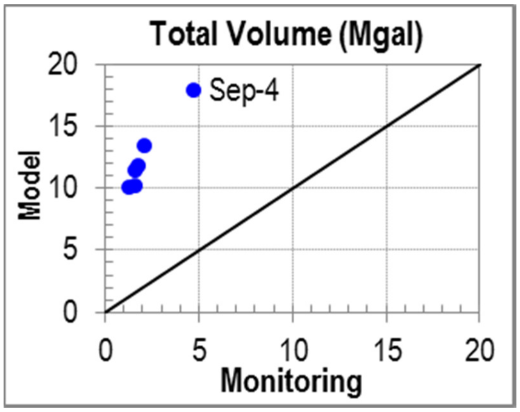


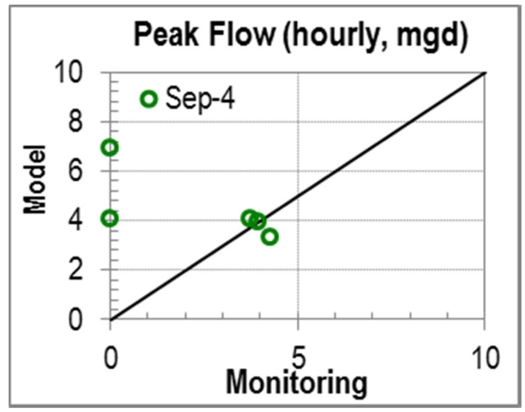


Sep-4 Model Validation Results (Metered and Modeled Flow)



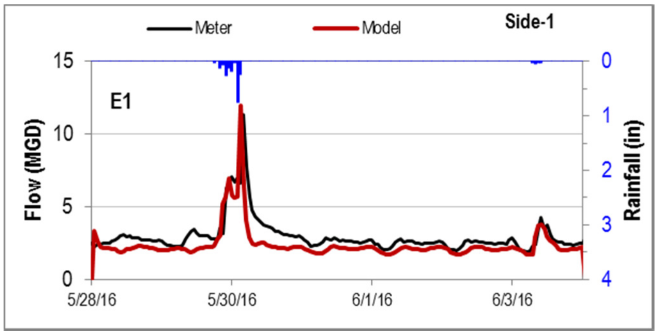
Sep-4 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

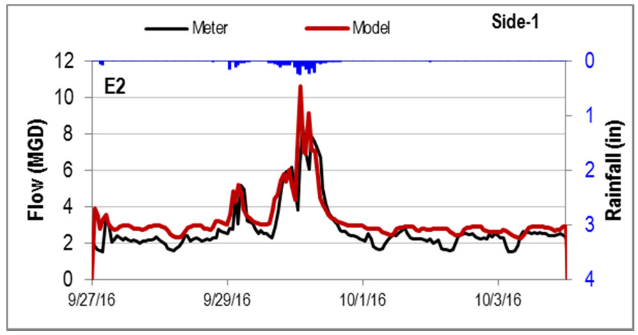


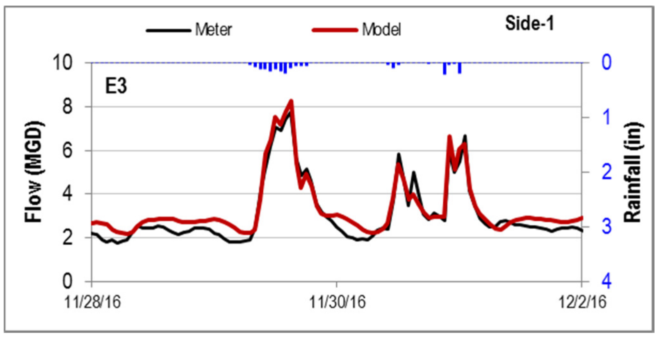


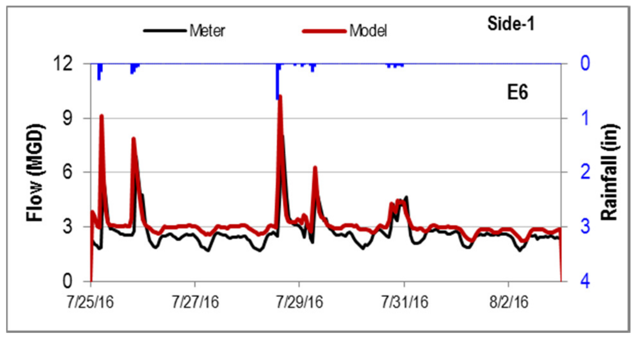
FLOW METER Side-1 MODEL CALIBRATION AND VALIDATION RESULTS

Side-1 Model Calibration Results (Metered and Modeled Flow)

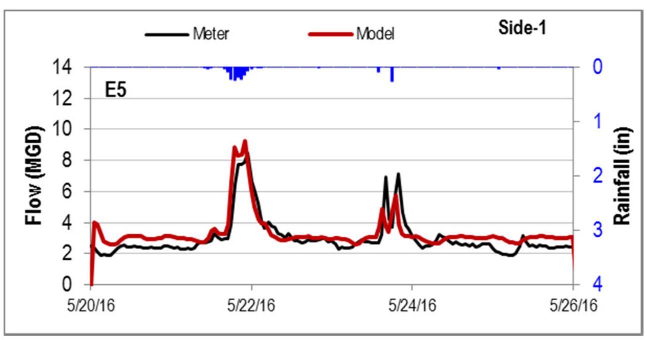




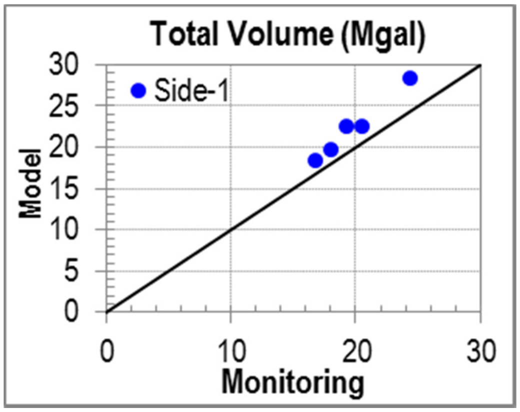


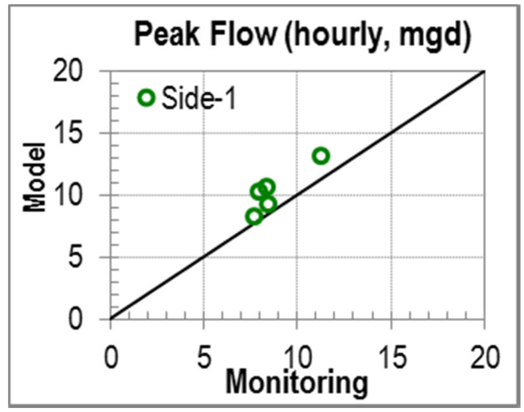


Side-1 Model Validation Results (Metered and Modeled Flow)



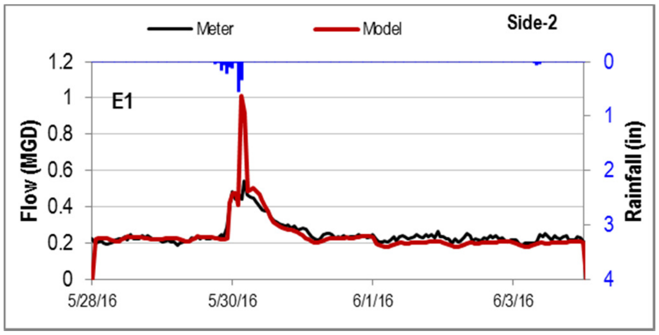
Side-1 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

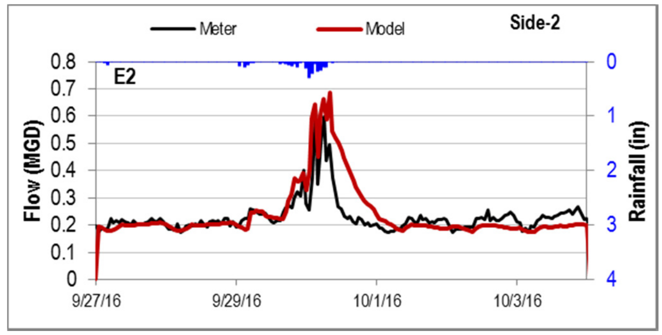


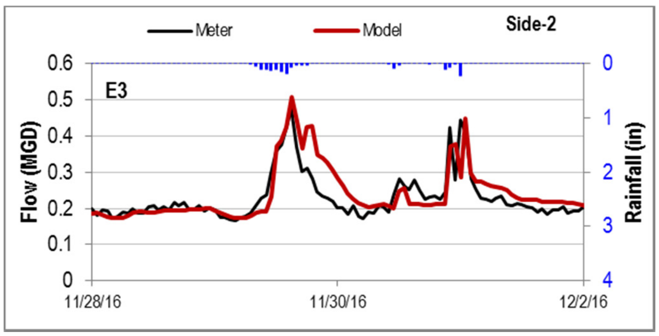


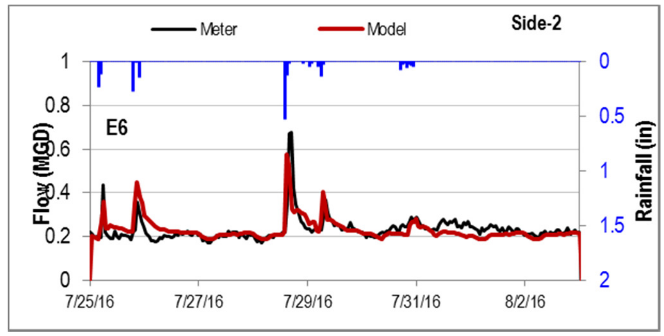
FLOW METER Side-2 MODEL CALIBRATION AND VALIDATION RESULTS

Side-2 Model Calibration Results (Metered and Modeled Flow)

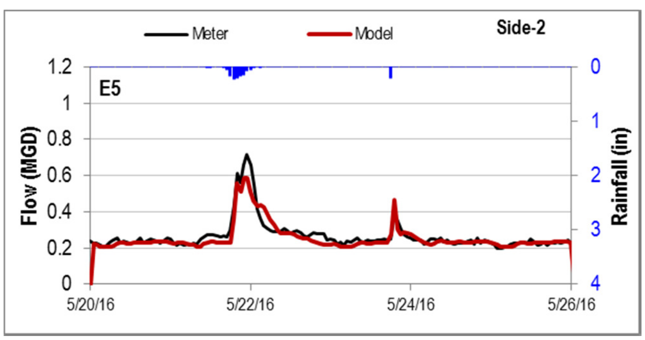




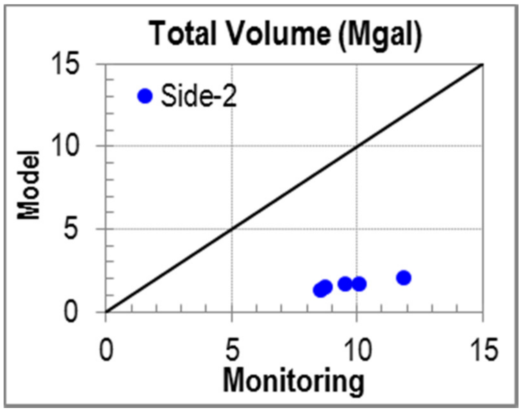


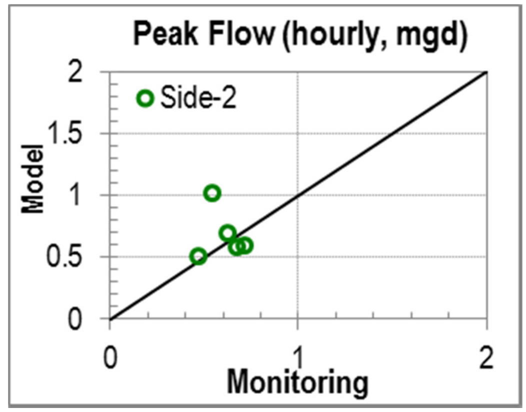


Side-2 Model Validation Results (Metered and Modeled Flow)



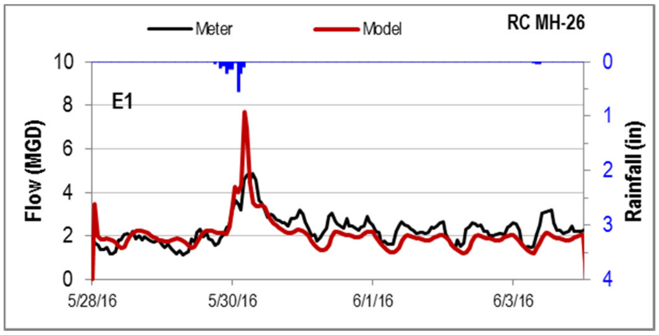
Side-2 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

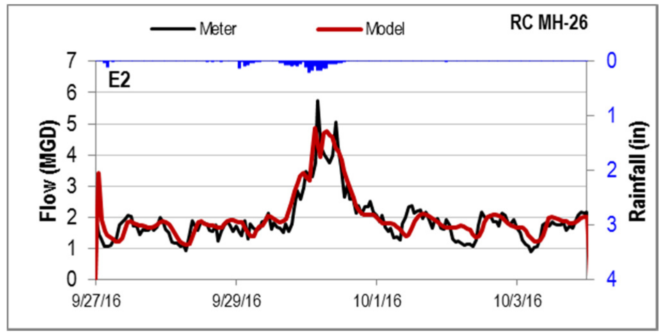


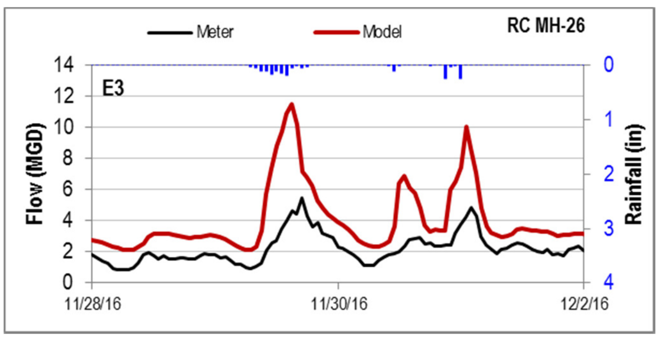


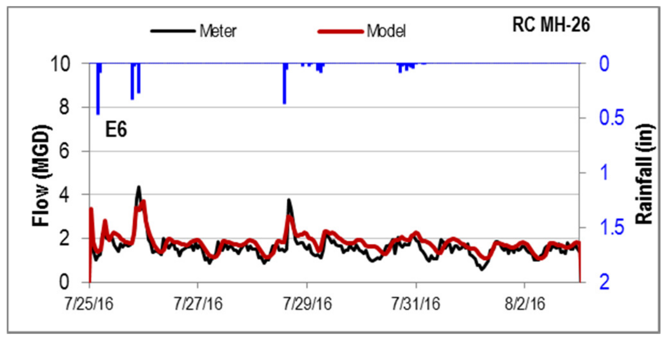
FLOW METER RC MH-26 MODEL CALIBRATION AND VALIDATION RESULTS

RC MH-26 Model Calibration Results (Metered and Modeled Flow)

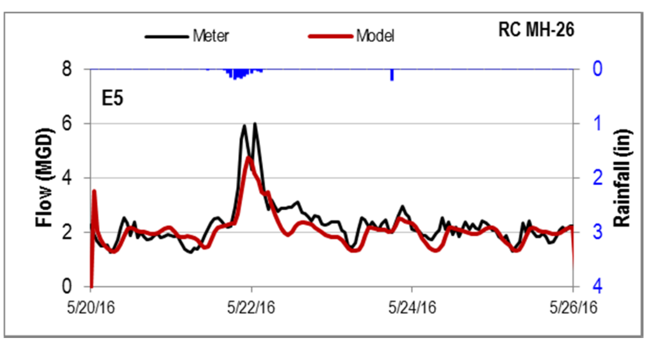




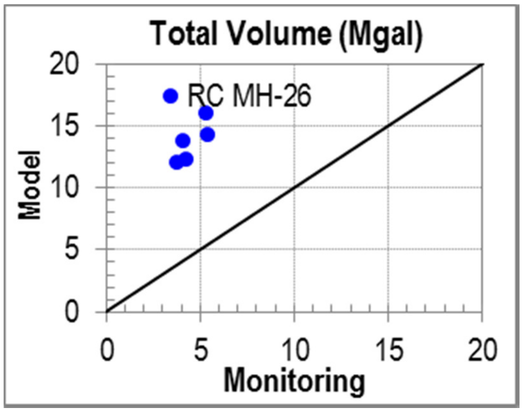


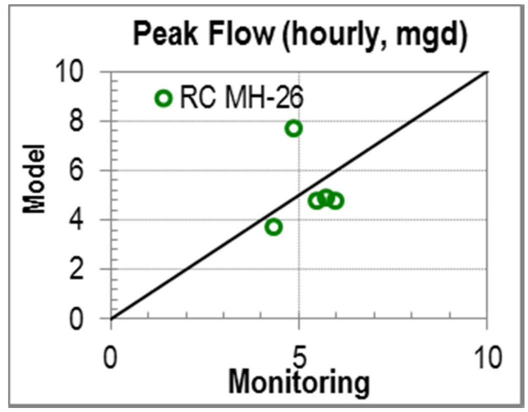


RC MH-26 Model Validation Results (Metered and Modeled Flow)



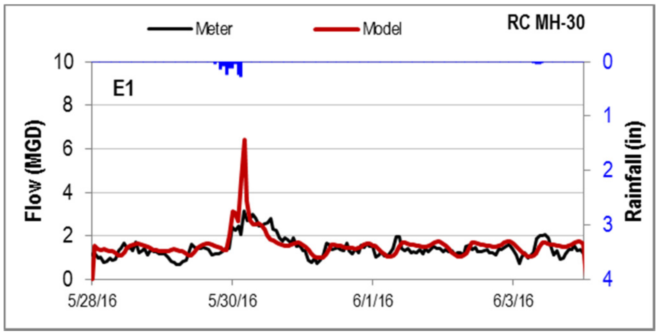
RC MH-26 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

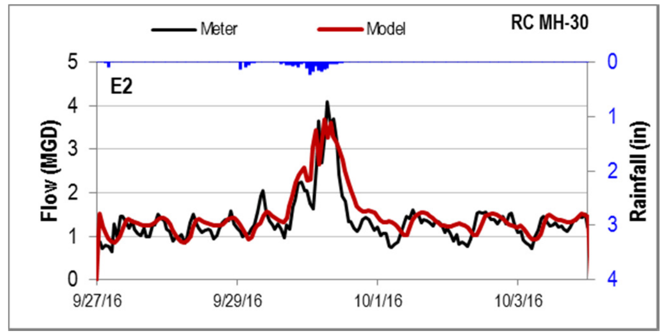


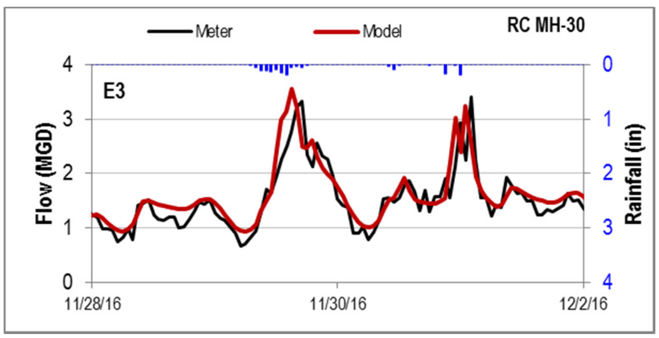


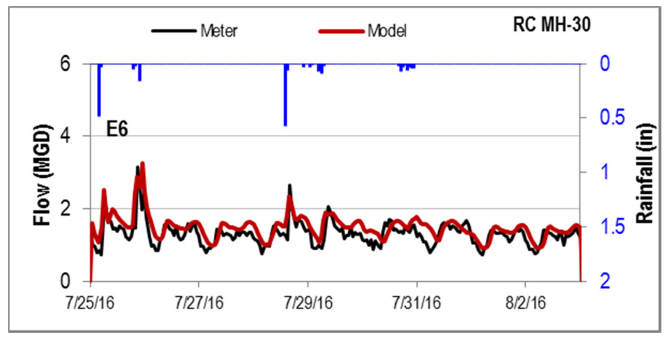
FLOW METER RC MH-30 MODEL CALIBRATION AND VALIDATION RESULTS

RC MH-30 Model Calibration Results (Metered and Modeled Flow)

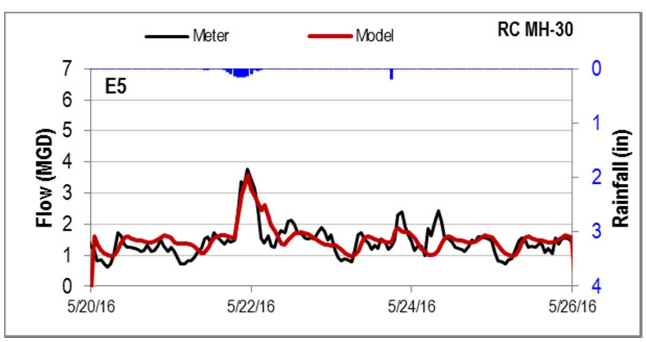




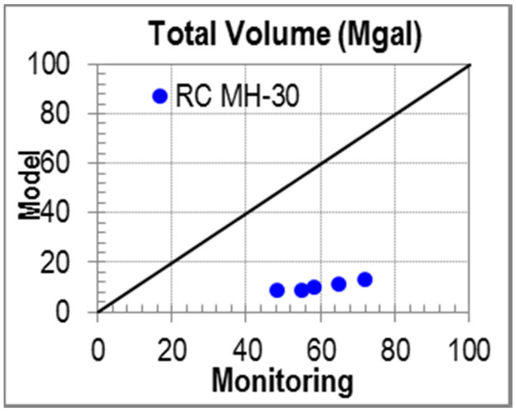


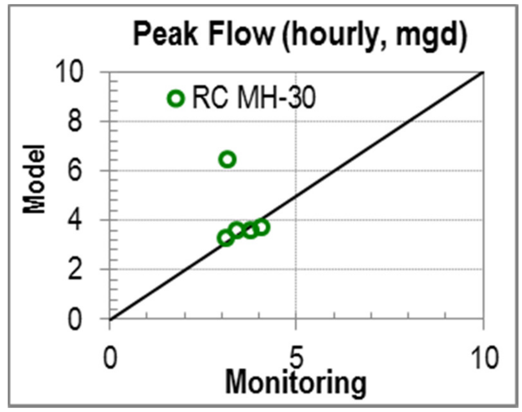


RC MH-30 Model Validation Results (Metered and Modeled Flow)



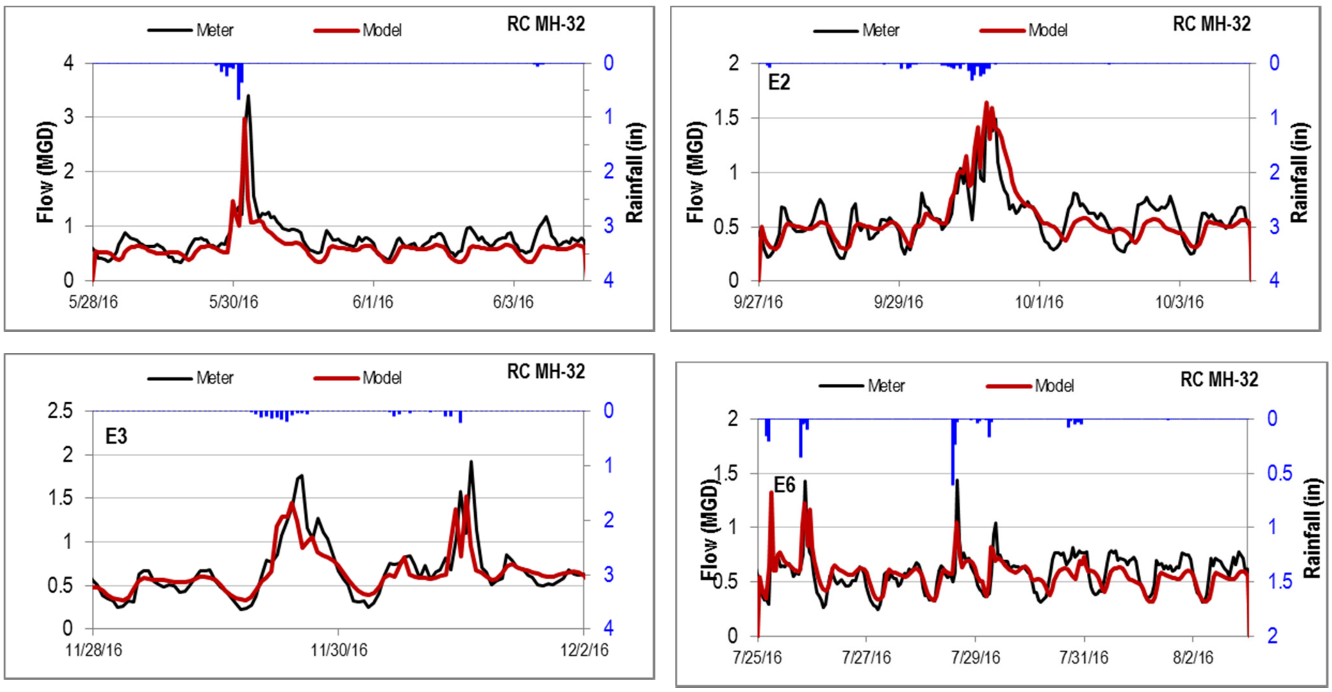
RC MH-30 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



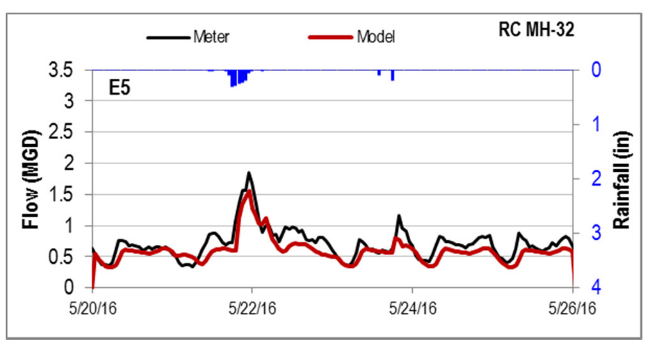


FLOW METER RC MH-32 MODEL CALIBRATION AND VALIDATION RESULTS

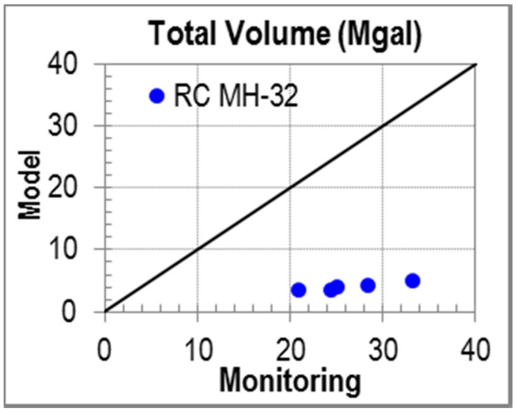
RC MH-32 Model Calibration Results (Metered and Modeled Flow)

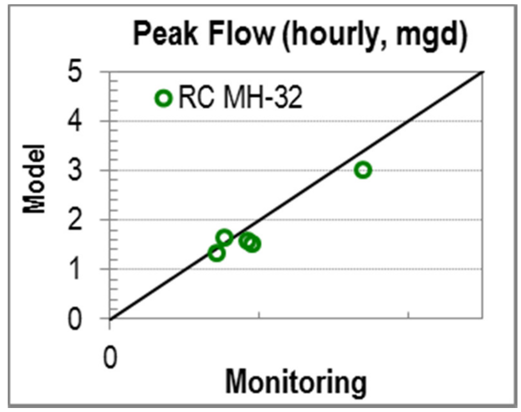


RC MH-32 Model Validation Results (Metered and Modeled Flow)



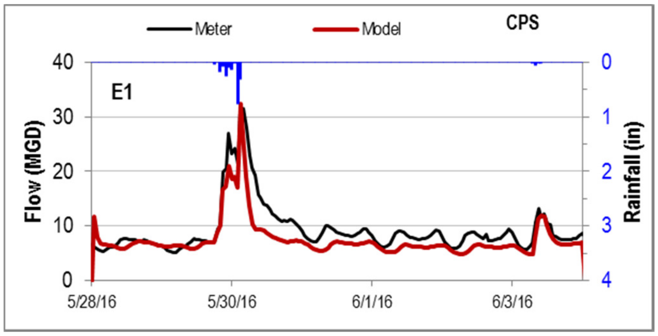
RC MH-32 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

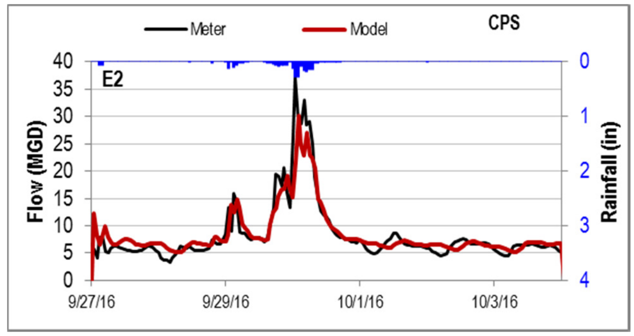


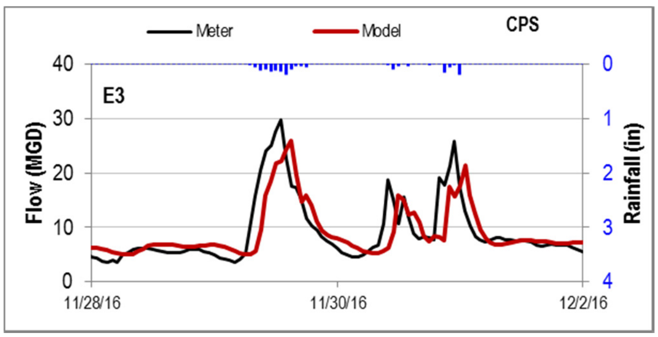


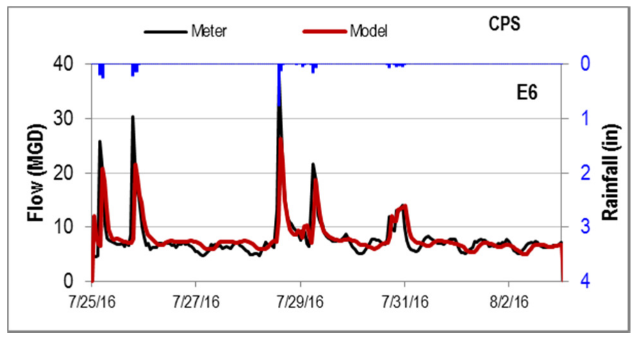
FLOW METER CPS MODEL CALIBRATION AND VALIDATION RESULTS

CPS Model Calibration Results (Metered and Modeled Flow)

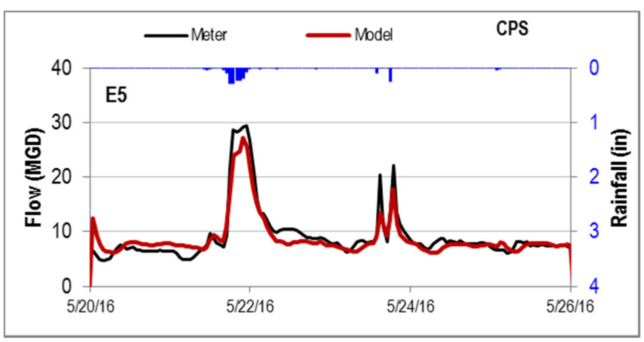




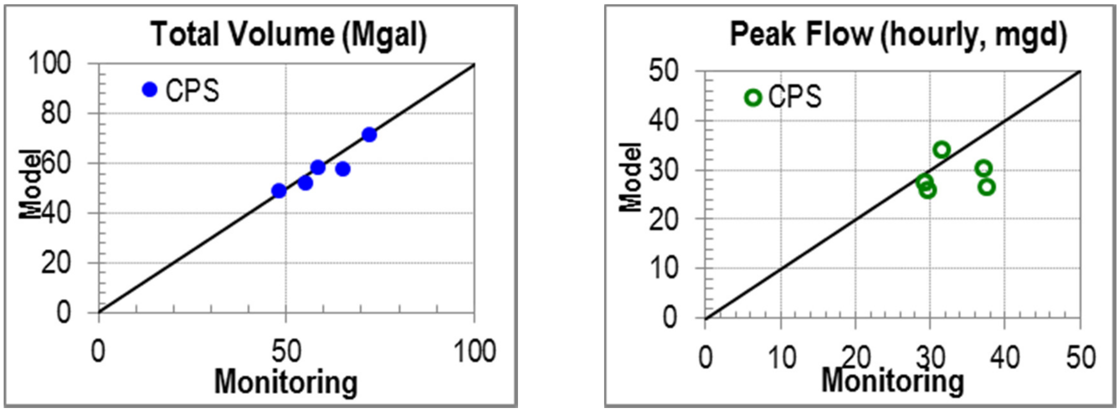




CPS Model Validation Results (Metered and Modeled Flow)

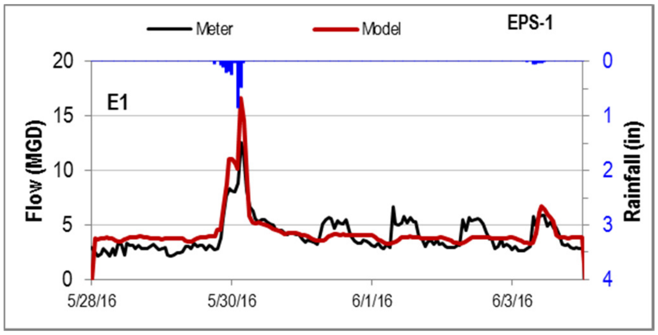


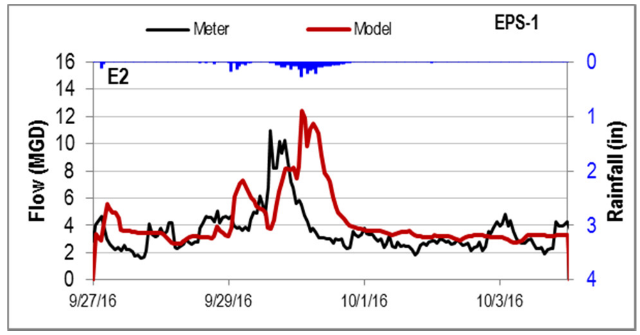
CPS Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

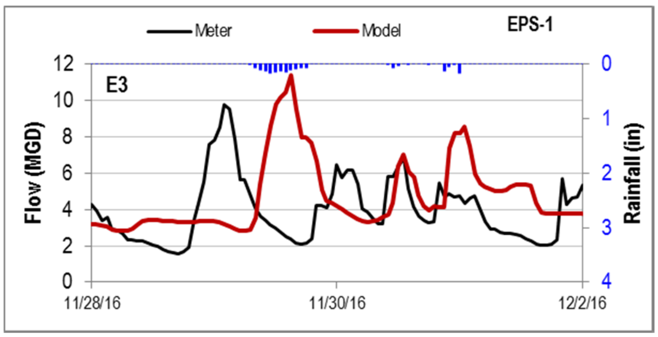


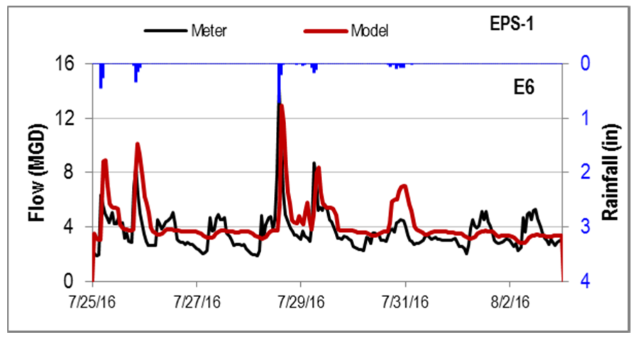
FLOW METER EPS-1 MODEL CALIBRATION AND VALIDATION RESULTS

EPS-1 Model Calibration Results (Metered and Modeled Flow)

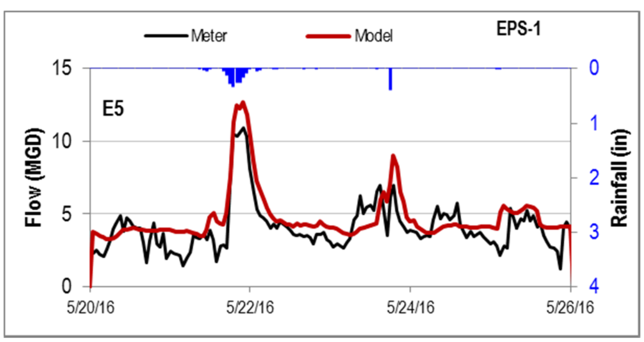




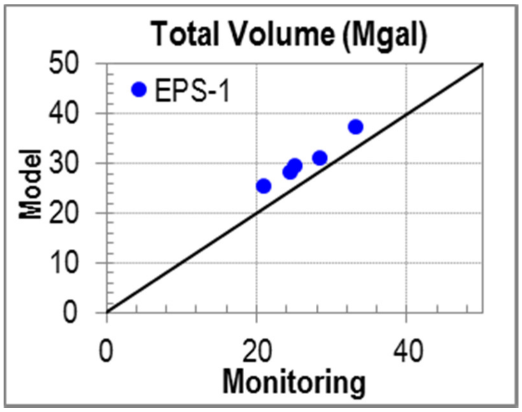


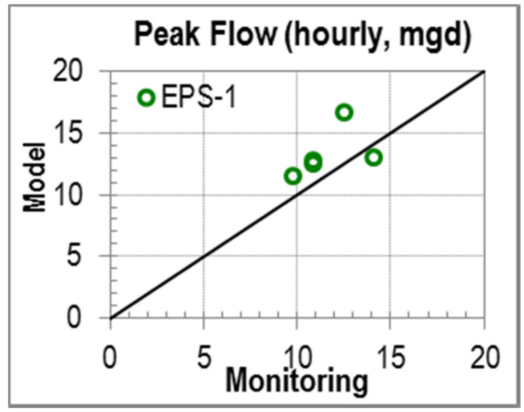


EPS-1 Model Validation Results (Metered and Modeled Flow)



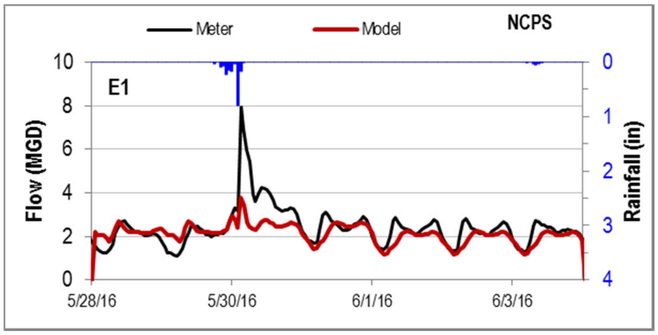
EPS-1 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

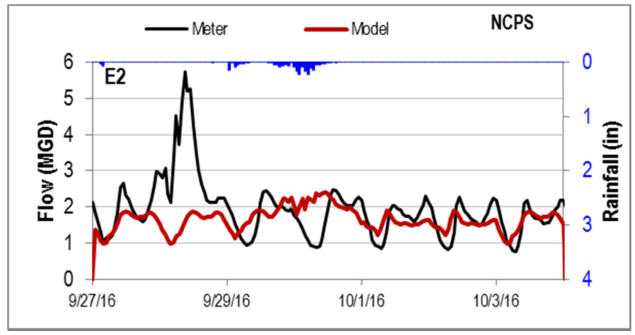


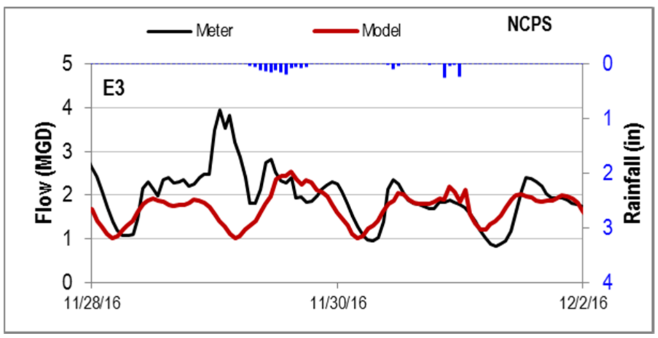


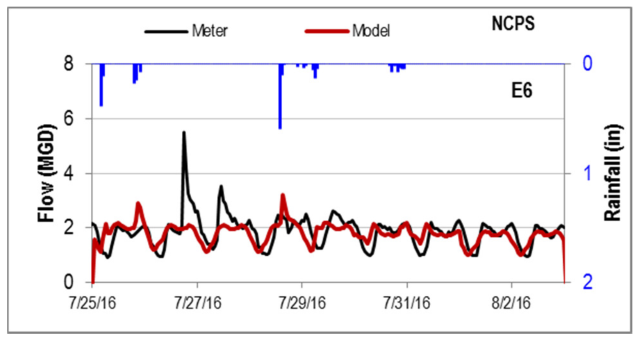
FLOW METER NCPS MODEL CALIBRATION AND VALIDATION RESULTS

NCPS Model Calibration Results (Metered and Modeled Flow)

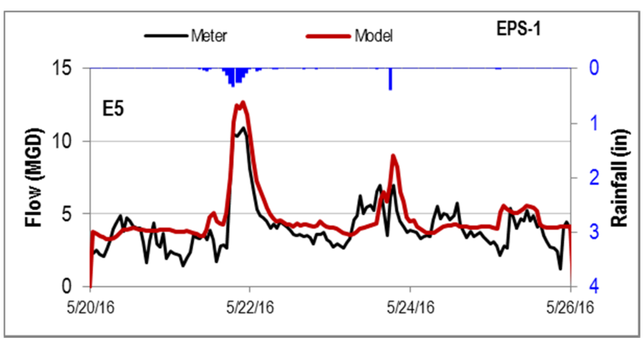




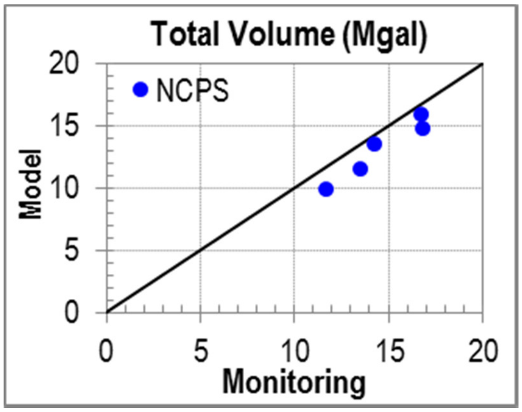


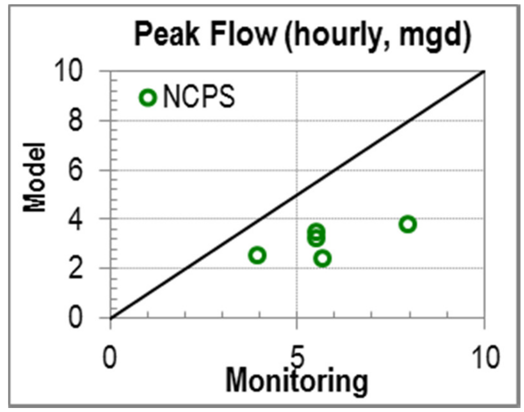


NCPS Model Validation Results (Metered and Modeled Flow)



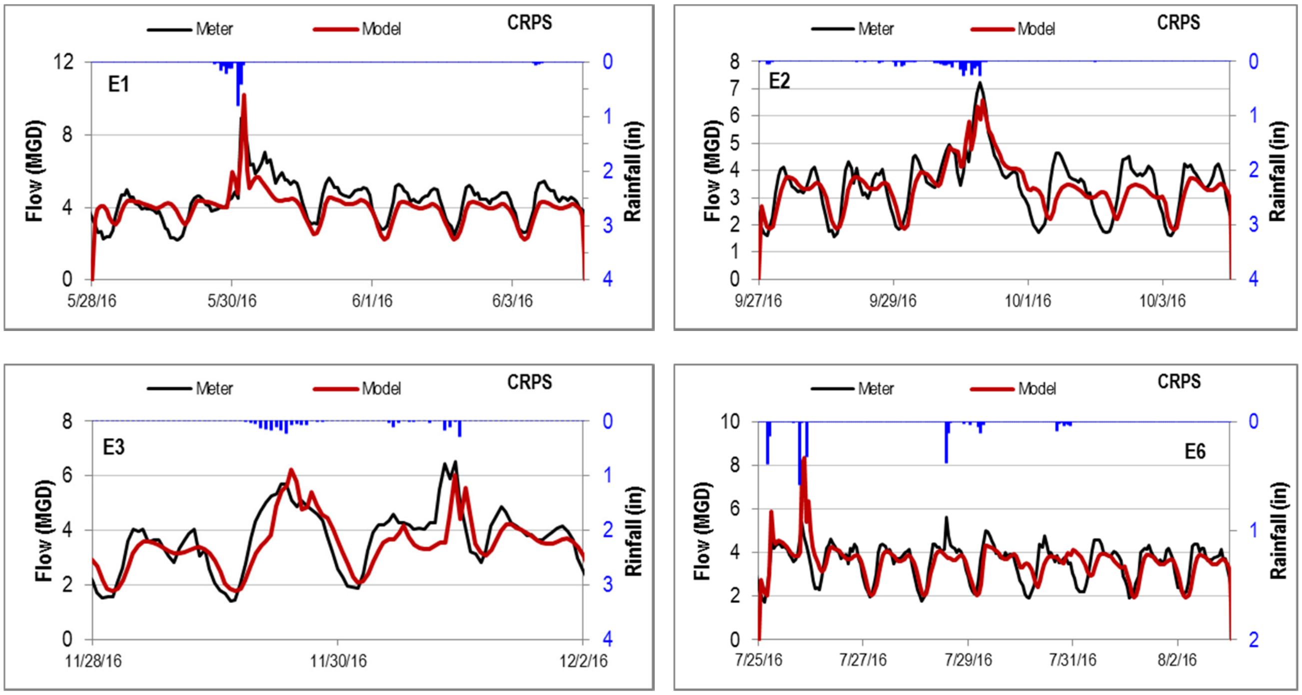
NCPS Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



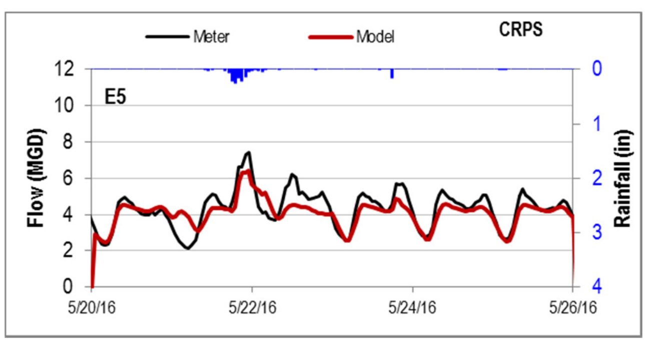


FLOW METER CRPS MODEL CALIBRATION AND VALIDATION RESULTS

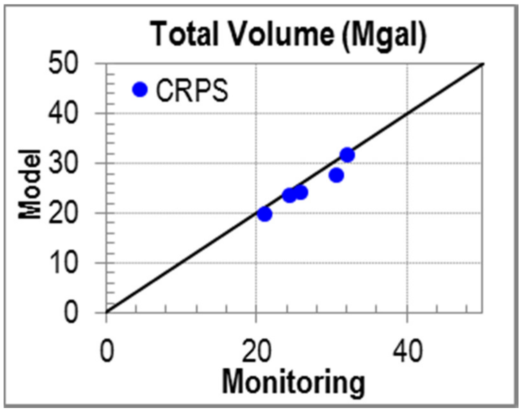
CRPS Model Calibration Results (Metered and Modeled Flow)

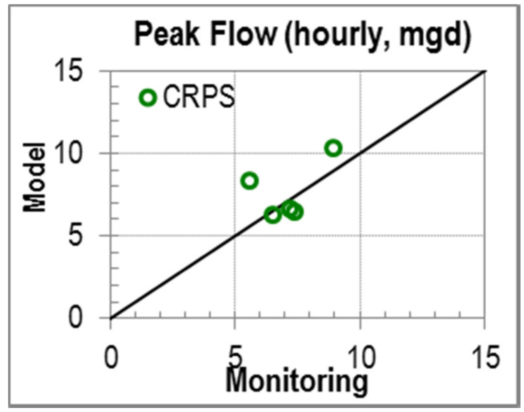


CRPS Model Validation Results (Metered and Modeled Flow)



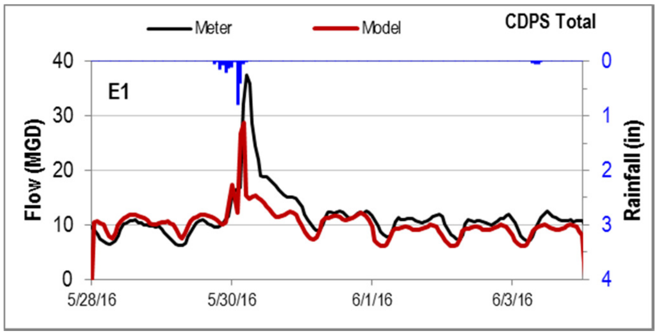
CRPS Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

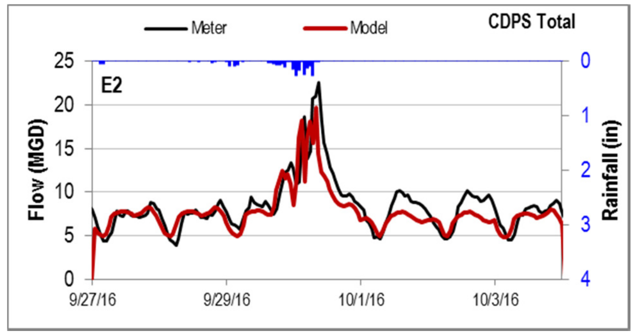


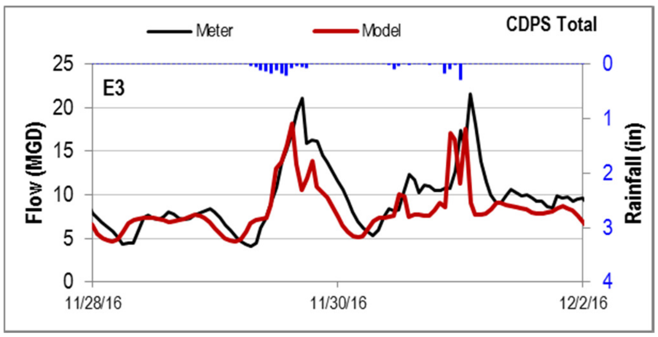


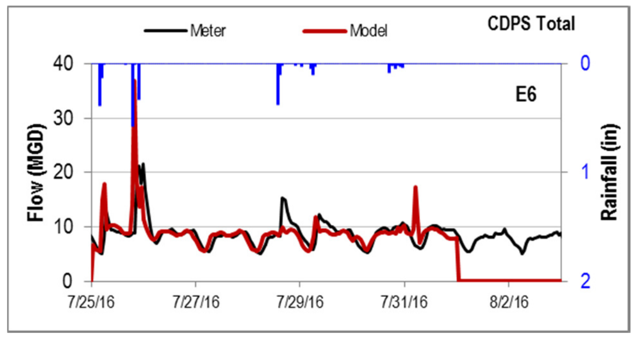
FLOW METER CDPS TOTAL MODEL CALIBRATION AND VALIDATION RESULTS

CDPS Total Model Calibration Results (Metered and Modeled Flow)

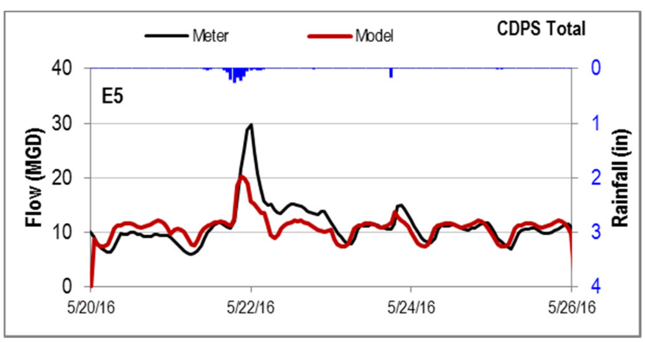




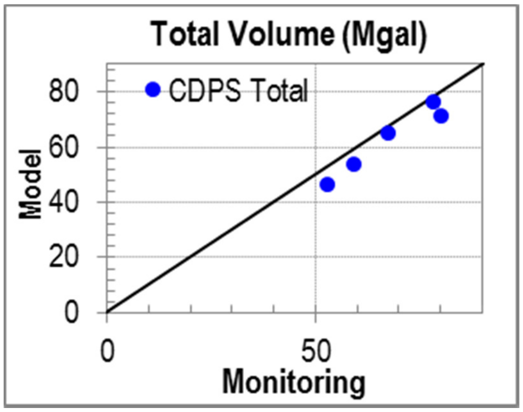


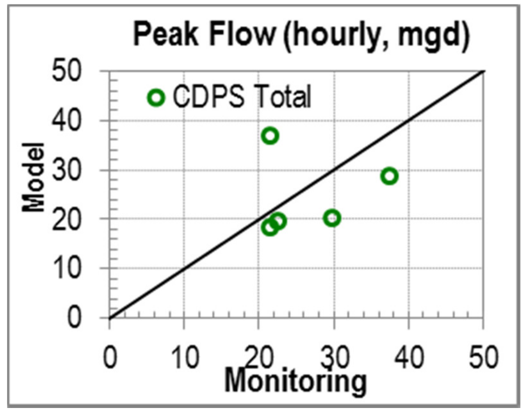


CDPS Total Model Validation Results (Metered and Modeled Flow)



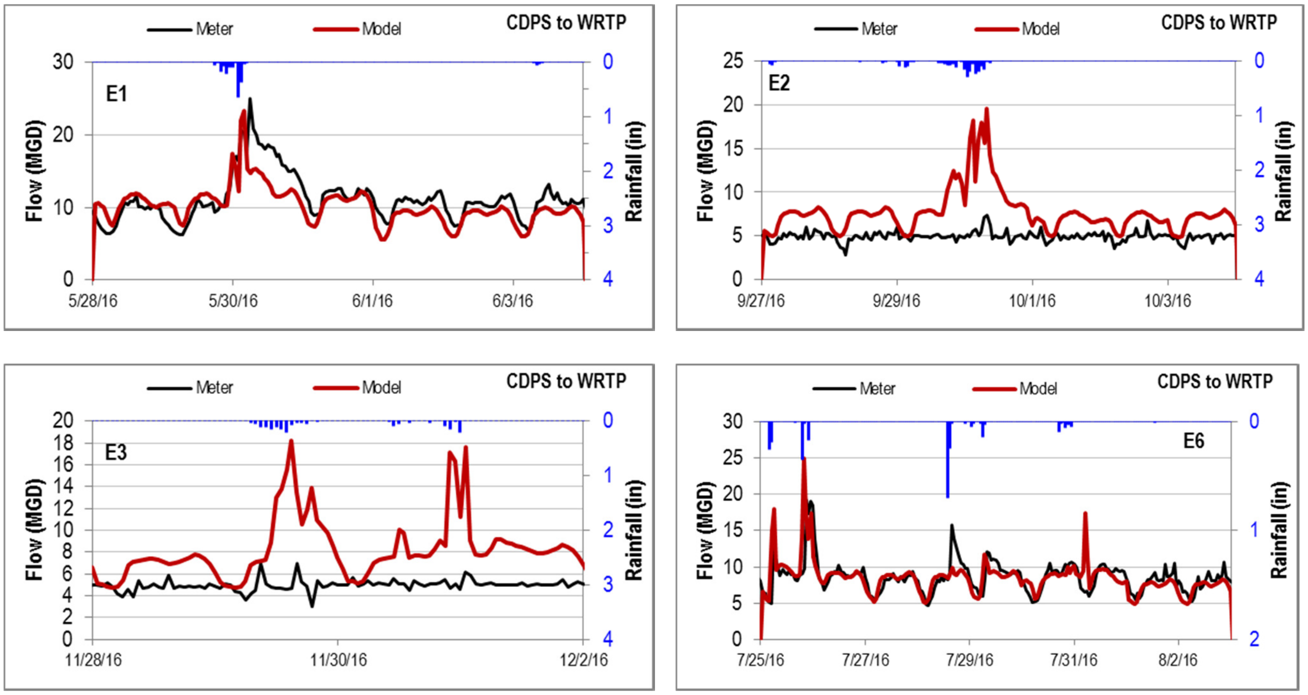
CDPS Total Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



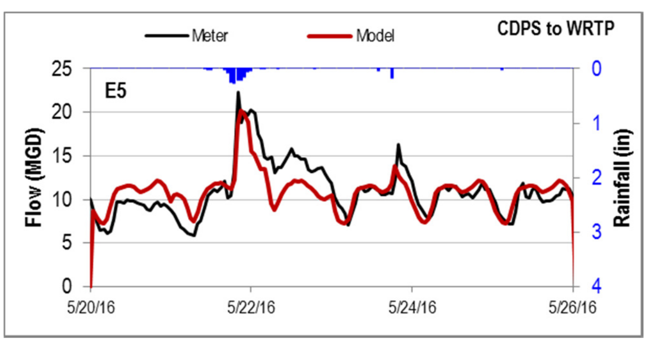


FLOW METER CDPS TO WRTP MODEL CALIBRATION AND VALIDATION RESULTS

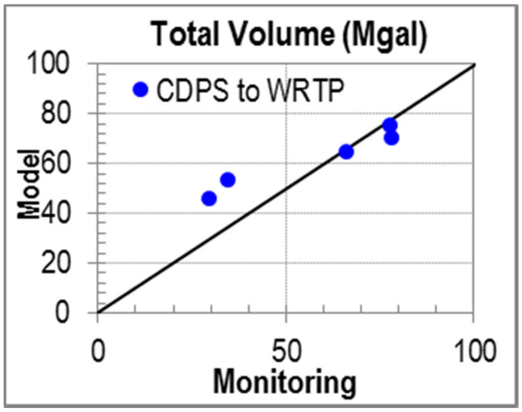
CDPS to WRTP Model Calibration Results (Metered and Modeled Flow)

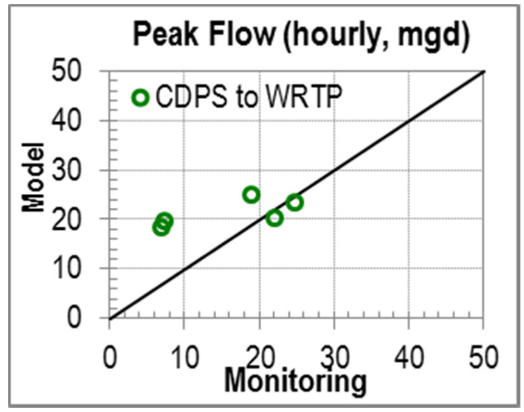


CDPS to WRTP Model Validation Results (Metered and Modeled Flow)



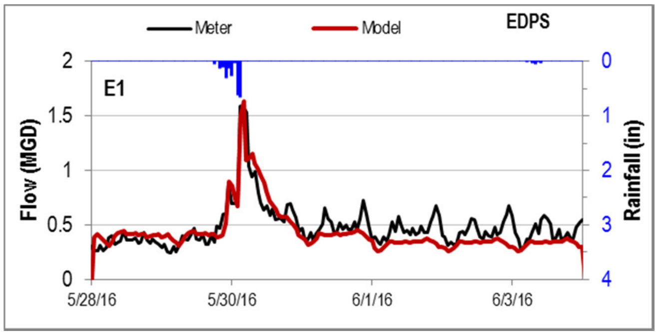
CDPS to WRTP Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

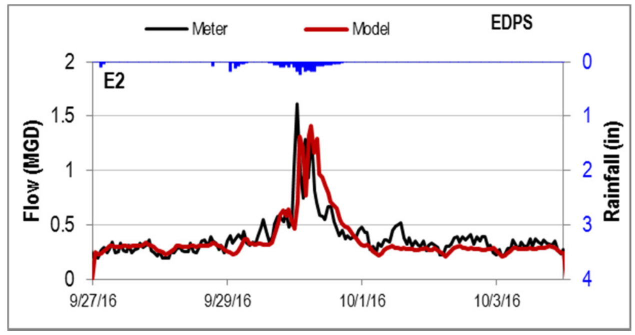


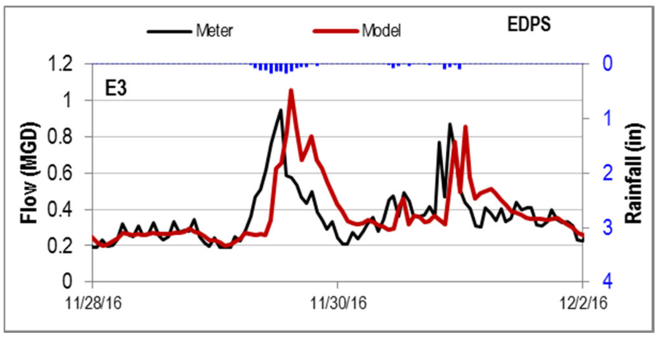


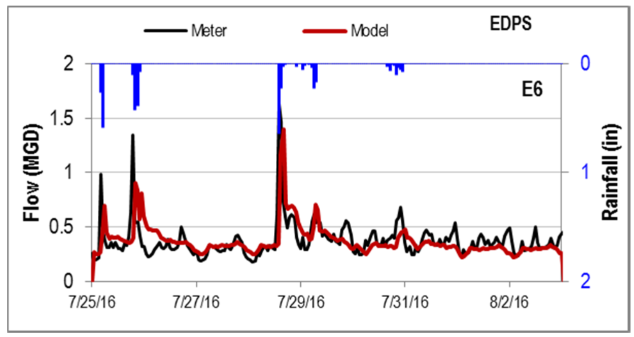
FLOW METER EDPS MODEL CALIBRATION AND VALIDATION RESULTS

EDPS Model Calibration Results (Metered and Modeled Flow)

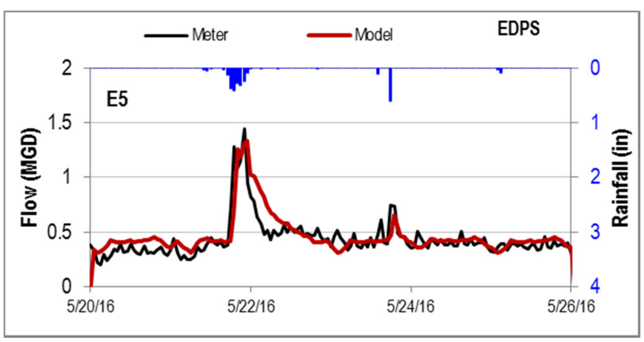




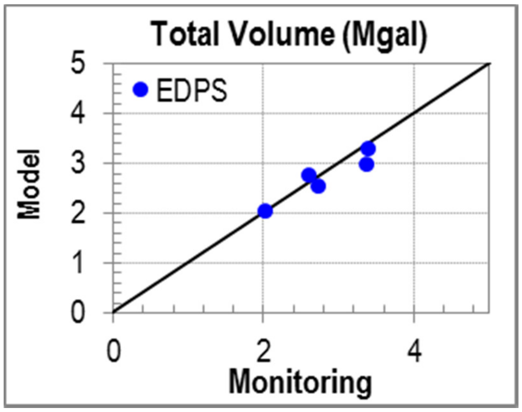


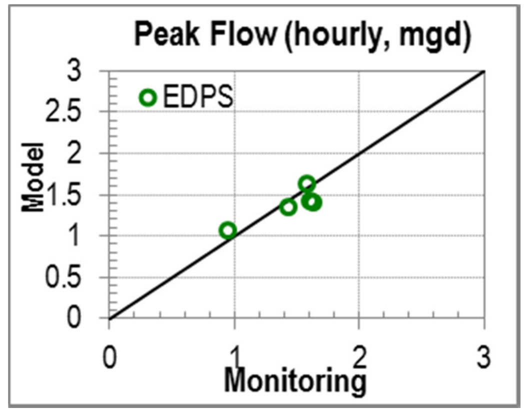


EDPS Model Validation Results (Metered and Modeled Flow)



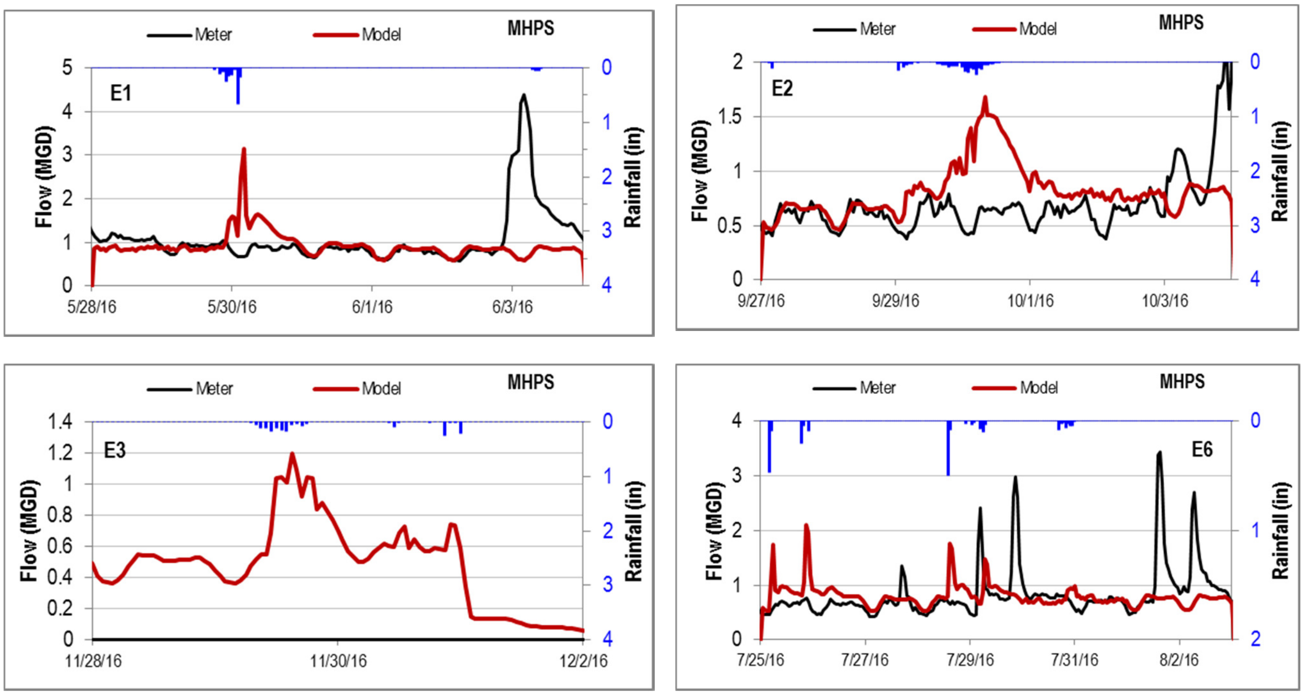
EDPS Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



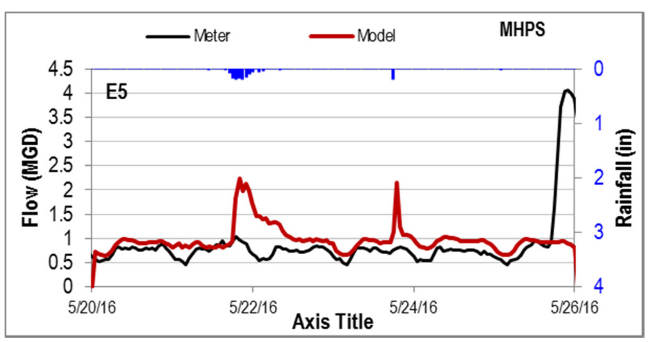


FLOW METER MHPS MODEL CALIBRATION AND VALIDATION RESULTS

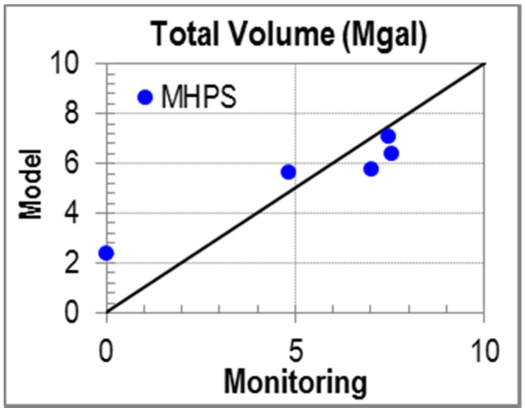
MHPS Model Calibration Results (Metered and Modeled Flow)

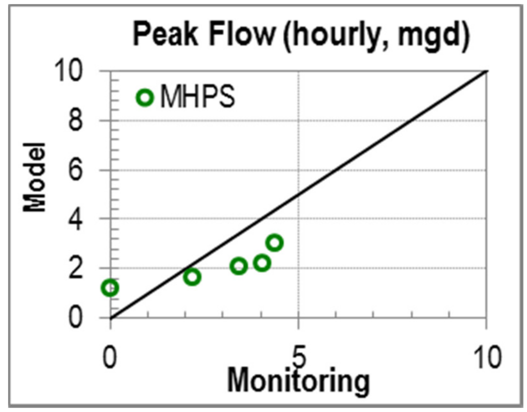


MHPS Model Validation Results (Metered and Modeled Flow)



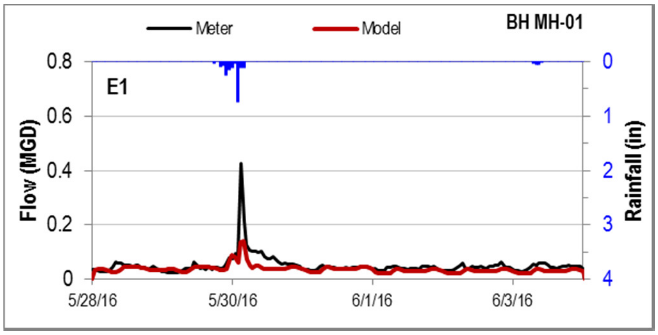
MHPS Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

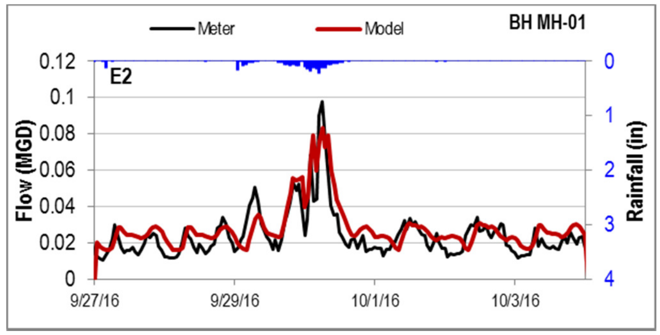


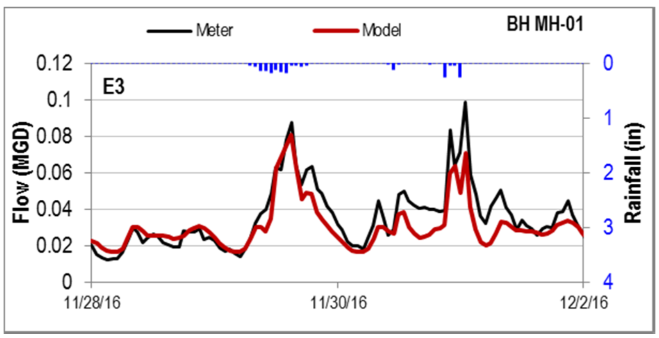


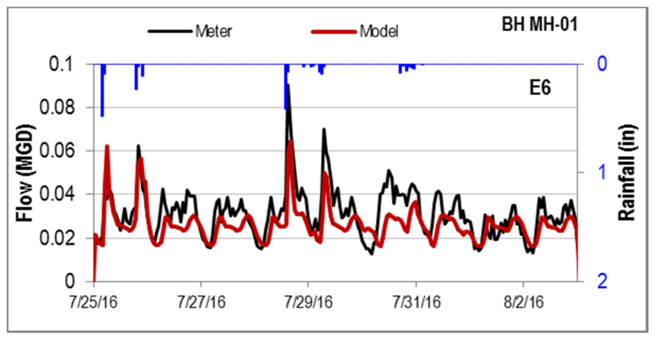
FLOW METER BH MH-01 MODEL CALIBRATION AND VALIDATION RESULTS

BH MH-01 Model Calibration Results (Metered and Modeled Flow)

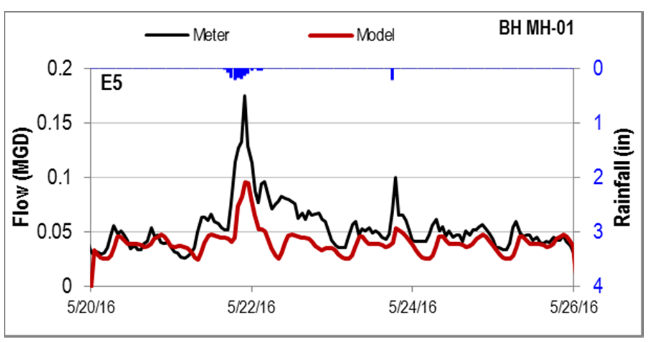




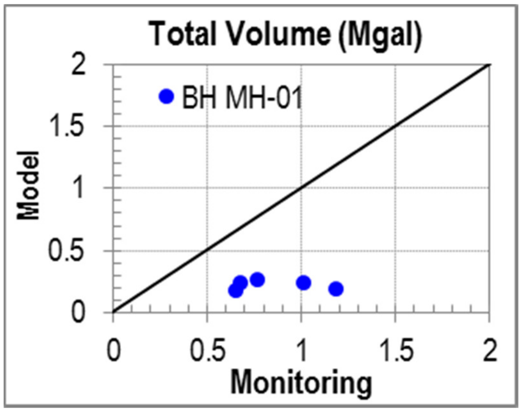


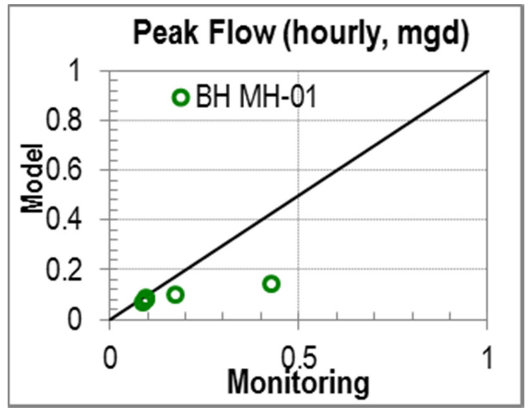


BH MH-01 Model Validation Results (Metered and Modeled Flow)



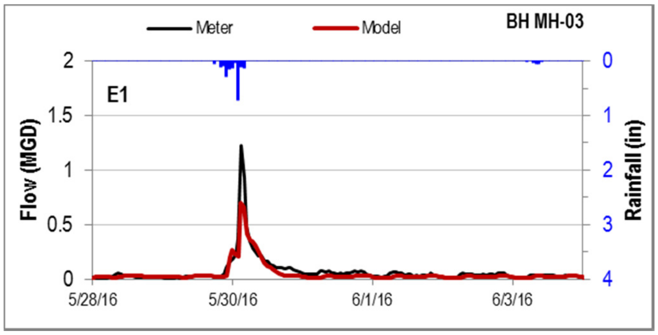
BH MH-01 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

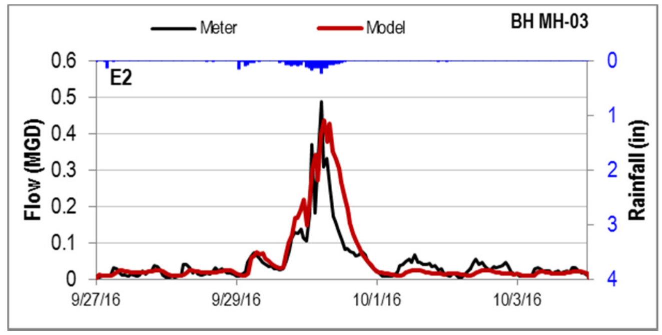


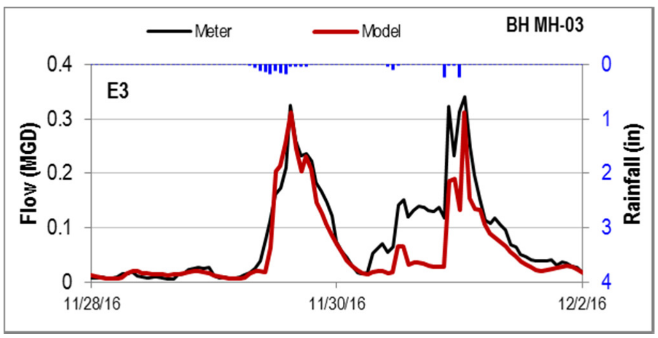


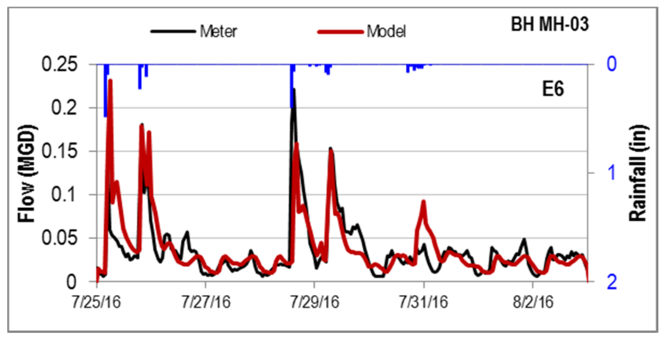
FLOW METER BH MH-03 MODEL CALIBRATION AND VALIDATION RESULTS

BH MH-03 Model Calibration Results (Metered and Modeled Flow)

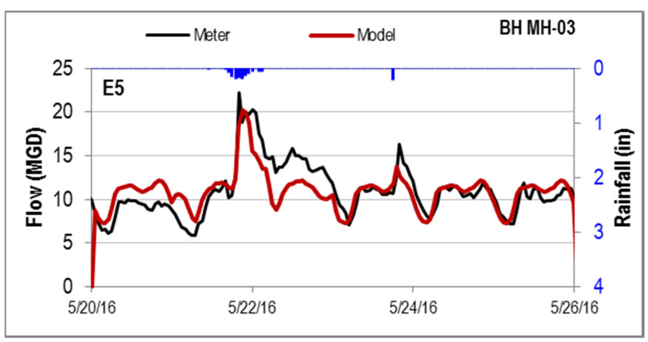




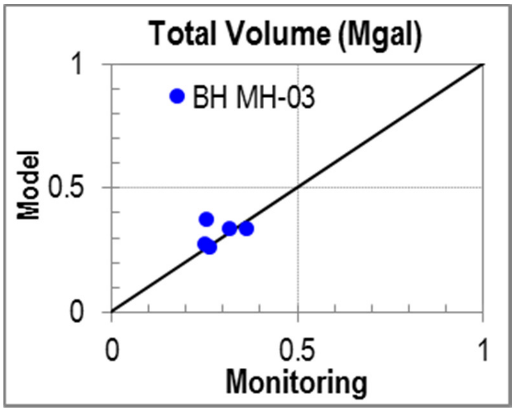


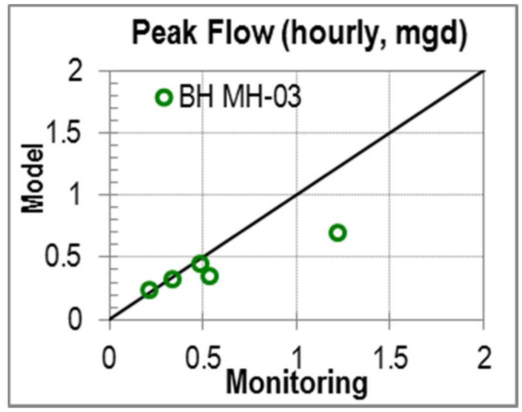


BH MH-03 Model Validation Results (Metered and Modeled Flow)



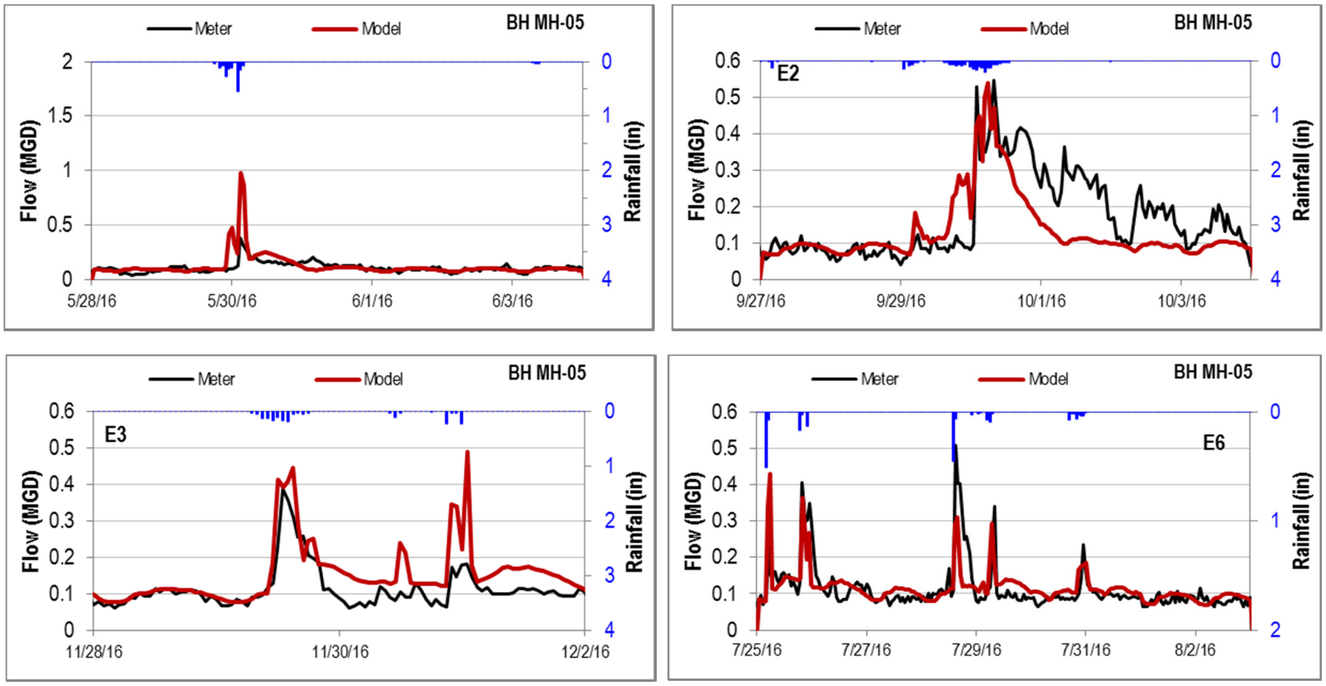
BH MH-03 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



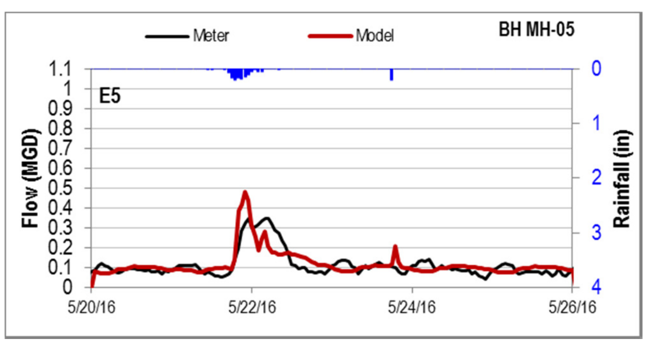


FLOW METER BH MH-05 MODEL CALIBRATION AND VALIDATION RESULTS

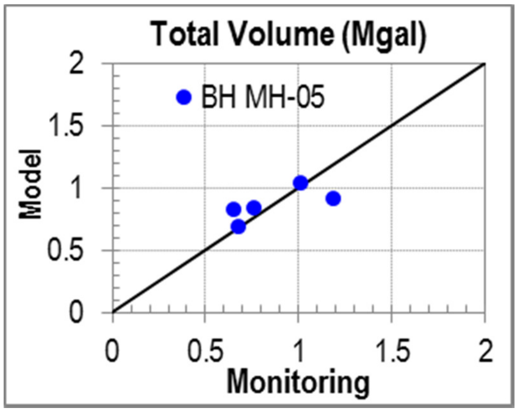
BH MH-05 Model Calibration Results (Metered and Modeled Flow)

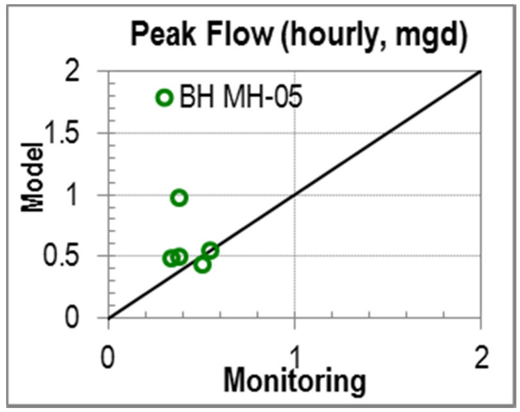


BH MH-05 Model Validation Results (Metered and Modeled Flow)



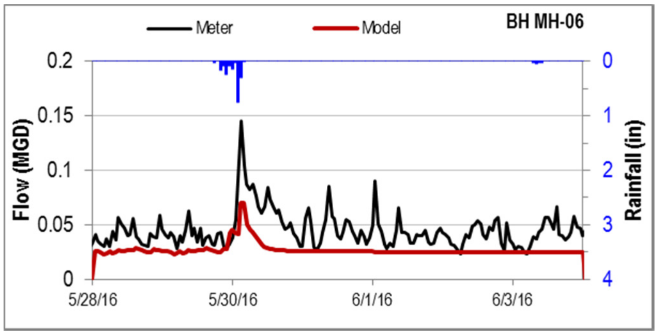
BH MH-05 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)

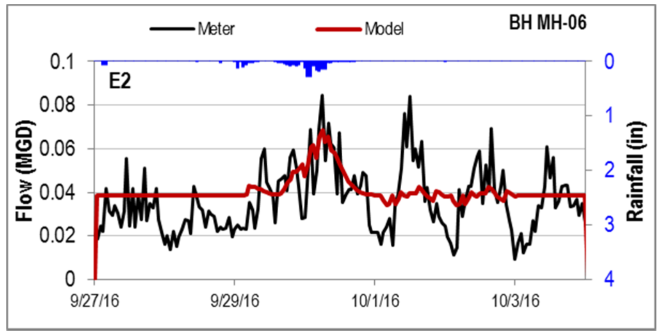


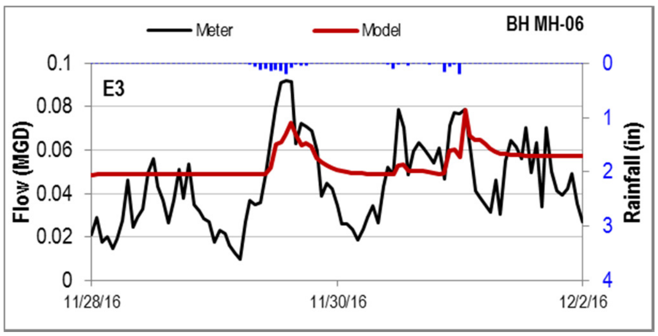


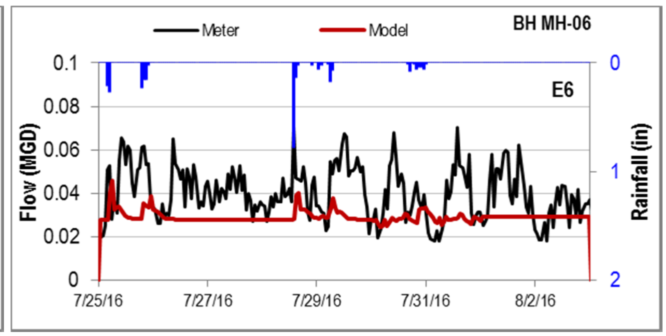
FLOW METER BH MH-06 MODEL CALIBRATION AND VALIDATION RESULTS

BH MH-06 Model Calibration Results (Metered and Modeled Flow)

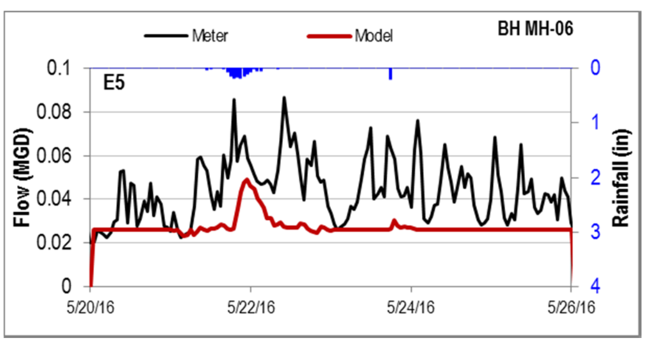




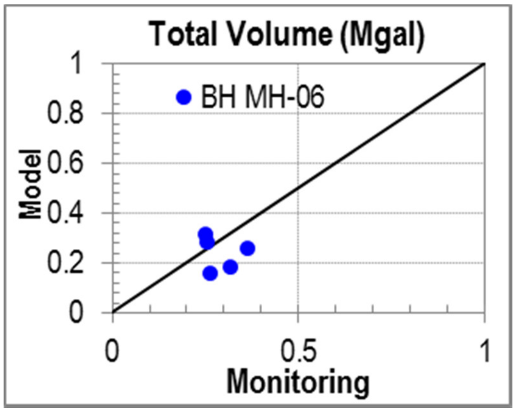


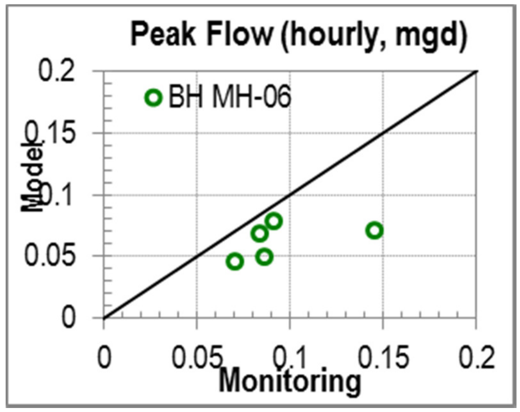


BH MH-06 Model Validation Results (Metered and Modeled Flow)



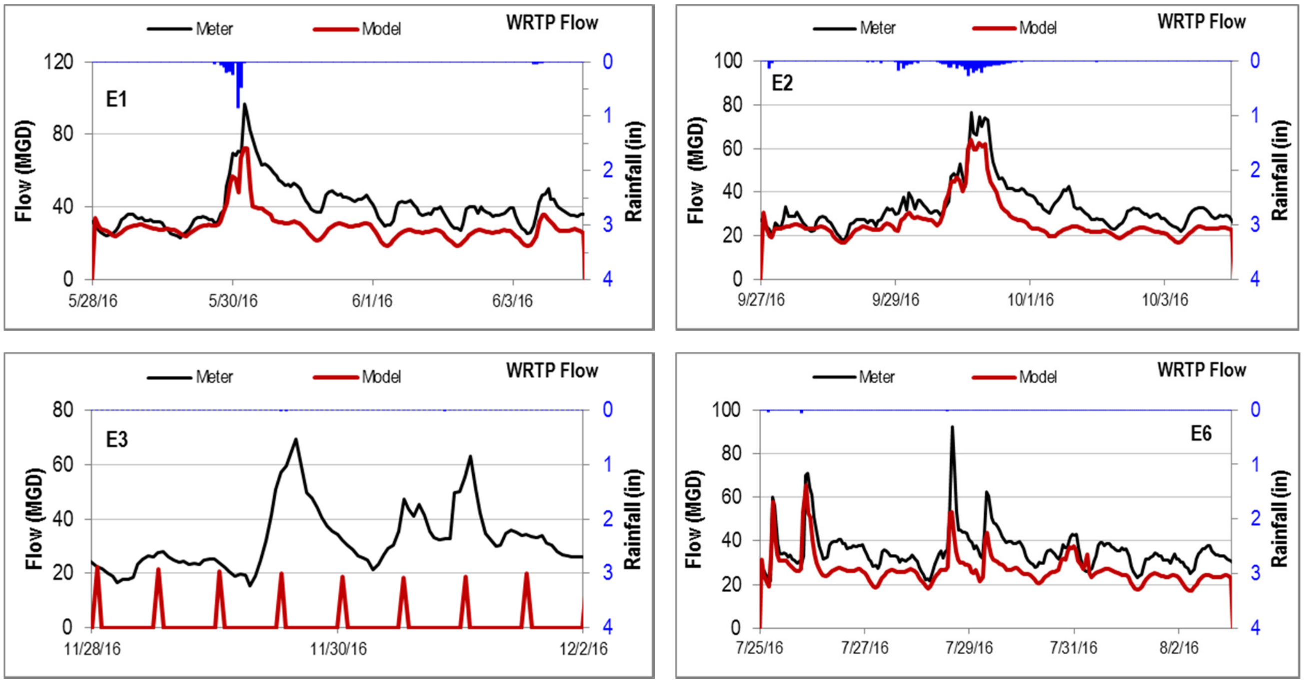
BH MH-06 Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)



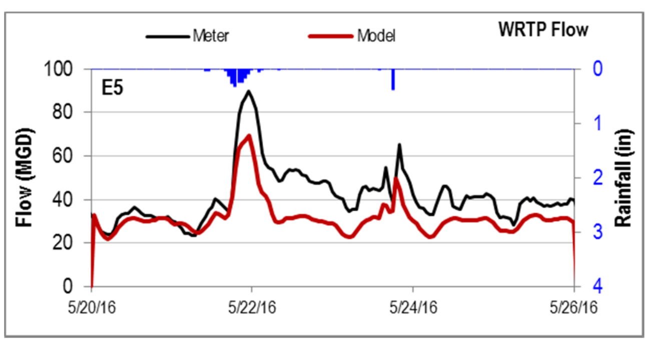


FLOW METER WRTP Flow MODEL CALIBRATION AND VALIDATION RESULTS

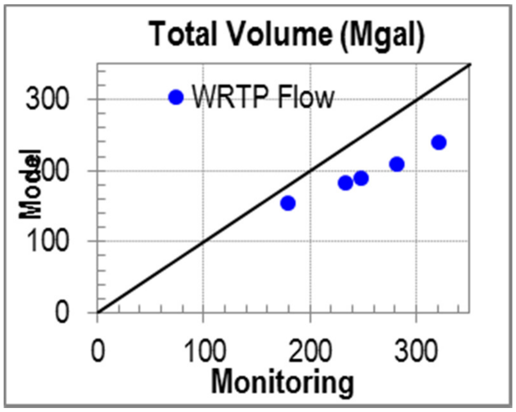
WRTP Flow Model Calibration Results (Metered and Modeled Flow)

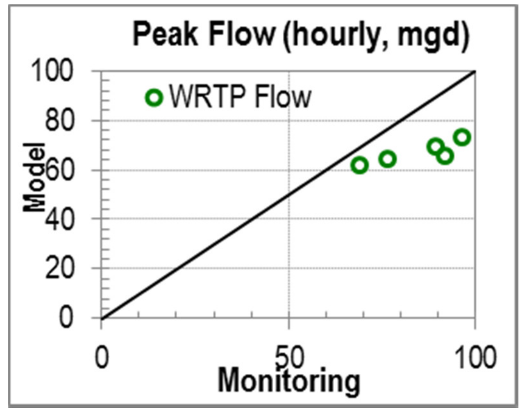


WRTP Flow Model Validation Results (Metered and Modeled Flow)



WRTP Flow Overall Model Calibration and Validation Results (Volume and Flow 1:1 Plots)





Greeley and Hansen LLC
1700 Market Street, Suite 2130
Philadelphia, PA 19103
(215) 563-3460
www.greeley-hansen.com

GREELEY AND HANSEN