SKYWAY INFILTRATION AND INFLOW REDUCTION DEMONSTRATION PROJECT EVALUATION REPORT

March 2014

King County
Department of Natural Resources and Parks
Wastewater Treatment Division

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Project #3630037

Skyway Initial Infiltration and Inflow Reduction Demonstration Project Evaluation Report

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CHAPTER 1.
PROJECT OVERVIEW

In 2012, King County's Wastewater Treatment Division and the Skyway Water and Sewer District (WSD) repaired and replaced sewer mains, side sewers, laterals and manholes in a residential sewer service basin near the southwest end of Lake Washington (Skyway Basin BLS002). The goal of this demonstration project was to reduce infiltration and inflow (I/I) to the sewer system, increasing the unused capacity of the wastewater conveyance system and eliminating the need for a planned wastewater storage facility downstream.

This report summarizes the history of the project, the work performed, follow-up investigations, and findings about the project's effectiveness in reducing I/I. It describes lessons learned from the project that can be applied to similar work in the future and outlines additional steps needed in order to use the project results for future decision-making.

1.1 PROJECT HISTORY

Reducing I/I, which consists of stormwater and groundwater entering a sanitary sewer system from various sources, makes more capacity available for sewage in King County's wastewater system. This increased capacity helps to prevent overflows and reduces the need for capital projects to expand system capacity. The Skyway I/I Reduction Demonstration Project was an early test of the effectiveness of I/I reduction measures over a large area. The following County programs and projects provided the foundation for developing and implementing the project:

- **Regional Infiltration/Inflow Control Program**—The King County Regional I/I Control Program was created in 1999 to reduce I/I in the County's wastewater conveyance system when it is cost-effective to do so. Under this program, the County implemented multiple pilot projects in 2003 and 2004 to test various I/I reduction methods and technologies. For these projects, the County performed sewer system evaluation surveys that included cleaning, CCTV inspection and smoke testing for sources of inflow. Sewer system evaluation survey results were used to design I/I reduction pilot projects that included pre- and post-construction flow monitoring to determine the projects' effectiveness. Results of the pilot projects were used to establish assumptions for estimating costs for subsequent I/I reduction projects and the expected amount of I/I reduction. One of the pilot projects, the Skyway Pilot Project, was in a portion of Skyway Basin BLS002.
- **Draft Standards, Guidelines, Procedures and Policies**—King County and local sewer agencies developed a draft set of design and inspection standards to be used on future projects to reduce and control I/I, based on engineering judgments of best practices. The standards, guidelines, procedures and policies were applied and tested in the Skyway I/I Demonstration Project.
- **Executive's Recommended Regional Infiltration and Inflow Control Program**—The six-year I/I program development process culminated in consensus recommendations by the County and local agencies about the future direction of the County's I/I program. The consensus drew from findings of the flow monitoring, modeling and pilot projects and a benefit-cost analysis, all conducted during the I/I control study. A key recommendation was for the County to implement and evaluate two or three "initial" I/I reduction projects to test the cost-effectiveness of I/I reduction on a larger scale than the pilot projects.

- **Conveyance System Improvement Program**—King County's Conveyance System Improvement (CSI) Program outlines needed capital improvements to provide adequate capacity in the County-owned regional wastewater conveyance system. Among the CSI program's current recommendations is the 0.27-million-gallon Bryn Mawr Storage Facility, which would help to accommodate high system flows downstream of Skyway Basin BLS002.
- **King County Initial I/I Reduction Project Predesign Report**—Preliminary design recommendations were published in March 2010 for King County's Initial I/I Reduction Demonstration Projects. The report documents preliminary design evaluations and findings, provides estimates of project cost and benefit, and presents considerations for implementing I/I reduction projects in three basins (see Figure 1-1): Bellevue Basin BEL031, Issaquah Basin ISS003, and Skyway Basin BLS002. Following completion of the Initial I/I Reduction Project Predesign Report, only the Skyway basin project was moved forward to final design and implementation due to budget constraints.

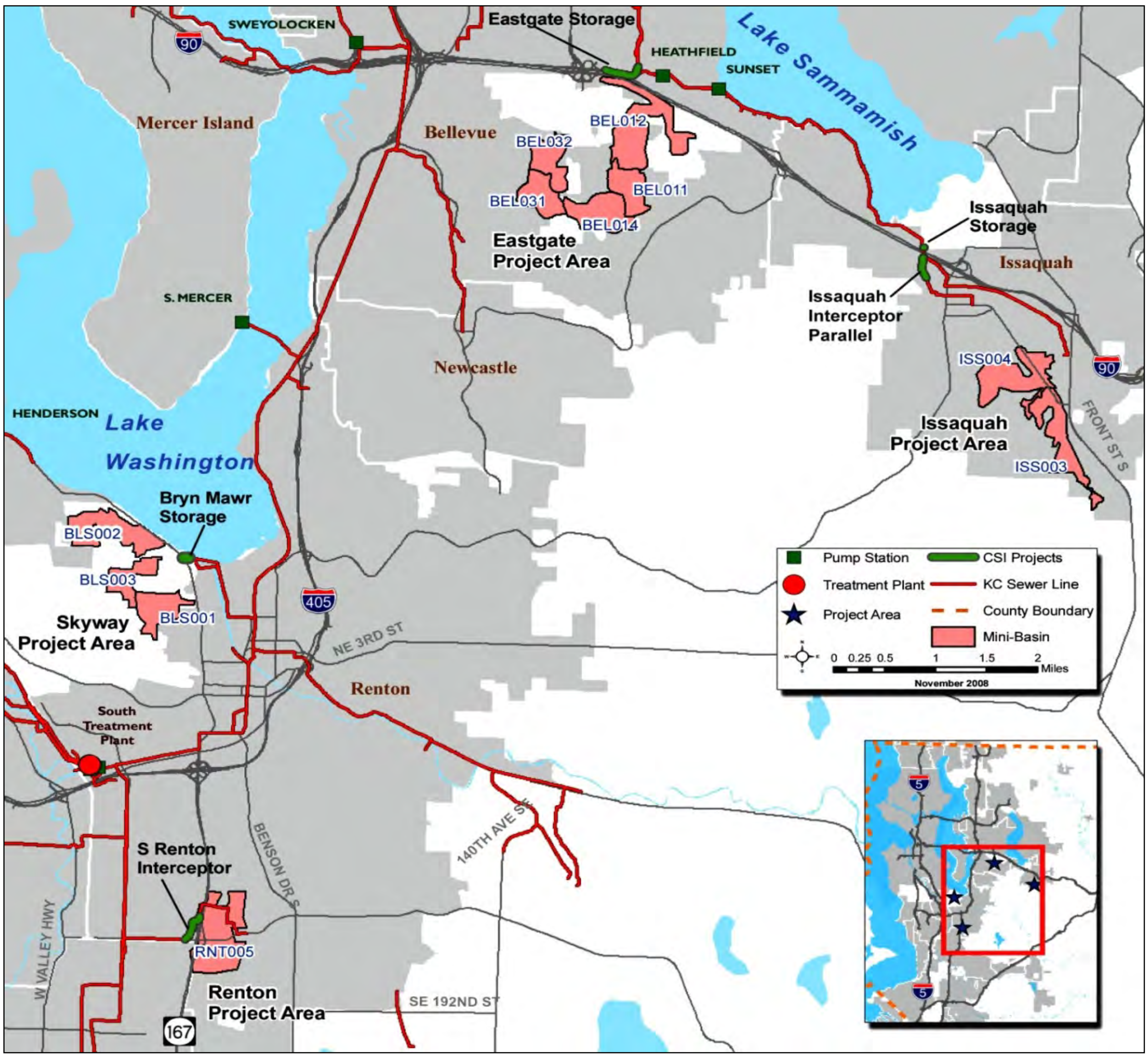

Figure 1-1. Initial I/I Reduction Project Candidate Basins and Related CSI Projects

1.2 PROJECT DESCRIPTION

1.2.1 Project Scope

The Skyway Initial I/I Reduction Project, hereafter called the Demonstration Project, aimed to rehabilitate side sewers and laterals serving 343 of the 375 properties in Basin BLS002 using pipe bursting with 4-inch-diameter HDPE pipe. See Section 2.1 Final Design. Figure 1-2 shows an overview of the project area. As an additional project component, the Skyway WSD financed replacement of approximately 20,000 feet of primarily 8-inch diameter sewer mains by pipe bursting and replacement of 90 manholes.

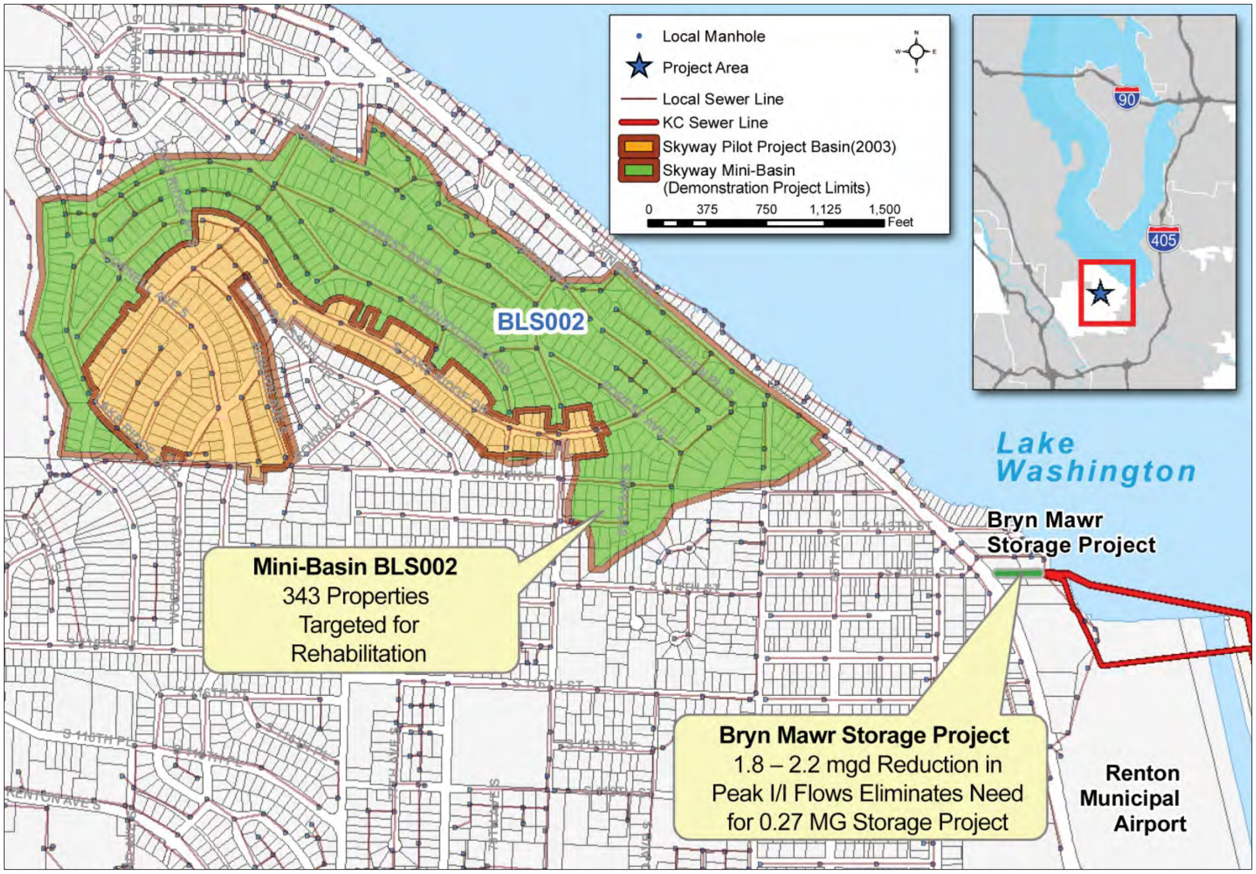

Figure 1-2. Skyway I/I Reduction Demonstration Project Location

1.2.2 Predicted I/I Reduction

The Demonstration Project was similar in many ways to the earlier pilot project in this basin, the location of which is also shown on Figure 1-2. Similarities include the age of the sewer pipe, the materials used for rehabilitation, neighborhood characteristics, and the condition of the sewers. The 2003/2004 Skyway Pilot project resulted in an 88.5-percent reduction in peak I/I. However, the County and local sewer agencies established a more conservative reduction target range of 60 to 75 percent for the Demonstration Project. Based on this assumption, the Demonstration Project was predicted to reduce I/I in Basin BLS002 by a range of 1.8 million gallons per day (mgd) to 2.2 mgd. This reduction estimate was based on the assumption of rehabilitating only the laterals and side sewers. Additional reduction expected from replacement of sewer mains and manholes was not accounted for in the estimate. Achieving the lower end of the reduction range (60 percent) would provide sufficient downstream system capacity to eliminate the need for the Bryn Mawr Storage Facility.

1.2.3 Cost-Effectiveness

To evaluate cost-effectiveness, a benefit/cost ratio was calculated as follows:

$$\text{Benefit/Cost Ratio} = \frac{\text{CSI Project Savings After I/I Reduction}}{\text{Cost of I/I Reduction Project}}$$

Projects with benefit/cost ratios greater than or equal to 1.0 are considered to be cost-effective. For the Skyway Demonstration Project, the benefit/cost ratio was calculated based on the County portion of the estimated project cost (the cost for rehabilitating the laterals and side sewers) and the projection that the project would allow for elimination of the Bryn Mawr Storage Project:

- Benefit—Avoided project cost for Bryn Mawr Storage Project: $5.37 million
- Cost—Estimated King County project cost for Skyway Demonstration Project: $5.62 million:
  - Total project cost consists of construction cost plus King County allied cost
  - This estimate is the pre-design estimate that was used at the time the cost-effectiveness evaluation was performed; the estimate was revised prior to project bid
- Benefit-to-cost ratio—0.95.

To increase the County’s benefit-to-cost ratio for the Demonstration Project to 1.0, the Skyway WSD planned to contribute $250,000 for lateral and side sewer rehabilitation, reducing the total cost to King County.

1.2.4 Identified Risks

A risk assessment of the proposed project was performed during predesign, based on the understanding of project conditions in the basin. Table 1-1 lists risks identified in the predesign report with medium or high impact potential and probability, along with their estimated risk costs and potential measures to mitigate the risks.

TABLE 1-1.
MEDIUM- AND HIGH-RATED RISK ELEMENTS AND MITIGATION MEASURES

Risk Element	Probability /Impact Rating[a]	Potential Risk Mitigation / Response
Rights-of-entry are attained for too few low- and medium-difficulty properties, requiring more work on high-difficulty properties, at a higher cost.	M/H	• Obtain sufficient rights-of-entry to allow for addition of properties to reach reduction targets.
Too few rights-of-entry are attained to perform the targeted amount of private property rehabilitation. Project cannot proceed to implementation.	H/H	• Obtain sufficient rights-of-entry to allow for addition of properties to reach reduction targets.
I/I is not uniformly distributed across project areas as assumed; and reduction targets are not achieved in the project area.	M/H	• Work in additional areas to get a greater I/I reduction. • Could require multiple phases of construction over several years so that flows can be checked as rehabilitation work proceeds.
I/I removal targets in the basin are achieved; however, a lesser reduction rate at the location of the downstream CSI project is realized because additional flows enter the system from other tributary areas	H/H	• Work in additional areas to get a greater I/I reduction. • Could require multiple phases of construction over several years so that flows can be checked as rehabilitation work proceeds.
High bids	M/M	• Early timing for bids and award, before contractors are booked for upcoming construction season. • Bid marketing, advance notice to contractors. • Structure bid packages to allow for release of smaller packages to more contractors if necessary.

a. M/M = Medium probability/medium impact; M/H = Medium probability/high impact; H/H = High probability/high impact

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CHAPTER 2.
FINAL DESIGN, BIDDING AND CONSTRUCTION

2.1 FINAL DESIGN

Final design for the Skyway Demonstration Project, completed in 2010, originally considered rehabilitation for 375 properties. Of these, about 25 were in the lower portion of the basin along Rainier Avenue South, a heavily traveled arterial roadway. These properties were omitted from the final work, due to the challenges of and cost and time associated with working in heavy traffic. The number of properties to be rehabilitated was further reduced based on whether rights of entry could be acquired from the property owners. Ultimately, 343 properties were included for rehabilitation in the final design.

An important bid item incorporated into the design for maintaining project flexibility during construction was the use of closed-circuit video inspection (CCTV) by the contractor prior to construction, to verify the side sewer alignments assumed in the design. The design of lateral and side sewer replacements drew upon information included in side sewer cards. Although the CCTV found that most of the information from the side sewer cards was accurate; some side sewer cards were found to be incorrect. Performance of the CCTV prior to construction allowed the correct alignments to be used in deciding whether to proceed with rehabilitation on each property.

In preparing bid documents, the design was based on unit costs for construction, rather than the lump sum bid approach typically used for King County construction projects. This approach provided greater flexibility during construction to add or remove properties from the project or to otherwise make changes based on unforeseen construction conditions.

2.2 BID RESULTS

The project was advertised for bid in December 2010 as two schedules: Schedule A for rehabilitation of the side sewers and laterals, and Schedule B for replacement of sewer mains and manholes. Six bids were received, and in March 2011 the contract was awarded to low bidder Buno Construction. This is the same contractor that constructed the 2003/2004 pilot project work. Table 2-1 summarizes the engineer's estimate, average bid and low bid.

TABLE 2-1.
BID RESULTS

Description	Engineers Estimate	Average Bid Cost	Low Bid Cost
Schedule A – Side Sewers and Laterals	$3,157,000.00	$2,609,377.28	$1,253,387.50
Schedule B – Sewer Mains and Manholes	$1,924,100.00	$2,084,064.26	$2,028,800.00
Sales Tax	$482,704.50	$445,876.95	$311,807.81
Bid Schedule Subtotal Cost	**$5,563,804.50**	**$5,139,318.49**	**$3,593,995.31**

The low bid was substantially below the engineer's estimate—low enough that no cost-sharing was required from the Skyway WSD for the Schedule A work. That left King County's cost responsibility (for Schedule A work) at $1.25 million plus tax and the Skyway WSD responsibility (for Schedule B work) at

$2.03 million plus tax. The low bid seemed to further ensure a cost/benefit ratio of 1.0 or greater, as long as expected I/I reduction goals could be met.

The low bid differed from the engineer's estimate and the other bids received in that it included more cost for Schedule B than for Schedule A. The low bidder may have assumed that portions of the planned lateral and side sewer replacement would be dropped from the contract based on field conditions following CCTV inspection. In fact, less than 70 percent of the lateral and side sewer pipe length identified in the final design was ultimately rehabilitated, as described in the next section.

2.3 CONSTRUCTION HIGHLIGHTS

2.3.1 Variations from Final Design

Schedule A – Side Sewers and Laterals

Laterals and side sewers were CCTV-inspected from the sewer main connection onto the private property immediately prior to work on each property. This allowed the sewer to be exactly located on the property, as a check of what was shown on the side sewer cards. Once the line was accurately located, an assessment was made of where pits would be required for pipe bursting and what surface features would be disturbed. The CCTV also allowed confirmation of the materials of side sewers on each property and whether a line was recently replaced, which would have already eliminated I/I from the line.

Decisions on the extent of rehabilitation for each property were made immediately following the CCTV work. Direction came from King County inspectors who monitored all construction activities for the duration of the project. Rehabilitation, if performed, followed within a day or two. Rehabilitation was ultimately performed on 298 of 343 properties included in the final design. The other 45 properties were omitted for one or more of the following reasons:

- CCTV revealed that the lateral and side sewer were recently replaced with PVC or other newer pipe material that appeared to be free from I/I (13 properties).
- The side sewer crossed beneath landscape or hardscape features such as rockeries, patios, entries or other improvements, making rehabilitation risky or overly difficult (20 properties).
- Property owner decided against rehabilitation after learning which landscape or hardscape features would be disturbed (4 properties).
- Property shared a common side sewer with one or more other properties that were not being replaced for any of the reasons above (8 properties).

Table 2-2 shows the quantity of lateral and side sewer pipe that was designed and bid for rehabilitation vs. how much was actually constructed. Less than 70 percent of side sewer and lateral pipe length that was bid was actually replaced. In addition to the 45 properties that were not rehabilitated at all, this difference between bid quantities and implementation quantities is attributable to properties where the level of replacement was stopped short of full completion. This is discussed further in Chapter 3.

Schedule B – Sewer Mains and Manholes

There were few uncertainties regarding main and manhole replacement under Schedule B, because good as-built information on the existing system was available and nearly the entire alignment could be CCTV-inspected during project design. As shown in Table 2-3, 95 percent of the bid sewer main and 94% of manhole replacements were constructed.

TABLE 2-2.
SCHEDULE A SIDE SEWER AND LATERAL VARIATIONS

Example Bid Items	Bid Quantity	Final Quantity
Preconstruction CCTV of side sewers and laterals	32,965 feet	28,990 feet
Side sewer and lateral replacement by pipe bursting	32,965 feet	21,981 feet
Side sewer and lateral replacement by open cut	500 feet	1,300 feet
Lateral reconnections to sewer main	374	345
Cleanouts installed on side sewers	472	371

TABLE 2-3.
SCHEDULE B SEWER MAIN AND MANHOLE VARIATIONS

Example Bid Items	Bid Quantity	Final Quantity
Preconstruction CCTV of sewer main	21,400 feet	20,630 feet
Sewer main replacement by pipe bursting	21,400 feet	20,369 feet
Manhole replacements	99	93

2.3.2 Construction Challenges

Side Sewer Location and Connections on Private Property

Some side sewer connections on private property were found to be deeper than expected, making connection to the home difficult. Challenges also were faced when clearance constraints on private property made it difficult to place construction equipment as needed to reach sewer connection points. On many properties designated for rehabilitation, the side sewer was only partially replaced because extensive hardscapes or landscaping would have had to be removed or were at risk of being damaged.

Groundwater Issues Following Construction

Groundwater appeared around sites disturbed by construction, surfacing in alleys, in manhole excavations, at side sewer connection excavations in yards, and occasionally in pavement cracks above undisturbed trench lines. Because pipe bursting is primarily a trenchless option, it limits the possibility to install groundwater drainage concurrent with sewer installation.

Pavement Settling Occurred Above Sewer Main Trench Lines in the Right of Way

Pavement settlement occurred in a number of locations. This likely was due to groundwater, which was no longer infiltrating into the sewer system, following pipe-burst mains and causing settlement in the trench backfill of the original pipeline construction (see Figure 2-1). In one case, where there was a steep gradient down a roadway, groundwater traveling along the trench line actually broke surfaced through the asphalt (see Figure 2-2).

The largest cost of change orders on the project were related to addressing these groundwater issues in the right of way. Trench drains were constructed to mitigate the possibility of groundwater issues beneath pavement in high problem areas (see Figure 2-3). In some cases, additional or enlarged trench patch repairs were constructed.

Figure 2-1. Pavement Settlement Along Sewer Main Alignment Following Construction

Figure 2-2. Groundwater Following Burst Sewer Main Trench Breaks Out of Pavement

Figure 2-3. Retrofit Trench Drain Captures Groundwater Flow and Alleviates Pavement Settlement

2.4 FINAL COSTS

The final construction cost was $3,417,625.50, somewhat below the low bid cost of $3,593,995.31 (both numbers with tax). Seven change orders included a total of $150,760.69 in additional costs. An eighth and final change order formalized the reduced unit quantities of $311,829.14. The reduced quantities were primarily related to fewer laterals and side sewers being rehabilitated.

2.5 WARRANTY INSPECTION

The County initiated the inspection of a representative sample of the constructed mains—13 sewer main segments totaling 2,800 feet of pipe and the adjoining manholes. The inspections were completed during the wet season in January 2013 using CCTV equipment. Inspection data included raw video footage of each pipe segment, selected still captures from the video footage, and summary inspection reports describing the pipeline observations, side sewers, evidence of I/I, and distances from upstream and downstream manhole numbers. Documented observations within the new sewer main initially included rock and other debris blockage problem sites, a vertical joint offset concern, and high water levels from sags and debris obstacles. The offset and sags are likely reflective of the original pipeline's alignment. These inspection results were evaluated to determine conditions and whether additional warranty enforcement work was appropriate.

In subsequent communication, it was learned that some pipes with identified debris problems had been cleaned by the Skyway WSD after the video inspection. Also, there may have been upstream debris that migrated into the newly constructed pipes. An additional warranty CCTV inspection was therefore performed in the two pipe segments after the cleaning, resulting in the conclusion that no further cleaning of potential construction debris was necessary. A second CCTV inspection of a pipe joint vertical deflection was also completed, and the interior of the joint appeared to be tight and intact, with no evidence of outside debris or infiltration water entering through the joint.

It was concluded that all pipeline inspection issues of initial concern were reconciled and that no remaining issues merited warranty enforcement was merited. Overall, constructed conditions were as would be expected for construction using pipe burst methods. The completed conveyance system was recommended for acceptance.

CHAPTER 3.
PROJECT EFFECTIVENESS EVALUATION

A key objective of the Demonstration Project was to evaluate the effectiveness of sewer rehabilitation. Rainfall and flow data were evaluated to determine if rehabilitation reduced I/I enough to allow for delaying, reducing the size of, or eliminating the Bryn Mawr Storage Project. I/I reduction was quantified by comparing model results based on flow data collected before and after construction of the Demonstration Project (pre-rehabilitation and post-rehabilitation). The methodology is described in the appendix to this report.

3.1 BASIN DELINEATION AND MONITORING

3.1.1 Basin Boundaries and Flow Meter Locations

Pre-project modeling was based upon flow modeling completed after the pilot project. Flow monitoring following construction was conducted during the 2012/2013 wet season. Four hydrologic basins (see Figure 3-1) were initially delineated to evaluate I/I rehabilitation effectiveness:

- The 157-acre Skyway Basin BLS002 consists of the three colored areas shown in Figure 3-1 (green, blue and orange). Rehabilitation work as part of the Demonstration Project was performed only in the green and blue highlighted portions of the basin, covering 111 acres.
- The 46-acre Skyway Pilot Basin (shown in orange in Figure 3-1) is the area that was rehabilitated during the 2003/2004 Skyway pilot project. The area is tributary to downstream Flow Meter BLS002 and was monitored to assess the level of I/I remaining in this previously rehabilitated portion of the system. No rehabilitation work was performed in this area of the basin during the Demonstration Project.
- The 38-acre Skyway Control Basin (shown in blue in Figure 3-1) was established at the time of the 2003/2004 Skyway pilot project to define baseline conditions without I/I rehabilitation, for comparison with the Skyway Pilot Basin. It was monitored before and after the 2003/2004 Skyway pilot project, concurrently with the Skyway Pilot Basin, and the results were compared to verify that flow reductions in the Skyway Pilot Basin were a result of the rehabilitation work. For the Demonstration Project, rehabilitation was performed in the Skyway Control Basin.
- The 506-acre Model Basin M_BLS43B (see the Figure 3-1 inset) covers multiple basins acres, including BLS002. The outlet from this basin is the location where the peak flow reduction of 1.8 mgd must be attained to eliminate the need for the Bryn Mawr storage facility.

Flows from these basins were monitored at the following flow-meter locations, which are shown on Figure 3-1:

- Pilot Flow Meter at the downstream end of the Skyway Pilot Basin
- Control Flow Meter at the downstream end of the Skyway Control Basin
- BLS002 Meter at the downstream end of Skyway Basin BLS002
- BLS43B Meter at the downstream end of Model Basin M_BLS43.

Figure 3-1. BLS002 Demonstration Project Basin Boundary with Meter Locations

3.1.2 Basin Boundary Issues

When post-rehabilitation flow monitor locations were being established, a previously unrecognized flow diversion was identified, contributing flow to the Skyway Basin BLS002 from the area immediately to the south. The area is shown as the 148F Basin in Figure 3-2. Prior to the Demonstration Project construction, flow from the 148F Basin entered a manhole near the intersection of South 112th Street and 80th Avenue South. Low flows were routed to Basin BLS006, immediately south of BLS002. As flow rates increased during periods of wet weather, some of the flow from the 148F Basin was diverted east along South 112th Street, to the Skyway Basin BLS002 system.

The manhole containing this flow diversion was removed during construction of the Demonstration Project, at the direction of Skyway WSD staff, and all flow from the 148F Basin now flows through the Skyway Basin BLS002 system; the area is therefore now part of Skyway Basin BLS002. The 148F Basin covers 62 acres and includes 240 homes. Following discovery of this basin boundary issue, an additional meter (148F Flow Meter) was installed to record flows from the area and factor them into the project effectiveness evaluation. The meter location is shown on Figure 3-2.

Figure 3-2. Connected Basin 148F

3.2 MODELING

Data collected during the 2012/2013 wet-weather post-rehabilitation flow monitoring was input into the County's MOUSE hydrologic model to estimate the I/I remaining in Skyway Basin BLS002 and Modeling Basin M_BLS43B, and assess the effectiveness of the I/I removal efforts. The modeling included the following elements:

- Collection of rainfall and evaporation records
- Characterization of dry-weather flow
- Calibration of the hydrologic model for the monitoring period
- Simulation of an extended time series to process results into flow events and develop peak 20-year I/I.

Pre-rehabilitation modeling results were compared to the post-rehabilitation modeling results to calculate the I/I removal effectiveness of the Demonstration Project.

3.3 I/I REDUCTION EFFECTIVENESS RESULTS

3.3.1 Flow Reduction by Basin

Table 3-1 summarizes I/I removal effectiveness. For the Demonstration Project, peak I/I was reduced by 0.6 mgd in the Control Basin, a 48-percent reduction. At the BLS002 Flow Meter, peak I/I was reduced by 0.78 mgd, or 19 percent. At the BLS043B meter, no reduction in peak I/I was seen. The estimated peak post-rehabilitation flows calculated for this location were a bit higher than the pre-rehabilitation values, by about 3 percent. These results fell well short of the reductions predicted during the project design.

TABLE 3-1.
REMOVAL EFFECTIVENESS BASED ON POST-PROJECT FLOW MONITORING

	Peak 20-Year I/I			
	Pilot Meter	Control Meter	BLS002 Meter	BLS043B Meter
Demonstration Project Effectiveness				
Pre-Demonstration Project	0.25 mgd	1.24 mgd	4.07 mgd	11.05 mgd
Post-Demonstration Project	0.25 mgd	0.64 mgd	3.29 mgd	11.43 mgd
Percent Reduction	N/A	48%	19%	-3%
Pilot Project Effectiveness				
Pre-Pilot Project	2.15 mgd	1.24 mgd	5.97 mgd	12.62 mgd
Post-Pilot Project	0.25 mgd	1.24 mgd	4.07 mgd	11.05 mgd
Percent Reduction	89%	N/A	32%	13%

For comparison purposes, the reduction effectiveness of the 2003/2004 Skyway pilot project is also listed in Table 3-1. Following completion of that construction, peak I/I in the Skyway Pilot Basin was reduced by 1.9 mgd, a reduction of 89 percent. The same 1.9-mgd reduction in I/I was registered downstream at the BLS002 Meter, representing a 32-percent reduction for the entire basin. At the BLS043B Meter, peak I/I was reduced slightly less, by 1.6 mgd, representing a 13-percent reduction for the modeling basin.

Flows at the Pilot Basin boundary were also measured as part of the Demonstration Project to confirm the ongoing effectiveness of the previous I/I reduction measures. The new monitoring shows that I/I remains controlled in this area, with a peak calculated 20-year I/I value of 0.25 mgd.

3.3.2 I/I During a Selected Storm Event

Figure 3-3 shows measured flow at each meter location for a particular rainfall event that occurred during the post-rehabilitation monitoring period. The hydrograph helps demonstrate where I/I remains in the area. The red line represents the flow measured at the BLS002 Meter. For this event, there was a peak flow of approximately 2.2 mgd. The other lines on the graph represent how flows were apportioned within Skyway Basin BLS002:

- The green and blue lines indicate flows in the area where rehabilitation work was performed for the Demonstration Project.
- The orange line indicates flow from the previously rehabilitated Skyway Pilot Basin,
- The purple line indicates flow from the 148F Basin, where no rehabilitation work occurred.

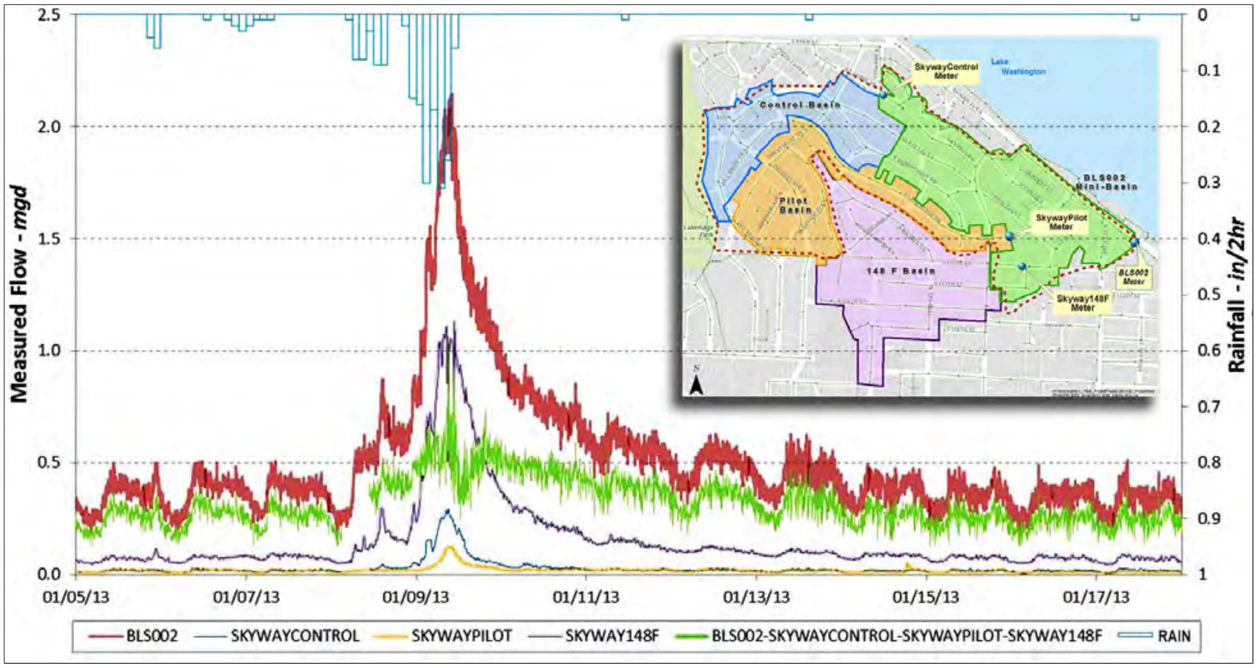

Figure 3-3. Flow by Basin Area for Post-Rehabilitation Storm Event in January 2013

Flows from the Skyway Pilot Basin and the Skyway Control Basin represent a small percentage of the post-rehabilitation I/I flows in Skyway Basin BLS002. About one-third of the remaining I/I can be attributed to the lower end of the Demonstration Project area (green), and about one-half to 148F Basin where no rehabilitation work was performed. Each of these areas had peak flows of nearly 1.0 mgd for the monitored event.

While approximately equal portions of I/I appear to remain in the green and purple areas of the basin, the response of the I/I is quite different between the two areas. In the purple area, the rapid rise and fall of the hydrograph in unison with the rainfall is typical of flow patterns attributable to leaky side sewers. The rise and drop-off of flows from the green area is much more gradual. This could indicate infiltration into portions of the sewer system that were not rehabilitated, especially in lower portions of the basin where groundwater is higher. These lower areas also may experience I/I that has migrated from rehabilitated system areas where it is no longer able to enter the sewers. The gradual response also may be the result of sump pumps in this lower portion of the basin where groundwater impacts are more pronounced.

3.4 I/I REDUCTION EFFECTIVENESS SUMMARY

The reduction effectiveness of the Skyway I/I Reduction Demonstration Project is strongly counter to project expectations, even after accounting for the flow contribution from the 148F Basin. That area accounts for nearly half of the post-rehabilitation I/I remaining in the project area, but the I/I reduction in the delineated project area for the Demonstration Project was still far below the expected 60-percent removal. The 2003/2004 Skyway Pilot Project achieved an I/I reduction of 89 percent in the area where work was performed, and the Demonstration Project had strong similarities to the Pilot Project:

- The neighborhood was of the same age of construction with similar sewer system materials.
- The same design and pipe bursting replacement concept were used.
- The same contractor performed the rehabilitation on both projects.
- The same inspector observed construction on both projects.

The sections below describe factors that may have influenced I/I reduction effectiveness from the Demonstration Project.

3.4.1 Effect of Sump Pumps and Foundation Drains

Foundation drains and sump pumps in the Demonstration Project area might contribute flow to the sewer system that negates reduces the effectiveness of I/I rehabilitation measures. Side sewers that collect I/I effectively act as drains to remove groundwater from the property. When those sewers have been rehabilitated and no longer convey I/I, the groundwater may increase against the house foundations, causing more flow to foundation drains and sumps. Direct and indirect evidence indicates a number of private property connections discharging to the sanitary sewer from inside the foundation walls. No sump pumps or foundation drains were disconnected from the sewer system as part of this project.

3.4.2 Groundwater at Sewers Downslope of Improved Area

When side sewers were stopped from behaving as groundwater drains, the groundwater level may have become temporarily amplified in areas downslope of the rehabilitated sewers, depending on soils and topography. This could cause higher infiltration pressures on unimproved sewer facilities in those downslope areas. The susceptible unimproved sewers could even include portions of the side sewer system and building plumbing that are within the footprint of homes, especially those with crawl spaces where drainage is a concern.

3.4.3 Incompletely Rehabilitated Properties

The ideal project on each rehabilitated property would replace the entire side sewer and lateral from the main sewer in the street to the extension of the internal plumbing (often cast iron pipe) outside the footprint of the house. However, conditions on individual properties can prohibit replacement of that entire sewer length. Where less than 75 percent of the line was replaced, the work was designated as a “partial” rehabilitation. In the 2003/2004 Skyway Pilot Project, total rehabilitation was completed on almost all properties included in the final design. For the Demonstration Project, many more properties were only partially rehabilitated. The final rehabilitation work was categorized as follows (see Figure 3-4):

- **Total or Near Total Side Sewer Replacement** (224 Properties)—Replacement of 75 percent or more of the total length of side sewer and lateral.
- **Partial Side Sewer Replacement** (72 Properties)—Replacement of less than 75 percent of the total length of side sewer and lateral. Partial replacements resulted almost exclusively from constructability constraints due to the location of side sewer in relation to property improvements, such as decks and patios.
- **No Side Sewer Replacement** (79 Properties)—The final design omitted 32 properties in the project area, primarily because rights-of-entry could not be attained or because the side sewer and lateral for the property had already been replaced within the last 10 years. Another 45 properties were not rehabilitated for the reasons described in Section 2.3.1.

Figure 3-4. Side Sewer Replacement Status

Figures 3-5 and 3-6 provide an example of a site where a full replacement was called for in the contract documents but field conditions dictated a modified plan. Figure 3-5 shows the replacement that was originally designed for five properties that shared a single lateral connection to the sewer main. Between the two homes near the connection to the main (10867/10873) and the three properties to east (10948/10950/10954) the contractor was to burst the existing 6-inch line and pull three separate 4-inch side sewers so that these three homes would each be on an individual dedicated side sewer. It was discovered during construction that multiple utilities cross the 6-inch line between the homes. These utilities were at risk of being damaged by pipe-bursting of the existing line. The decision was therefore made not to replace this approximately 100-foot section of line. The length of line actually replaced is shown on Figure 3-6 and is representative of a partial sewer replacement.

3.4.4 Diminished Effectiveness Downstream From Project

The Demonstration Project's effectiveness as measured at different flow meters suggests that I/I reduction benefits may not extend far downstream from the immediate area where rehabilitation is performed:

- Peak I/I was reduced by 0.6 mgd at the Control Meter, representing the benefit of Skyway Control Basin rehabilitation in the work area immediately upstream of that meter.
- Because the BLS002 Meter measures all flow from the Skyway Control Basin plus additional area with more rehabilitated properties than were in the Control Basin, it would be reasonable to expect I/I reduction on the order of double what was measured at the Control Meter. This would assume the same proportion of side sewer replacement occurred in both areas, but Figure 3-4 shows that is not the case. The measured I/I reduction at the BLS002 Meter was 0.78 mgd—only slightly greater than the 0.6 mgd measured at the Control Meter. This suggests the full benefit of work in the Control Basin may not have extended downstream to the BLS002 Meter.

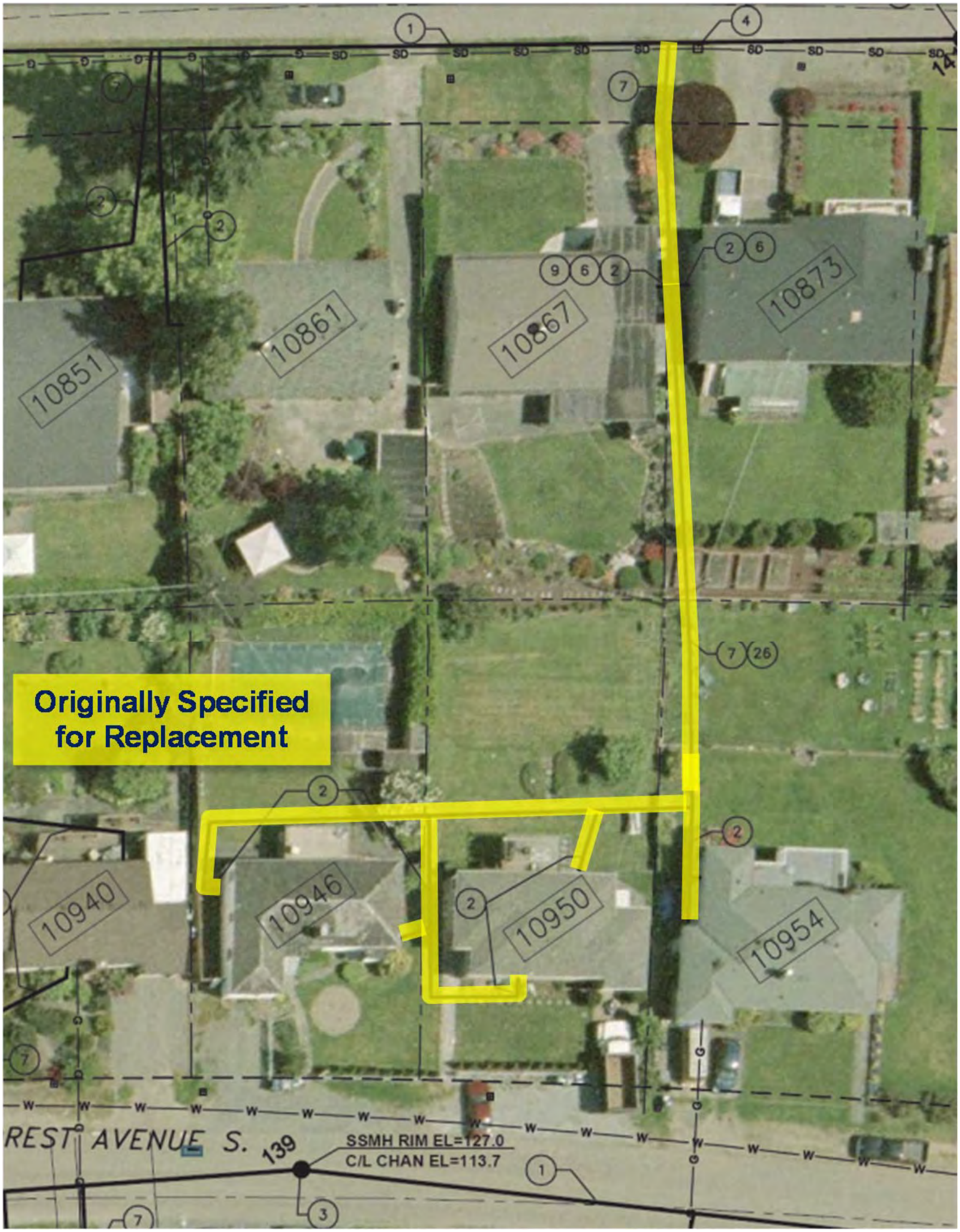

Figure 3-5. Full Side Sewer Rehabilitation as Designed

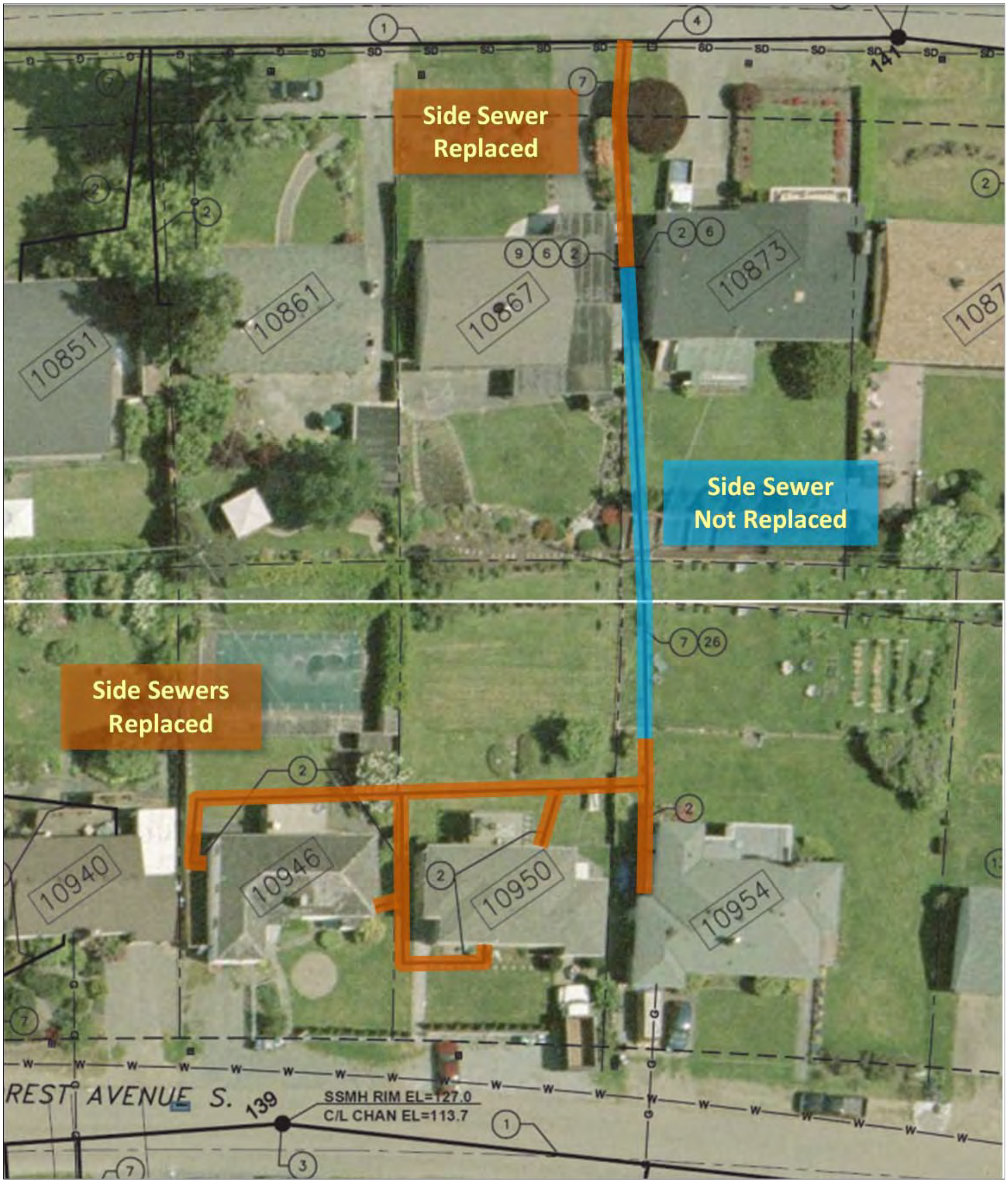

Figure 3-6. Partial Side Sewer Rehabilitation as Constructed

- Further downstream, at the BLS043B Meter, the post-project peak I/I is about the same as the pre-project value; so it appears that none of the benefit of the project extended that far downstream.

Overall, these results suggest that the benefits of rehabilitation work are most apparent in the local system where the work is performed and that downstream translation of I/I reduction is more difficult to achieve.

3.4.5 Impact on Need for Other Capital Projects

The goal of the Demonstration Project in Skyway was to delay, downsize, or eliminate the need for the Bryn Mawr Storage Project. While this project has not demonstrated that the storage project can be eliminated, it does appear that it can be delayed. Further, the rehabilitation work may have led to a reduction in required storage volume despite the slightly higher peak flow rate due to a change in shape of the hydrograph (narrowing of the peak flow portion of the curve). These positive results were achieved with a capital cost to King County of less than $2 million. The County will continue with flow monitoring in Skyway and elsewhere and will consider future I/I reduction projects where they may be of value.

CHAPTER 4.
LESSONS LEARNED

Extensive work went into development, implementation and evaluation of the Skyway I/I/ Reduction Demonstration Project—from pilot testing in 2003 through project evaluation completed with this report. The following sections summarize general lessons learned from the process that can be used to guide design and construction of future I/I reduction projects in King County.

4.1 DESIGN

4.1.1 Identifying Problem Areas

An essential first step in developing an I/I reduction project is the identification of geographical areas where I/I is entering the sewer system in quantities that can be cost-effectively reduced. Sources of infiltration to a collection system can seldom be pinpointed with certainty or precision. The work leading up to the Skyway Demonstration Project found that an acceptable approach to identifying suitable areas for I/I/ reduction is to compare a basin’s peak I/I flow to its population density. A rule of thumb developed during the alternatives analysis for initial I/I reduction projects is that, in residential areas, a peak I/I flow equivalent to an average of 3 gallons per minute or more from each property is a good indicator of where to focus rehabilitation efforts.

4.1.2 Basin Characterization

Typical gravity sewer collection systems are branched networks with discrete boundaries. In practice, however, conditions in aging sewer systems are impacted by decades of degradation, sedimentation, grease accumulations, and modifications by homeowners or contractors. Lost or incomplete records from years past can impact the ability to clearly define the configuration of the sewer system in a study area. A thorough assessment of physical conditions and a comparison to records are important to defining basin boundaries and selecting flow meter locations for optimal hydraulics. This is in addition to sewer system evaluation survey activities such as cleaning, CCTV and smoke testing. Those activities may not, by themselves, provide all the information necessary. Additional investigation is appropriate, especially at the basin periphery and at connections with adjacent basins.

4.1.3 Design Certainty and Priority of Project Expenditures

By the nature of the work involved, I/I reduction projects pose challenges to the development of a precise and accurate design. It will seldom be possible to identify in advance, with any degree of certainty, the locations of significant I/I flows or the private property conditions that can affect construction. The inability of the Demonstration Project to match the I/I reduction achieved by the Skyway Pilot Project, despite the strong similarities in project area and approach, brings into question the ability to develop I/I reduction project designs with a high degree of certainty and points to differences between the Pilot and Demonstration projects.

For the Skyway Demonstration Project, assumptions were made about the project area to simplify the design effort—such as the assumption that the level of I/I is uniformly distributed across the basin. While this is obviously a simplification, developing a more detailed distribution of I/I levels across a basin would require flow data from significantly more locations within the basin, at a high cost. Such prolonged and expensive investigations and design work may not be an effective use of project funding. Rather, the focus should be on an efficiently developed design that leaves funding available to modify work as needed during construction.

4.1.4 Consideration of Sump Pumps

Based on the findings of the effectiveness evaluation for the Demonstration Project, it is recommended that design of an I/I reduction project take into account the prevalence of foundation sump pumps discharging into the sewer system. The likely effect of sump pumps on I/I removal effectiveness should be considered greater when the following conditions are noted:

- High groundwater is already a documented or anecdotal problem in the neighborhood
- High percentage of full or daylight basements
- Observations of periodic clean, cold water discharge noted in side sewer(s), reportedly when no one was home

4.2 CONSTRUCTION

4.2.1 Flexibility

Given the complexity of preparing accurate, detailed designs for I/I reduction projects, construction should be implemented with maximum potential for modifying the design as needed based on conditions encountered in the field. During the Skyway Demonstration Project an owner's representative was constantly available for field decision-making. Contract documents also provided flexibility for private property work, through a separate bid item for CCTV, which allowed field determination of the appropriate extent of side sewer replacement based on considerations of equipment clearance and hardscape and landscaping constraints. Structuring the contract with unit prices allows for deleting or adding work on individual properties.

4.2.2 Performance-Based Scheduling

Tighter performance-based restoration scheduling should be used for private property side sewers. Contract documents for the Demonstration Project required notification to homeowners prior to construction disturbances and defined the method of notification, but no time limit was set as to how soon after construction restoration must be substantially completed. A performance schedule strategy should suggest options, including the number of crews, etc., but should avoid prescribing means and methods.

4.2.3 Groundwater Issues

Based on conditions encountered during the Demonstration Project, I/I reduction projects should anticipate the possibility of groundwater issues that may follow disturbed ground associated with pipe bursting, open trenching and manhole and side sewer connections. Projects should consider the possibility of groundwater interception and discharge methods to function as groundwater pressure relief points, discharging to storm drain collection systems. Coordination with the respective roadway and/or drainage agency is helpful.

If groundwater interception and discharge methods are applicable, they should be limited to strategic locations in the collection system already disturbed by construction activities, such as junction manholes at intersections and side sewer connections at the base of steep streets.

4.2.4 Contingency Bid items

I/I reduction project documents should include contingency bid items or funding for unusual or unexpected side sewer route adjustments drainage problems, landscape restoration, hardscape restoration, or other unintended consequences.

4.2.5 Side Sewer Replacement

Reasonable measures should be taken, to the extent they are cost-effective, to replace as much of side sewers as possible.

4.2.6 Foundation Drains

Explore the possibility of routing foundation drains into the storm system.

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APPENDIX. SKYWAY INFILTRATION AND INFLOW REDUCTION PILOT PROJECT AND DEMONSTRATION PROJECT METHODOLOGY AND RESULTS

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King County

SKYWAY INFILTRATION AND INFLOW REDUCTION PILOT PROJECT AND DEMONSTRATION PROJECT METHODOLOGY AND RESULTS

MARCH 2014

King County

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King County

Skyway Initial Infiltration and Inflow Reduction Pilot Project and Demonstration Project Methodology and Results

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1. INTRODUCTION

This technical memorandum presents methodology and results of the King County Wastewater Treatment Division's (KC-WTD) Skyway Infiltration/Inflow (I/I) Pilot Project and Skyway I/I Demonstration Project. These results contribute to King County's 13-year, $60 million I/I Control Program exploring the feasibility of I/I reduction as a cost-effective alternative to traditional conveyance system improvements. I/I is assessed at four basins in the Skyway area before and after I/I rehabilitation, and the resulting I/I reductions are evaluated. The basins vary in size and proximity to the project sites to determine the effectiveness of maintaining upstream I/I reductions at downstream locations. A downstream peak I/I reduction of 1.8 million gallons per day (mgd) to 2.2 mgd has been defined by previous I/I Control Program efforts as the program target. This reduction would eliminate a planned 0.22-million-gallon storage facility upstream of the Bryn Mawr Siphon.

1.1 BACKGROUND

KC-WTD created the King County Regional Infiltration and Inflow Control Program in 1999. This program investigated the feasibility of I/I control as an alternative to traditional conveyance system improvement projects, such as parallel pipelines or storage facilities, in the separated collection system. KC-WTD performed extensive flow monitoring and numerical modeling throughout King County to assess local agency I/I from 2000 to 2003. Various methods of I/I rehabilitation were conducted at 10 pilot projects, and their costs and effectiveness were evaluated by methodology and location, in 2004. The results of these evaluations were interpreted and adopted as initial standards, procedures, policies and guidelines for local agency I/I reduction programs, also in 2004. Using these standards, KC-WTD completed a benefit-cost analysis that identified nine cost-effective conveyance system improvement projects for I/I rehabilitation in 2005. The KC-WTD Long-Term Regional I/I Control Plan recommended large-scale demonstration projects to evaluate I/I rehabilitation effectiveness in 2006. With local agency participation, KC-WTD completed an alternatives analysis that selected Bellevue, Issaquah, and Skyway for demonstration projects in 2009. However, budget restrictions reduced the selection to only Skyway in 2010. Construction of the Skyway I/I Demonstration Project was completed in 2012.

1.2 OUTLINE

This technical memorandum establishes the criteria used by KC-WTD to assess I/I. It then describes the use of numerical modeling with recurrence analysis to derive these criteria. The memorandum then presents an assessment of I/I in four basins in the Skyway Water and Sewer District (Skyway WSD) service area before and after the Skyway I-I Pilot Project and Skyway I/I Demonstration Project. The results are interpreted to evaluate the Pilot Project and Demonstration Project effectiveness, separately and in combination. Finally, the conclusions present the I/I reductions by basin and discuss the success of the program toward meeting the downstream target I/I reduction.

1.3 EVALUATION CRITERIA

KC-WTD established the peak 20-year I/I as the criterion to evaluate I/I reduction effectiveness. This flow is defined as the peak I/I that occurs, on average, once every 20 years. Peak 20-year I/I, new construction I/I, and base flow are the components of KC-WTD's peak 20-year flow standard used for regional conveyance system planning. Peak 20-year I/I is derived from hydrologic modeling and recurrence analysis. A hydrologic basin model that has been calibrated to flow meter data is used to simulate an extended time series, and the results are processed into flow events. These events are ranked and plotted, and the peak 20-year I/I is interpolated from the trendline.

2. HYDROLOGIC AND HYDRAULIC MODELING

KC-WTD performs all hydrologic and hydraulic modeling with the Danish Hydraulic Institute's 2009 Model for Urban Sewers (MOUSE). Hydrologic modeling simulates the rainfall response of a catchment, or basin, in terms of flow hydrographs. Hydraulic modeling simulates the operation of pipe networks in terms of flows and water levels. I/I reduction in Skyway was evaluated almost exclusively using hydrologic modeling, so only hydrologic modeling is described in the following sections.

2.1 HYDROLOGIC MODEL DESCRIPTION

The MOUSE hydrologic model combines two types of hydrologic models to simulate inflow and infiltration. Inflow, or fast response, is the surface runoff that enters the collection system from improperly connected roof or storm drains. Inflow is simulated by MOUSE Model A, otherwise known as the Time/Area Method. Model A simulates basin runoff using unit hydrographs characteristic to basin size, shape, losses, and time of concentration. Unit hydrographs are scaled with rain, and superimposed over time, to produce inflow hydrographs in response to rainfall. Infiltration, or slow response, is the groundwater entering the collection system through pipeline and manhole deterioration, or faulty connections. Infiltration is simulated by the MOUSE Rainfall Dependent Inflow and Infiltration (RDII) Model. The RDII model simulates the hydrologic cycle within the basin. Flow is continuously transferred between surface, lower zone, and groundwater storages to produce infiltration hydrographs in response to both rainfall and evaporation. The hydrologic parameters used by Model A and the RDII models are listed in Attachment 1.

2.1.1 Develop Hydrologic Models

A consistent methodology was followed to develop hydrologic models of basins. The tributary area of interest, or basin, was first delineated. Next, flow meters were installed downstream of the basin to monitor flow for at least one wet-weather season. During this time, local rain and evaporation records were collected. Following monitoring, the dry-weather flow was characterized, and the basin hydrology separated from the flow meter time series. Finally, the rainfall and evaporation were applied to the hydrologic model, and the model parameters calibrated until the model results best fit the metered basin hydrology. This methodology is summarized as steps as follows:

- Delineate hydrologic basins
- Install portable flow meters and monitor flows
- Collect rainfall and evaporation records
- Characterize dry-weather flow
- Calibrate hydrologic model.

Each step of this methodology is described in general, and with specific application to Skyway I/I rehabilitation, in the following sections.

2.1.2 Delineate Hydrologic Basins

Hydrologic basins are natural drainage areas that collect rainfall and channel the runoff to downstream discharge points. They are generally delineated in GIS from overlays of topographic contours and local collection system pipe networks. Four hydrologic basins of varying size and location within the Skyway WSD collection system were initially delineated to evaluate I/I rehabilitation effectiveness:

- Skyway Control Basin
- Skyway Pilot Basin
- Minibasin BLS002
- Model Basin M_BLS43B

These basins were delineated at various stages in the KC-WTD Regional Infiltration and Inflow Control Program. A fifth hydrologic basin, Basin 148F, was delineated later in this project to address an additional source of flow to Minibasin BLS002. Figure 2-1 shows the basins described in this technical memorandum.

Figure 2-1. Delineated Basins and Portable Flow Monitoring Locations

2.1.2.1 Skyway Control Basin

Control basins establish a baseline of existing, or non-I/I rehabilitation conditions, for comparison with pilot basins. KC-WTD delineated 10 control basins adjacent to pilot basins for the Pilot Project Report in 2004. These were concurrently monitored with pilot basins before and after pilot basin I/I rehabilitation. Control basin and pilot basin I/I were compared to verify that flow reductions in the pilot basins were a result of I/I rehabilitation. Control basins encompassed approximately 110 sewered acres, and 16,000 linear feet, of separated collection system, and were delineated within existing minibasins.

Skyway Control Basin is located within the northwest of Minibasin BLS002 (Figure 2-1). The basin topography is uniformly sloped along a hillside, and land use is exclusively residential. Skyway Control Basin encompasses 38 sewered acres and 7,600 linear feet of separated Skyway WSD collection system. Basin flow is conveyed by gravity to a Skyway WSD 8-inch pipeline below South Laurel Street. Portable flow meter SKYWAYCONTROL monitored basin flows at this location between 2002 and 2013 (Section 2.1.3.1).

2.1.2.2 Skyway Pilot Basin

Pilot basins measure the effectiveness of various I/I rehabilitation technologies. KC-WTD delineated 10 pilot basins at locations determined to be cost-effective for I/I rehabilitation for the Pilot Project Report in 2004. Pilot basins were monitored before and after I/I rehabilitation to evaluate the reduction in I/I from the basin. Pilot basins encompassed approximately 110 sewered acres, and 16,000 linear feet, of separated collection system, and were delineated within existing minibasins.

Skyway Pilot Basin is located within the south of Minibasin BLS002 (Figure 2-1). The basin topography is uniformly sloped along a hillside, and land use is exclusively residential. Skyway Pilot Basin encompasses 46 sewered acres and 9,600 linear feet of separated Skyway WSD collection system. Basin flow is conveyed by gravity to a Skyway WSD 8-inch pipeline below South Lakeridge Drive. Portable flow meter SKYWAYPILOT monitored basin flows at this location between 2002 and 2013 (Section 2.1.3.2).

2.1.2.3 Minibasin BLS002

Minibasins measure local collection system I/I at a scale feasible for developing an I/I reduction program. KC-WTD delineated 775 minibasins throughout King County for the I/I Control Program in 2000. Minibasins encompassed approximately 150 sewered acres, and 22,000 linear feet, of separated collection system. Typically, minibasins were delineated within existing model basins.

Minibasin BLS002 is located within the northwest of Model Basin M_BLS43B (Figure 2-1). The basin topography is uniformly sloped along a hillside, and land use is exclusively residential. The basin area includes a creek within a riparian ravine and a culvert street crossing. Minibasin BLS002 encompasses 157 sewered acres and 33,700 linear feet of separated Skyway WSD collection system. Basin flow is conveyed by gravity to a Skyway WSD 18-inch interceptor below South Rainier Avenue. Portable Flow Meter BLS002 and SKYWAY148F monitored basin flow at this location between 2000 and 2013 (Section 2.1.3.3 and Section 2.1.3.4).

2.1.2.4 Model Basin M_BLS43B

Model basins provide regional measurements of sewered areas, populations, and I/I to project flows for conveyance system planning. KC-WTD delineated 147 model basins throughout King County for initial conveyance system improvement planning in 1999. Model basins encompassed approximately 1,000 sewered acres, and 100,000 linear feet, of local collection systems. Generally, model basins were delineated within local agency boundaries.

Model Basin M_BLS43B is located within the northeast of Skyway WSD (Figure 2-1). The basin topography varies in slope toward Lake Washington. Land use is primarily residential, and includes parks and schools. The basin area includes two creeks within riparian ravines and culvert street crossings. Model Basin M_BLS43B encompasses 506 sewered acres and 102,500 linear feet of separated Skyway WSD collection system. Basin flow is conveyed by gravity to the KC-WTD 24-inch Bryn Mawr Trunk in Lake Washington Beach Mobile Park. Portable Flow Meter BLS43B monitored basin flow at this location between 2000 and 2013 (Section 2.1.3.5). Downstream of this location, flow enters the inlet structure to the Bryn Mawr siphon, where stepped outlets and a weir regulate flow to an 8-in, 14-in, and 24-inch siphon below Lake Washington and the Cedar River. The inlet structure also contains an overflow weir to an outfall in Lake Washington.

2.1.3 Install Portable Flow Meters and Monitor Flows

KC-WTD monitored basin flows in the Skyway WSD collection system between 2000 and 2013 with five portable flow meters (Figure 2-1). Flows were monitored for periods of at least one wet-weather season to characterize basin hydrology before and after I/I rehabilitation. An additional flow-monitoring period was provided by the regional KC-WTD Decennial Flow Monitoring Program. From 2009 to 2011, this program monitored flow in the KC-WTD separated conveyance system for two wet-weather seasons for use in verifying conveyance system planning assumptions.

The portable flow meters were located at the downstream end of delineated basins and installed in the downstream end of sewer pipes. The meters continuously recorded depth and velocity of flow in the pipe every 15 minutes during the dry-weather season, and every 5 minutes during the wet weather season. Depth and velocity were processed to remove bad or missing data, and flow calculated as the product of velocity and area of flow. The following portable flow meters were used to monitor basin flows before and after I/I rehabilitation:

- SKYWAYCONTROL
- SKYWAYPILOT
- BLS002
- SKYWAY148F
- BLS43B

Each portable flow meter is described in the following sections.

2.1.3.1 Portable Flow Meter SKYWAYCONTROL

Portable Flow Meter SKYWAYCONTROL monitored flows for the sewered area of the Skyway Control Basin (Section 2.1.2.1). The meter is located in a Skyway WSD 8-inch pipe at Manhole 332. It measured depth and velocity for three monitoring periods between 2002 and 2013 (Table 2-1). SKYWAYCONTROL was used to evaluate the downstream effectiveness of I/I rehabilitation from the Skyway I/I Demonstration Project.

During installation, site hydraulics were described as “shallow depth.” No silt deposits were noted. Velocity-depth scatter graphs of the meter data demonstrated supercritical flow that generally followed the theoretical Manning’s Curve during large flows. No surcharge was apparent.

TABLE 2-1.
SKYWAYCONTROL FLOW MONITORING SUMMARY

Monitoring Effort	Start	End
Pre- I/I Pilot Project	10/30/02	05/02/03
Post- I/I Pilot Project	10/07/03	02/02/04
Post- I/I Demonstration Project	08/31/12	06/20/13

2.1.3.2 Portable Flow Meter SKYWAYPILOT

Portable Flow Meter SKYWAYPILOT monitored flows for the sewered area of the Skyway Pilot Basin (Section 2.1.2.2). The meter is located in a Skyway WSD 8-inch pipe at Manhole 70. It measured depth and velocity for three monitoring periods between 2002 and 2013 (Table 2-2). SKYWAYPILOT was used to evaluate the downstream effectiveness of I/I rehabilitation for the Skyway I/I Pilot Project.

TABLE 2-2.
SKYWAYPILOT FLOW MONITORING SUMMARY

Monitoring Effort	Start	End
Pre- I/I Pilot Project	10/30/02	05/02/03
Post- I/I Pilot Project	10/10/03	02/02/04
Post- I/I Demonstration Project	11/01/12	06/20/13

During installation, site hydraulics were described as "shallow depth, flows slightly off-center to the left." No silt deposits were noted. Velocity-depth scatter graphs of the meter data demonstrated supercritical flow that tightly followed the theoretical Manning's Curve. No surcharge was apparent.

2.1.3.3 Portable Flow Meter BLS002

Portable Flow Meter BLS002 monitored flows for the sewered area of Minibasin BLS002 (Section 2.1.2.3). The meter is located in a Skyway WSD 16-inch pipe at Manhole 13A. It measured depth and velocity for five monitoring periods between 2001 and 2013 (Table 2-3). Portable Flow Meter BLS002 was used to evaluate the downstream effectiveness of I/I rehabilitation from the upstream Skyway I/I Pilot Project, and the effectiveness of I/I rehabilitation from the Skyway I/I Demonstration Project.

During installation, site hydraulics were described as "laminar flow, velocity less than 1.0 fps." Minor silt deposits between 0.5 in and 1.0 in were noted. Velocity-depth scatter graphs of the meter data demonstrated subcritical flow that tightly followed the theoretical Manning's Curve. During large flow events, water levels would surcharge above the crown of the pipe due to downstream capacity restrictions. During an extreme flow event on December 3, 2007, the scatter graph indicated a downstream overflow.

TABLE 2-3.
BLS002 FLOW MONITORING SUMMARY

Monitoring Effort	Start	End
I/I Control Program 2000-2001	11/01/00	01/15/01
I/I Control Program 2001-2002	11/01/01	01/15/02
Post- I/I Pilot Project	11/21/03	02/02/04
Pre- I/I Demonstration Project	11/10/07	06/14/08
Post- I/I Demonstration Project	08/29/12	06/24/13

2.1.3.3.1 BLS002 Flow Adjustment

During the Skyway I/I Pilot and Demonstration Projects, Skyway WSD modified some flow connections within Minibasin BLS002. Flow records from Portable Flow Meter BLS002 were adjusted to account for the modifications to the basin flow for consistent comparison with previous monitoring periods.

Originally, flow from a portion of Minibasin BLS002 was regulated at Manhole A. A weir in this manhole directed overflow through a sluice gate to Manhole B, and underflow to Manhole 71. Additionally, flow from a portion of adjacent Minibasin BLS006, and the overflow from Minibasin BLS002, were regulated at Manhole 133A. This portion of Minibasin BLS006 is referred to in this memorandum as Basin 148F. A timber stop log weir extending to half-pipe height in this manhole directed overflow to Manhole 148F in Minibasin BLS002, and underflow to Basin 148F (Figure 2-2).

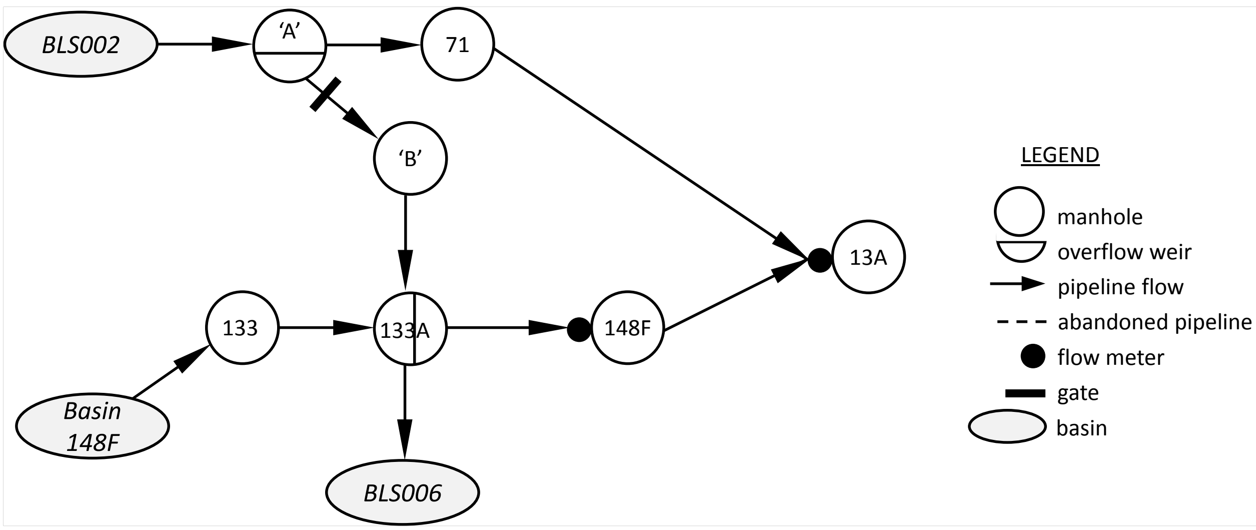

Figure 2-2. Skyway Pre- I/I Pilot Configuration (original)

Following the Skyway I/I Pilot Project construction, Skyway WSD closed the overflow gate at Manhole A, directing all flow from a portion of Minibasin BLS002 to Manhole 71 (Figure 2-3). It was assumed that the overflow from the weir in Manhole A would overflow the weir in Manhole 133A and join the underflow at Manhole 13A. Accordingly, no flow adjustment for this modification was necessary. However, it should be noted that the overflow from the weir in Manhole A may not have overflowed the weir in Manhole 133A and proceeded instead as underflow to Minibasin BLS006, reducing the Pre- I/I Pilot Project flows monitored at Portable Flow Meter BLS002.

During the Skyway I/I Demonstration Project construction, Skyway WSD removed Manhole 133A, and directly connected Manhole 133 to Manhole 148F (Figure 2-4). Both underflow and overflow from Basin 148F were now directed to Portable Flow Monitor BLS002 in Manhole 13A. Flow monitored by Portable Flow Meter BLS002 after the demonstration project required adjustment to remove the underflow from Basin 148F for comparison with previous flow monitoring periods.

To make this adjustment, portable flow meter SKYWAY148F was installed in Manhole 148F to monitor post-construction flows. A hydraulic model was then constructed of the original pipe network connected to the weir. A time series of processed flow from portable flow meter SKYWAY148F provided the inflow to the hydraulic model. The resulting hydraulic model underflow was subtracted from a concurrent time series of processed flow from Portable Flow Meter BLS002 to complete the adjustment.

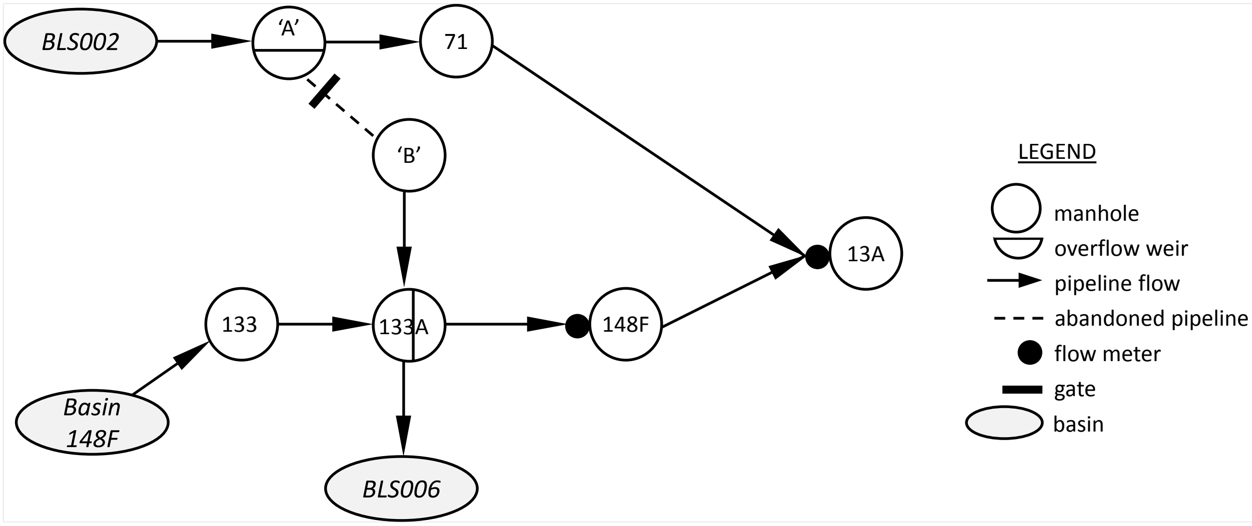

Figure 2-3. Skyway Post- I/I Pilot Configuration (interim)

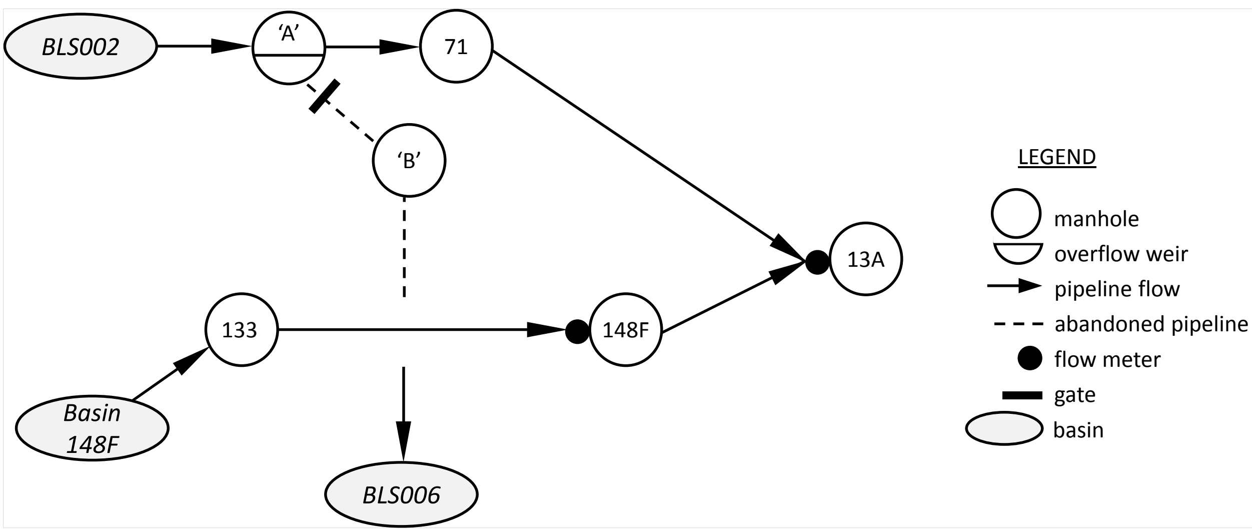

Figure 2-4. Skyway Post- I/I Demonstration Configuration (current)

In summary, flow measured by Portable Flow Meter BLS002 during the Post- I/I Demonstration Project monitoring period was adjusted by subtracting the estimated Basin 148F underflow. The adjusted BLS002 flow data was used for subsequent calibration, recurrence analysis, and interpretation and estimation of results.

2.1.3.4 Portable Flow Meter SKYWAY148F

Portable Flow Meter SKYWAY148F monitored flows from Basin 148F. The meter is located in a Skyway WSD 8-inch pipe at Manhole 148F. It measured depth and velocity for one monitoring period between 2012 and 2013 (Table 2-4). SKYWAY148F was used to adjust flows at Portable Flow Meter BLS002 during Post- Skyway I/I Demonstration Project monitoring.

TABLE 2-4.
SKYWAY148F FLOW MONITORING SUMMARY

Monitoring Effort	Start	End
Post- I/I Demonstration Project	11/10/12	06/20/13

During installation, site hydraulics were described as "flows move very fast through invert, some turbulence through invert during higher flows." No silt deposits were noted. Velocity-depth scatter graphs of the meter data demonstrated supercritical flow that followed the theoretical Manning's Curve. No surcharge was apparent.

2.1.3.5 Portable Flow Meter BLS43B

Portable Flow Meter BLS43B monitored flows for the sewered area of Model Basin M_BLS43B (Section 2.1.2.4). The meter is located in a KC-WTD 24-inch pipe at Manhole RO1-43B. It measured depth and velocity for five monitoring periods between 2001 and 2013 (Table 2-5). Portable Flow Meter BLS43B was used to evaluate the downstream effectiveness of I/I rehabilitation from the upstream Skyway I/I Pilot Project and Skyway I/I Demonstration Project.

TABLE 2-5.
BLS43B FLOW MONITORING SUMMARY

Monitoring Effort	Start	End
I/I Control Program 2000-2001	11/01/00	01/15/01
I/I Control Program 2001-2002	11/01/01	01/15/02
Pre- I/I Demonstration Project	07/27/07	09/01/08
Decennial Flow Monitoring	08/01/09	05/18/11
Post- I/I Demonstration Project	05/10/11	04/22/13

During installation, site hydraulics were described as "flow moves well through invert with no backup occurring from downstream inputs." No silt deposits were noted. Velocity-depth scatter graphs of the meter data demonstrated subcritical flow that followed the theoretical Manning's Curve. During large flow events, water levels would surcharge above the crown of the pipe due to downstream capacity restrictions. During an extreme flow event on December 3, 2007, the surcharge levels exceeded the downstream overflow weir, resulting in a sanitary sewer overflow to Lake Washington.

2.2 COLLECT RAINFALL AND EVAPORATION RECORDS

Time series of local rainfall and evaporation are the boundary conditions of the hydrologic model. Rainfall generates the surface runoff for the Model A component, and recharges the groundwater storages in the RDII component. Evaporation reduces the net rainfall to both models, and further reduces the groundwater storages in the RDII component.

2.2.1 Rainfall Records

Rainfall from 2001 to 2003 was measured by the RG10 rain gauge, located at Rainier View Elementary School in Seattle. This rain gauge was owned and maintained by Seattle Public Utilities (SPU), and was removed in 2008. Rainfall records for RG10 were available in 5-minute intervals.

Rainfall from 2003 to 2013 was measured by the SKY1 rain gauge, located at Lakeridge Elementary School in Bryn Mawr-Skyway. The gauge is owned and maintained by the King County Water and Land Resources Division. Rainfall records for SKY1 were available in 15-minute intervals.

2.2.2 Evaporation Records

Evaporation was measured at the WSU Puyallup weather gauge, located at the Washington State University Puyallup Research & Extension Center in Puyallup. The gauge is owned and maintained by Washington State University (WSU). Evaporation records were averaged by month into an average evaporation year, which was repeated for all hydrologic simulations (Figure 2-5).

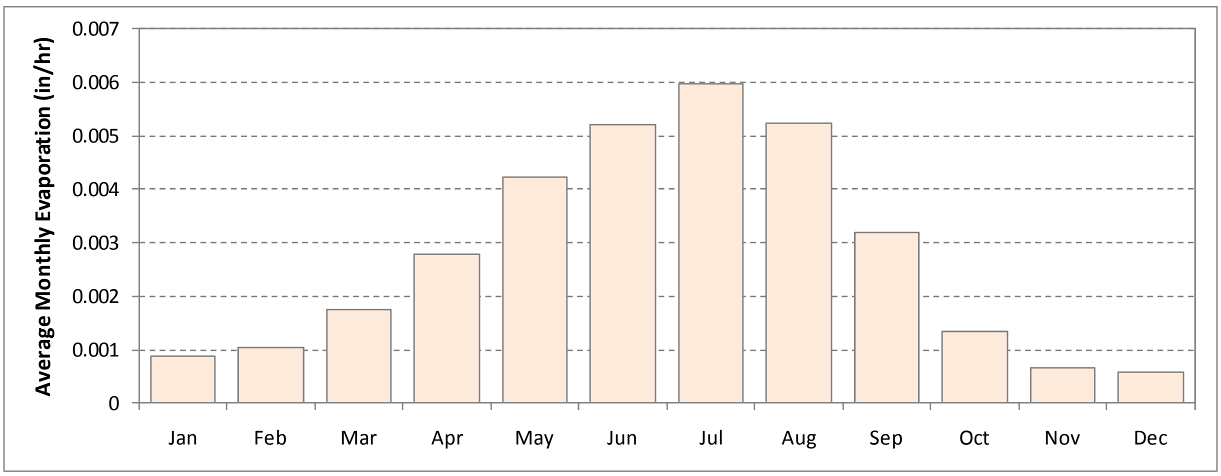

Figure 2-5. Average Evaporation Year for Calibration

2.3 CHARACTERIZE DRY-WEATHER FLOW

Dry-weather flow (DWF) is the regular daily collection system flow observed during periods without rainfall, or varying groundwater due to rainfall. It consists of domestic wastewater production (WWP) and base infiltration (BI).

Wastewater Production is the sanitary flow collected from residential, commercial, and industrial populations. Daily time series of WWP demonstrate regular flow patterns, or diurnals, that vary with water usage. Weekday diurnals generally peak before and after work hours, and are lowest in the very early morning. Weekend diurnals are similar, although their peaks are lesser, and occur later in the day, than weekday diurnals.

Base infiltration consists of groundwater entering the collection system due to pipeline and manhole deterioration, or faulty connections. In contrast to WWP, BI is constant and does not vary during weekdays and weekends.

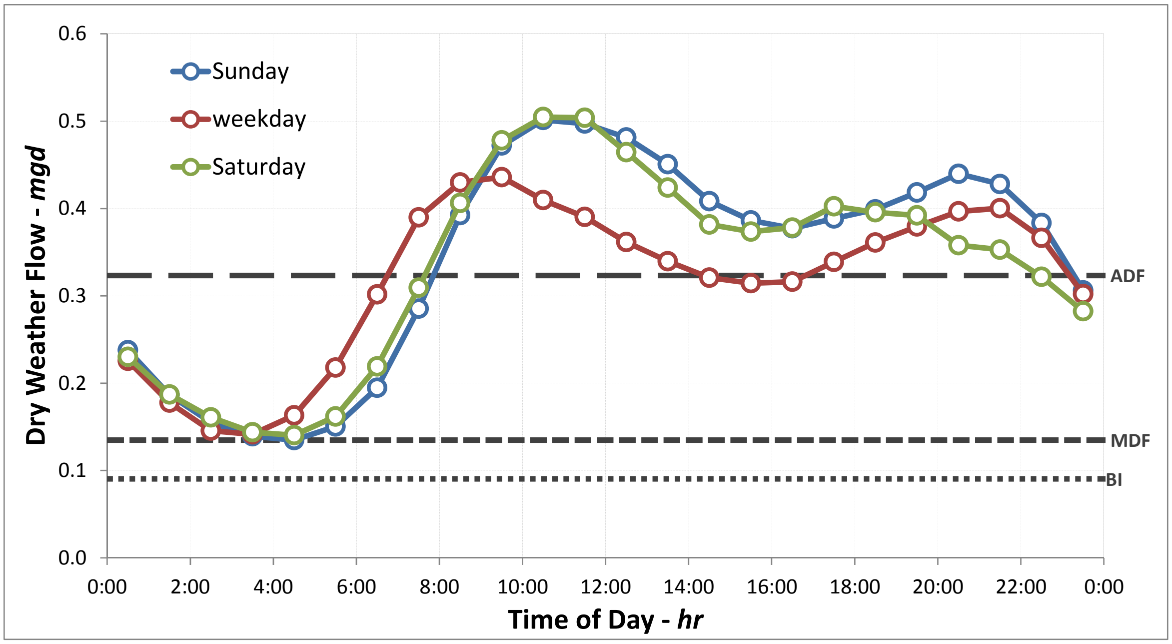

Figure 2-6. Example Dry-weather Flow Components and Diurnals

For this modeling effort, DWF was characterized between June and September. When only wet-weather seasons were monitored, DWF was characterized between significant rainfall events. This period was used to develop DWF hourly diurnals for the weekday, Saturday, and Sunday. The BI was estimated from the Stevens-Schutzbach Method, using the DWF diurnals to provide the minimum daily flow (MDF) and average daily flow (ADF). The Stevens-Schutzbach Method follows as:

$$BI = \frac{0.4\ (MDF)}{1 - 0.6(MDF/ADF)^{ADF^{0.7}}}$$

Once estimated, the BI was subtracted from the DWF diurnals to characterize the WWP diurnals, and added to the rainfall-dependent I/I to characterize the basin hydrology. Figure 2-6 demonstrates an example of BI, MDF, ADF, and WWP diurnals.

2.4 CALIBRATE HYDROLOGIC MODEL

Many of the basin parameters used by the hydrologic model to calculate surface runoff and groundwater I/I may be theoretical, vary by location, or cannot be measured in the field. Instead, their values can be estimated by calibrating each basin to flow data. Calibration is the iterative process of adjusting model parameters until the model results most closely simulates the metered hydrology. This process has been automated using Model-Independent Parameter Estimation and Uncertainty Analysis (PEST) software. PEST employs a steepest descent methodology to minimize the root mean square difference, or error, between model results and metered hydrology.

Nine significant flow events of varying magnitude and duration were selected from the flow data to calibrate each monitoring period. Events contained at least one storm, and included the storm recessional flow. A tenth event contained a dry-weather period. For monitoring periods of less than one wet-weather season, the entire monitoring period was distributed into ten events. Event hydrology was extracted from the flow meter time series by subtracting the WWP diurnals specific to Saturdays, weekdays, and Sundays.

During calibration, the period of simulation began three years before the first event to initialize, or set up, the ambient conditions, and ended one day after the last event. Prior to each simulation, PEST adjusted 4 of the 16 parameters in Model A, and 7 of the 23 parameters in RDII model (Attachment 1).

Following calibration, the goodness-of-fit, or agreement between model results and metered hydrology, was measured by the Nash Number, relative peak flow, and relative peak volume. These goodness-of-fit measures are described in Attachment 5.

The Skyway Pilot Basin, Skyway Control Basin, Minibasin BLS002, and Model Basin M_BLS43B were calibrated for the monitoring periods listed in Section 2.1.3. The graphs comparing metered flows, model results, WWP diurnals, and rainfall for all calibrations are found in Attachment 3. The hydrologic parameters optimized from all calibrations are listed in Attachment 4. The event goodness-of-fit measures from all calibrations are listed in Attachment 5.

3. RECURRENCE ANALYSIS

A consistent methodology was followed to derive the peak 20-year I/I from the calibrated hydrologic models. First, the models simulated extended time series using a synthetic rainfall and evaporation. Next, the model results were processed into a series of flow events. Each event was ranked by peak flow, and plotted as a flow-frequency curve. Finally, a trendline was fit to the curve, and the peak 20-year I/I interpolated from the trendline. This methodology is summarized as follows:

- Simulate extended time series
- Process results as flow events
- Develop event trendline
- Estimate trendline peak 20-year I/I

Each step of this methodology is described in the following sections.

3.1 SIMULATE EXTENDED TIME SERIES

The calibrated hydrologic models were simulated using Extended Time Series (ETS) to generate a sufficient number, and magnitude, of flow events for subsequent recurrence analysis. ETS simulations used continuous, synthetic rainfall and evaporation. Historical records from sites in the Puget Sound area have been analyzed and statistically representative evaporation and precipitation time series (Figure 3-1) have been developed based on 60-year records from SeaTac airport by MGS Engineers. Simulations with the 60-year ETS rainfall resulted in more statistically representative flow events than the combined 36-year RG10 and SKY1 available rainfall records used for calibration.

3.2 PROCESS RESULTS INTO FLOW EVENTS

Following ETS simulation, the results were processed into a partial duration series of flow events. By definition, the partial duration series allows any number of events to occur during any given year, in contrast to annual maximum series. Flow events were defined by flow above a threshold, and were separated by at least one day.

3.3 DEVELOP EVENT TRENDLINE

Flow events were sorted by peak flow, and plotted to a log-linear flow recurrence graph using the following equation for plot position:

$$T_r = \frac{N + 1}{i}$$

where: T_r is the recurrence interval, N is the number of simulation years, and i is the rank of the event peak flow in descending order

A log-linear trendline was then fit to the plotted flow events. The trendline only considered events at, or greater than, the two-year recurrence to avoid biasing towards smaller events.

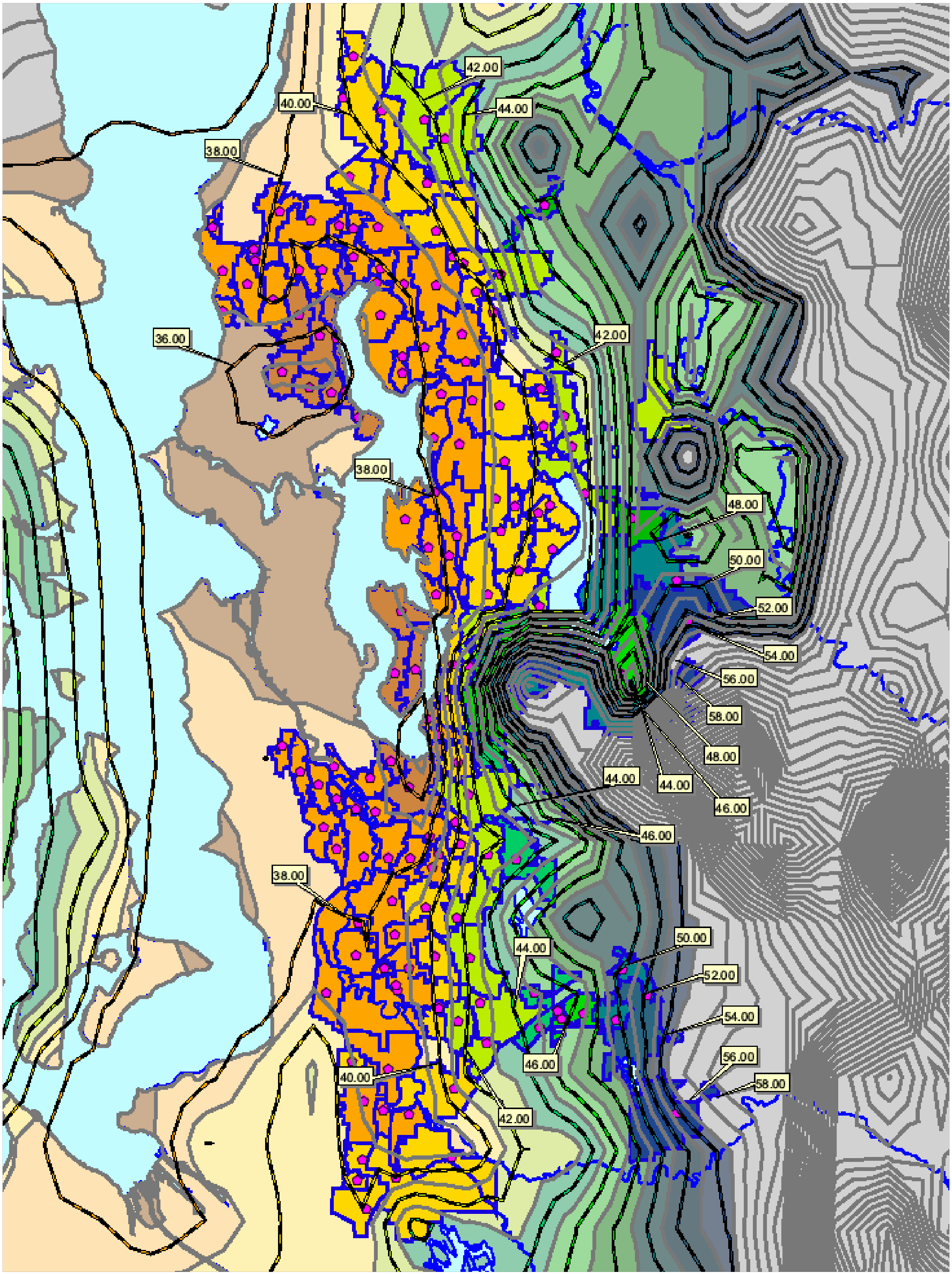

Figure 3-1. Zones of Statistically-Representative Mean Annual Precipitation (in)

3.4 ESTIMATE TRENDLINE PEAK 20-YEAR I/I

The peak 20-year I/I was interpolated from the log-linear trendline. This corresponds to the location of the third largest event in the partial duration series. Figure 3-2 demonstrates an example ETS flow frequency graph with plotted flow events, trendline, and interpolated peak 20-year I/I indicated by the dashed blue line.

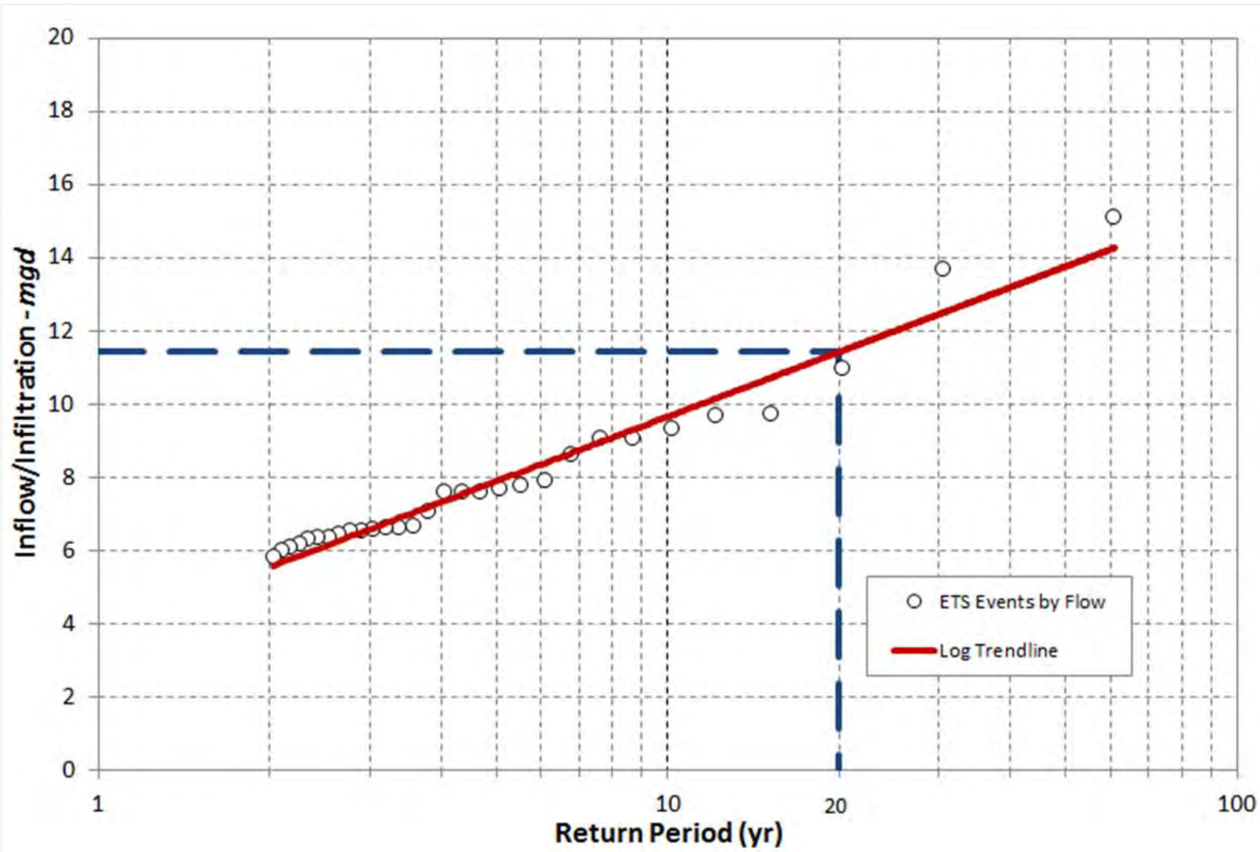

Figure 3-2. Example ETS Flow Frequency Graph

4. RESULTS

The results of the recurrence analyses from all calibrations are listed in Table 4-1 as follows.

TABLE 4-1.
SUMMARY OF PEAK 20-YEAR I/I BY BASIN AND MONITORING EFFORT

Basin / Monitoring Effort	Peak 20-Year I/I - mgd
SKYWAYCONTROL	
Pre- I/I Pilot Project	1.43
Post- I/I Pilot Project	1.05
Post- I/I Demonstration Project	0.64
SKYWAYPILOT	
Pre- I/I Pilot Project	2.15
Post- I/I Pilot Project	0.30
Post- I/I Demonstration Project	0.20
Minibasin BLS002	
I/I Control Program	5.97
Post- I/I Pilot Project	7.40
Pre- I/I Demonstration Project	3.55
Post- I/I Demonstration Project	3.29
Model Basin M_BLS43B	
I/I Control Program	12.62
Pre- I/I Demonstration Project	7.10
Decennial Flow Monitoring	11.05
Post- I/I Demonstration Project	11.43

Basin results are interpreted in terms of pre- and post- I/I Pilot Project and I/I Demonstration Project peak 20-year I/I estimates for use in evaluating I/I reductions in the following sections.

4.1 SKYWAY CONTROL BASIN

No I/I rehabilitation was performed in the Skyway Control Basin during the I/I Pilot Project. Accordingly, the average of the Pre- I/I Pilot Project and Post-I/I Pilot Project model results of 1.24 mgd was estimated as the Pre- I/I Pilot Project, Post-I/I Pilot Project, and Pre- I/I Demonstration Project peak 20-year I/I. The Post- I/I Demonstration Project model result of 0.64 mgd was estimated as the Post- I/I Demonstration Project peak 20-year I/I. Based on these estimations, the I/I Demonstration Project reduced the Skyway Control Basin peak 20-year I/I by 0.6 mgd.

4.2 SKYWAY PILOT BASIN

The Pre- I/I Pilot Project model result of 2.15 mgd was estimated as the Pre- I/I Pilot Project peak 20-year I/I. No I/I rehabilitation was performed in the Skyway Pilot Basin during the I/I Demonstration Project. Accordingly, the average of the Post- I/I Pilot Project and Post- I/I Demonstration Project model results, or 0.25 mgd, was estimated as the Post- I/I Pilot Project, Pre- I/I Demonstration Project, and Post- I/I Demonstration Project peak 20-year I/I. Based on these estimations, the I/I Pilot Project reduced the Skyway Pilot Basin peak 20-year I/I by 1.9 mgd.

4.3 MINIBASIN BLS002

The I/I Control Program model result of 5.97 mgd was estimated as the Pre- I/I Pilot Project peak 20-year I/I. The Post- I/I Pilot Project and Pre- I/I Demonstration Project model results of 7.40 mgd and 3.55 mgd, respectively, were inconsistent with results in the Skyway Control Basin and Skyway Pilot Basin for concurrent monitoring periods. Review of these calibrations concluded that these monitoring periods did not contain enough significant flow events to characterize the basin hydrology. Further, the latter monitoring period contained the extreme December 3, 2007 flow event, which could not be measured by the portable flow meter due to probable upstream overflow. Consequently, these results were not used for evaluation. Alternatively, the Skyway Pilot Basin reduction of 1.90 mgd was subtracted from Pre- I/I Pilot Project model result of 5.97 mgd to interpret 4.07 mgd as the Post- I/I Pilot Project and Pre- I/I Demonstration Project peak 20-year I/I. The Post- I/I Demonstration Project result of 3.29 mgd was estimated as the Post- I/I Demonstration Project peak 20-year I/I. Based on these estimations, the I/I Pilot Project and I/I Demonstration Project reduced Minibasin BLS002 peak 20-year I/I by 1.9 mgd and 0.78 mgd, respectively.

4.4 MODEL BASIN M_BLS43B

The I/I Control Program model result of 12.62 mgd was estimated as the Pre- I/I Pilot Project peak 20-year I/I. The Pre-I/I Demonstration Project model result of 7.10 mgd was inconsistent with results for Minibasin BLS002 for the concurrent monitoring period. Review of this calibration concluded that the monitoring period did not contain enough significant flow events to characterize the basin hydrology. The notable exception was the extreme December 3, 2007 flow event, which could not be measured by the portable flow meter due to probable upstream overflow.

The Decennial Flow Monitoring model result of 11.05 mgd was estimated as the Post- I/I Pilot Project and Pre- I/I Demonstration Project peak 20-year I/I. The Post- I/I Demonstration model result of 11.43 mgd was estimated as the Post- I/I Demonstration Project peak 20-year I/I. Based on these estimations, the I/I Pilot Project reduced Model Basin M_BLS43B peak 20-year I/I by 1.57 mgd and the I/I Demonstration Project increased the peak 20-year I/I by 0.38 mgd.

4.5 SKYWAY I/I PILOT PROJECT EVALUATION

Estimated results for each basin before and after the Skyway I/I Pilot Project are summarized in Table 4-2. Following the Skyway I/I Pilot Project (Table 4-2), Skyway Pilot Basin peak 20-year I/I was reduced by 1.9 mgd, or 89%. Minibasin BLS002 reduction could not be independently determined due to insufficient flow events for calibration. Model Basin M_BLS43B peak 20-year I/I was reduced by 1.57 mgd, or 13%. Most notably, this result suggests that upstream I/I reductions could be maintained downstream, without flow from downstream sources taking the place of the I/I reduced.

TABLE 4-2.
SKYWAY I/I PILOT PROJECT EFFECTIVENESS BY BASIN

Basin	Pre-I/I Pilot Project Peak 20-year I/I - mgd	Post-I/I Pilot Project Peak 20-year I/I - mgd	Reduction mgd	Effective Reduction
Skyway Control	1.24	1.24	n/a	n/a
Skyway Pilot	2.15	0.25	1.9	89%
Minibasin BLS002	5.97	4.07	1.9	32%
Model Basin M_BLS43B	12.62	11.05	1.57	13%

4.6 SKYWAY I/I DEMONSTRATION PROJECT EVALUATION

Estimated results for each basin before and after the Skyway I/I Demonstration Project are summarized in Table 4-3.

TABLE 4-3.
SKYWAY I/I DEMONSTRATION PROJECT EFFECTIVENESS BY BASIN

Basin	Pre-I/I Demonstration Project Peak 20-year I/I - mgd	Post-I/I Demonstration Project Peak 20-year I/I - mgd	Reduction mgd	Effective Reduction
Skyway Control	1.24	0.64	0.6	48%
Skyway Pilot	0.25	0.25	n/a	n/a
Minibasin BLS002	4.07	3.29	0.78	19%
Model Basin M_BLS43B	11.05	11.43	-0.38	-3%

Following the Skyway I/I Demonstration Project (Table 4-3), Skyway Control Basin I/I was reduced by 0.6 mgd, or 48%. Minibasin BLS002 peak 20-year I/I was reduced by 0.78 mgd, or 19%. This result suggests that the Skyway Control Basin may be responsible for the majority of the reduction in Minibasin BLS002. The remaining area of Minibasin BLS002 is located in areas of higher groundwater, includes a creek and culvert crossings, and receives flows from household sump pumps. It is possible that flow from these sources was able to take the place of the I/I reduced by the I/I Pilot Project and I/I Demonstration Project, effectively reducing the I/I reduction effectiveness. Model Basin M_BLS43B peak 20-year I/I was increased by 0.38 mgd, or 3%. It should be noted that this difference is within the accuracy of the metering and modeling methodology, and can be interpreted as non-significant. It is likely that I/I degradation outside of the Demonstration Project area negated any I/I reduction from inside the Demonstration Project area.

5. CONCLUSIONS AND DISCUSSION

Pre- I/I Pilot results from Table 4-2 and were combined with Post- I/I Demonstration Project results from Table 4-3 to summarize the results of the Skyway I/I Control Program in Table 5-1.

TABLE 5-1.
SKYWAY I/I CONTROL PROGRAM EFFECTIVENESS BY BASIN

Basin	Pre-I/I Control Program Peak 20-year I/I - mgd	Post-I/I Control Program Peak 20-year I/I - mgd	Reduction mgd	Effective Reduction
Skyway Control	1.24	0.64	0.6	48%
Skyway Pilot	2.15	0.25	1.9	88%
Minibasin BLS002	5.97	3.29	2.7	45%
Model Basin M_BLS43B	12.62	11.43	1.2	9%

The Skyway Control Basin and Skyway Pilot Basin demonstrated significant peak 20-year I/I reductions of 0.6 mgd or 48%, and 1.9 mgd or 88%, respectively. This effectiveness may be attributed to the proximity to the I/I rehabilitation, and the relatively low groundwater.

Minibasin BLS002 also demonstrated a significant peak 20-year I/I reduction of 2.7 mgd or 45%. This reduction was likely lessened by increased flow from groundwater, creek, and sump pump sources. Flow from Basin 148F also increased the non-I/I rehabilitated area for Minibasin BLS002, effectively decreasing the I/I reduction.

Model Basin M_BLS43B demonstrated a peak 20-year I/I reduction of 1.2 mgd or 9%. This reduction was likely lessened by I/I degradation from areas outside of Minibasin BLS002. Efforts by KC-WTD to quantify I/I degradation found highly localized results that varied widely. North Mercer Island, for example, has significant I/I similar to Skyway. Analysis suggests that North Mercer Island I/I is degrading by up to 30% in the last decade. KC-WTD planning is using a regional average of 7% per decade to estimate I/I degradation. Accordingly, this planned degradation would have added 0.9 mgd of peak 20-year I/I to Model Basin M_BLS43B. The net reduction in peak 20-year I/I would have increased from 1.2 mgd to 2.1 mgd to account for this planned degradation, and the I/I Control Program target I/I reduction would have been achieved.

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ATTACHMENT 1.
HYDROLOGIC MODEL PARAMETERS

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Table A-1 Model A Hydrologic Parameters

ID	Name	Calibration Parameter	Default Value	Unit	Description
LOCATION	Location			N/A	Node connecting the catchment to the hydraulic model
CatchmentID	ID			N/A	An identifier string of up to 25 ASCII characters of the catchment name
Inhab	Inhabitants			N/A	Number of inhabitants within the catchment used by dry water flow generator
Carea	Catchment Area			ac	Total area of the catchment
AFlow	Added Flow	**Yes**	0	cfs	Constant flow added to the runoff hydrograph (e.g., constant infiltration)
X	X-Coordinate			ft	Coordinates of the node connecting the catchment to the network (optional)
Y	Y-Coordinate			ft	Coordinates of the node connecting the catchment to the network (optional)
RDII_Set	RDII Set Name		DEFAULT	N/A	Name of set containing RDII parameters
RDII_Area	RDII Area	**Yes**		%	Percent of total catchment area that contributes RDII
A_IArea	Model A - Impervious Area	**Yes**		%	Fraction of catchment surface contributing to runoff
A_ILOSS	Initial Loss		0.024	in	Depression storage depth to be filled prior to surface runoff
A_RFACTOR	Hydrologic Reduction		0.9		Runoff reduction factor to account for losses (evapotranspiration, imperviousness, etc.)
A_TAC	Time/Area Curve		1		Pre-defined time-area curves for rectangular, divergent, or convergent catchment geometry
A_USE_TACOEF	Use Time/Area Coefficient		0		Use time/area coefficient instead of time/area curve number
A_TACOEF	Time/Area Coefficient				Coefficient to interpolate between pre-defined time-area curves for catchment geometry
A_CTIME	Concentration Time	**Yes**	7	min	Time for runoff to cross from most distant catchment location to catchment outflow

Table A-2. RDII Model Parameters

ID	Name	Calibration Parameter	Default Value	Unit	Description
Setname	Set Name for RDII Parameters		DEFAULT	N/A	Name of set containing RDII parameters
Evap	Evaporation Option		TRUE	N/A	Controls if the evapotranspiration process will be included in the runoff computations
Snowmelt	Snowmelt Option		FALSE	N/A	Controls if the snowmelt process will be included in the runoff computations
Snowmelt_C	Snowmelt Coefficient		0.0656	in/F/day	Rate at which snow is melted and the snow storage is diminished
Umax	Surface Storage Capacity	**Yes**	0.39	in	Maximum water content in the surface storage
Lmax	Root Storage Capacity	**Yes**	3.94	in	Maximum storage capacity of the lower zone (unsaturated zone)
CQof	Overland Flow Coefficient	**Yes**	0.3	N/A	Controls the distribution of runoff between overland flow and base flow
CK	Time Constant for Overland Flow	**Yes**	20	hr	Controls how fast the overland flow responds to a rainfall
CKIF	Time Constant for Interflow	**Yes**	500	hr	Time constant for routing of interflow
CKbf	Time Constant for Baseflow	**Yes**	2000	hr	Controls the hydrograph recession during dry periods
Tof	Overland Flow Threshold		0	%	Relative level of lower storage at which overland flow occurs
Tif	Interflow Threshold		0	%	Relative level of lower storage at which interflow occurs
Tg	Groundwater Recharge Threshold		0	%	Defines the relative level of lower storage at which groundwater recharge occurs
I_U	Initial Surface Storage		0	in	Initial value of the surface storage
I_L	Initial Lower Zone Storage		0	in	Initial value of the lower zone storage
I_GWL	Initial Groundwater Depth		32.8	ft	Initial value of the groundwater depth
I_OF	Initial Overland Flow		0	in/hr	Initial value of the overland flow
I_IF	Initial Interflow		0	in/hr	Initial value of the interflow
GW_Carea	Groundwater Catchment Area	**Yes**	1	N/A	Proportion of the groundwater catchment to the surface catchment area
GW_Sy	Specific Yield		0.1	N/A	Specific yield of the groundwater reservoir
GW_Lmin	Minimum Groundwater Depth		0	ft	Minimum depth of groundwater below surface, at which the groundwater recharge is diverted to the overland flow
GW_Lbf0	Maximum Groundwater Depth Causing Base Flow		32.8	ft	Maximum depth of groundwater below surface causing base flow
GW_Lfl1	Groundwater Depth for Unit Capillary Flux		0	ft	Depth of groundwater table below surface where unit capillary flux (1 mm/day) occurs

ATTACHMENT 2. CALIBRATION EVENTS

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Table B-1. Skyway Pilot Basin Calibration Events

Event	Pre- I/I Pilot Project		Post- I/I Pilot Project		Post- I/I Demonstration Project	
	Start	*End*	*Start*	*End*	*Start*	*End*
01	10/30/02	11/17/02	10/10/03	10/21/03	11/01/12	11/24/12
02	11/17/02	12/05/02	10/21/03	11/01/03	11/24/12	12/17/12
03	12/05/02	12/23/02	11/01/03	11/12/03	12/17/12	01/09/13
04	12/23/02	01/10/03	11/12/03	11/23/03	01/09/13	02/01/13
05	01/10/03	01/28/03	11/23/03	12/04/03	02/01/13	02/24/13
06	01/28/03	02/15/03	12/04/03	12/15/03	02/24/13	03/19/13
07	02/15/03	03/05/03	12/15/03	12/26/03	03/19/13	04/11/13
08	03/05/03	03/23/03	12/26/03	01/06/04	04/11/13	05/04/13
09	03/23/03	04/10/03	01/06/04	01/17/04	05/04/13	05/27/13
10	04/10/03	05/02/03	01/17/04	02/02/04	05/27/13	06/20/13

Table B-2. Skyway Control Basin Calibration Events

Event	Pre- I/I Pilot Project		Post- I/I Pilot Project		Post- I/I Demonstration Project	
	Start	*End*	*Start*	*End*	*Start*	*End*
01	10/30/02	11/17/02	10/07/03	10/18/03	08/31/12	09/29/12
02	11/17/02	12/05/02	10/18/03	10/29/03	09/29/12	10/28/12
03	12/05/02	12/23/02	10/29/03	11/09/03	10/28/12	11/26/12
04	12/23/02	01/10/03	11/09/03	11/20/03	11/26/12	12/25/12
05	01/10/03	01/28/03	11/20/03	12/01/03	12/25/12	01/23/13
06	01/28/03	02/15/03	12/01/03	12/12/03	01/23/13	02/21/13
07	02/15/03	03/05/03	12/12/03	12/23/03	02/21/13	03/22/13
08	03/05/03	03/23/03	12/23/03	01/03/04	03/22/13	04/20/13
09	03/23/03	04/10/03	01/03/04	01/14/04	04/20/13	05/19/13
10	04/10/03	05/02/03	01/14/04	02/02/04	05/19/13	06/20/13

Table B-3. Minibasin BLS002 Calibration Events

	I/I Control Program		Post- I/I Pilot Project		Pre- I/I Demonstration Project		Post- I/I Demonstration Project	
Event	*Start*	*End*	*Start*	*End*	*Start*	*End*	*Start*	*End*
01	11/01/00	11/15/00	11/21/03	11/24/03	11/15/07	11/21/07	11/16/12	11/22/12
02	11/16/00	11/30/00	12/03/03	12/07/03	12/01/07	12/12/07	11/23/12	11/28/12
03	12/01/00	12/15/00	12/08/03	12/12/03	12/16/07	12/30/07	11/29/12	12/11/12
04	12/16/00	12/30/00	12/13/03	12/17/03	01/02/08	01/19/08	12/12/12	12/31/12
05	12/31/00	01/14/01	12/25/03	12/29/03	02/05/08	02/13/08	01/06/13	01/17/13
06	11/01/01	11/15/01	01/13/04	01/15/04	03/08/08	03/19/08	01/23/13	02/12/13
07	11/16/01	11/30/01	01/16/04	01/19/04	03/22/08	04/06/08	02/20/13	03/04/13
08	12/01/01	12/15/01	01/20/04	01/23/04	04/18/08	04/25/08	03/05/13	03/17/13
09	12/16/01	12/30/01	01/24/04	01/27/04	05/01/08	05/15/08	03/19/13	04/01/13
10	12/31/01	01/14/02	01/28/04	02/01/04	06/03/08	06/11/08	04/03/13	04/12/13

Table B-4. Model Basin M_BLS43B Calibration Events

	I/I Control Program		Pre- I/I Demonstration Project		Decennial Flow Monitoring		Post- I/I Demonstration Project	
Event	*Start*	*End*	*Start*	*End*	*Start*	*End*	*Start*	*End*
01	11/01/00	11/15/00	07/28/07	09/05/07	08/02/09	08/16/09	03/09/12	03/27/12
02	11/16/00	11/30/00	09/06/07	10/15/07	11/05/09	11/14/09	03/28/12	04/15/12
03	12/01/00	12/15/00	10/16/07	11/24/07	11/15/09	12/02/09	07/01/12	07/15/12
04	12/16/00	12/30/00	11/25/07	01/03/08	01/01/10	01/22/10	10/26/12	11/09/12
05	12/31/00	01/14/01	01/04/08	02/12/08	07/01/10	07/15/10	11/10/12	11/27/12
06	11/01/01	11/15/01	02/13/08	03/23/08	10/30/10	11/12/10	11/28/12	12/10/12
07	11/16/01	11/30/01	03/24/08	05/02/08	12/07/10	12/21/10	12/12/12	01/01/13
08	12/01/01	12/15/01	05/03/08	06/11/08	01/05/11	01/27/11	01/02/13	01/18/13
09	12/16/01	12/30/01	06/12/08	07/21/08	03/07/11	03/20/11	01/22/13	02/08/13
10	12/31/01	01/14/02	07/22/08	09/01/08	04/01/11	04/12/11	04/04/13	04/10/13

ATTACHMENT 3.
CALIBRATION GRAPHS

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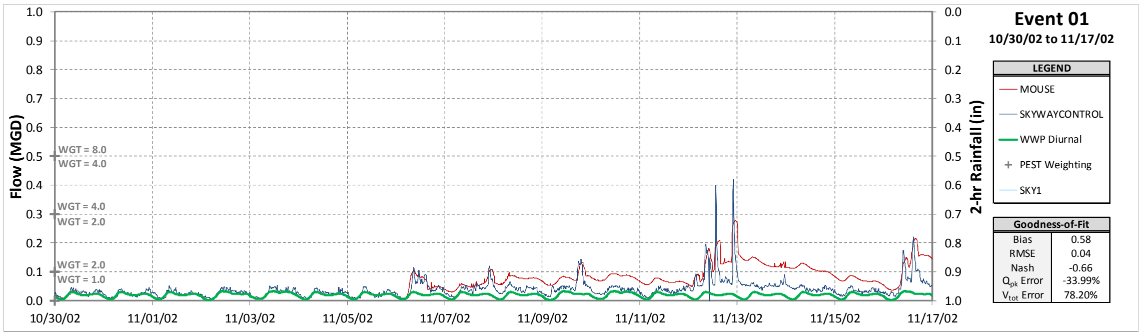
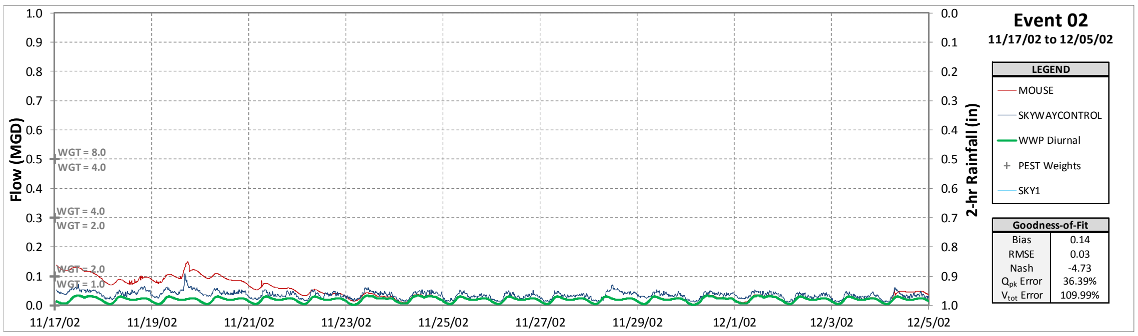
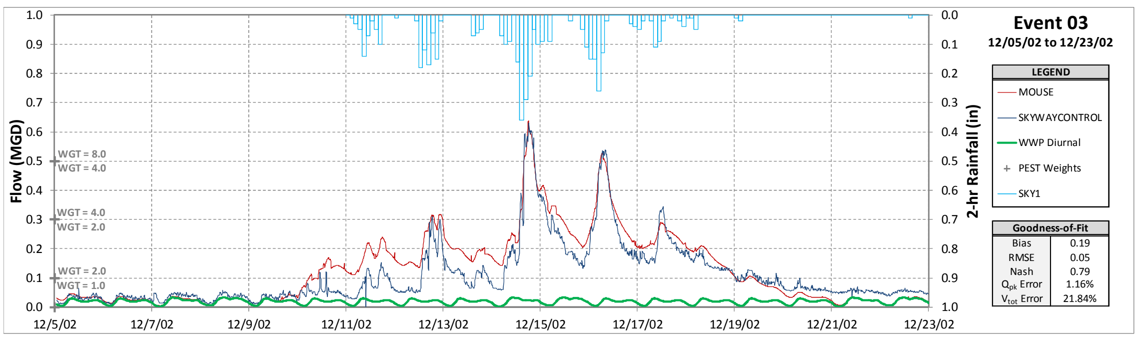
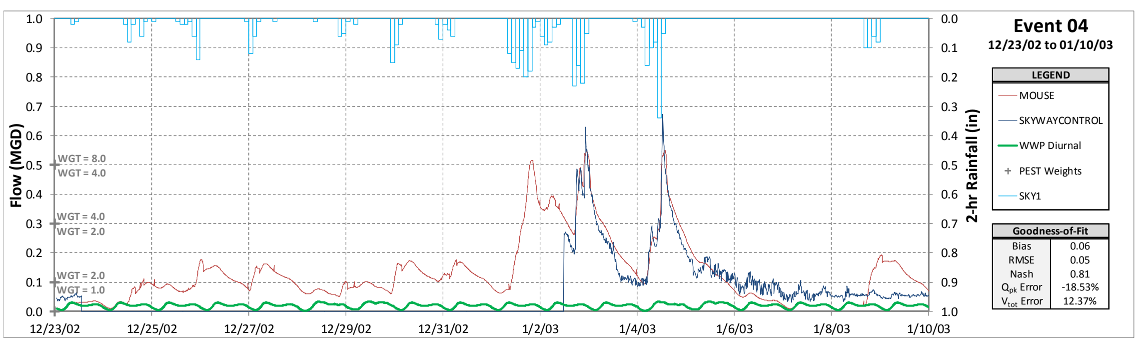
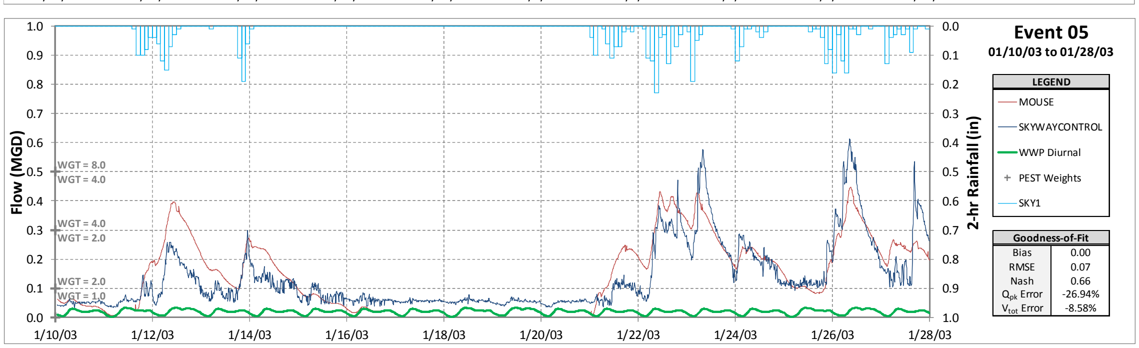


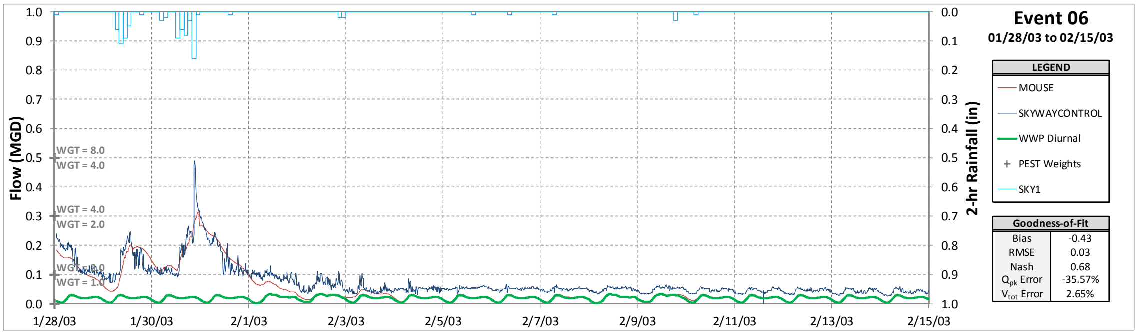


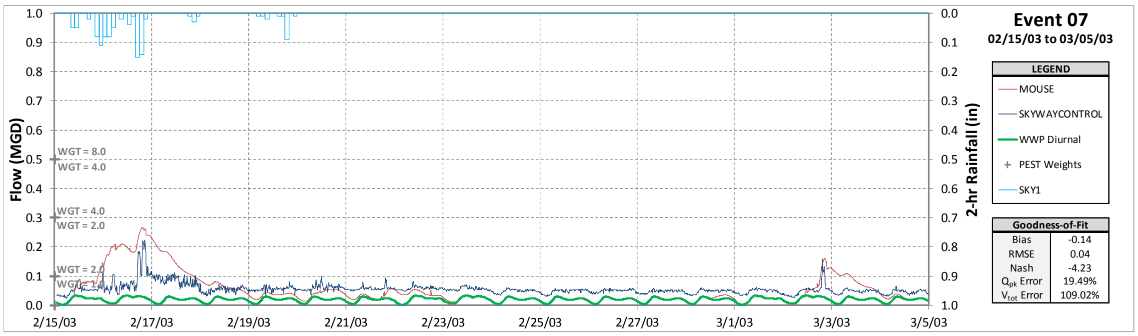


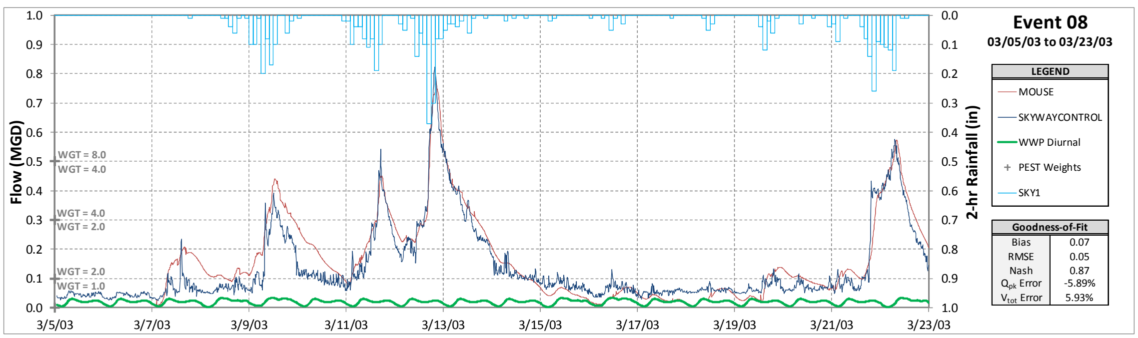


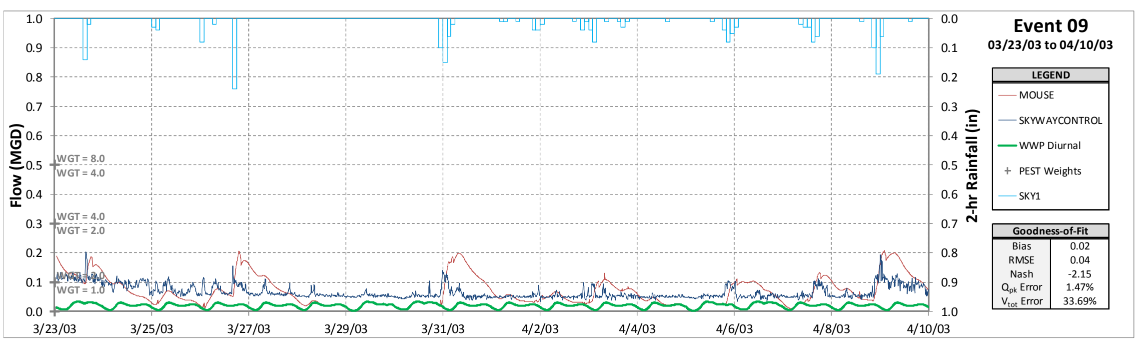


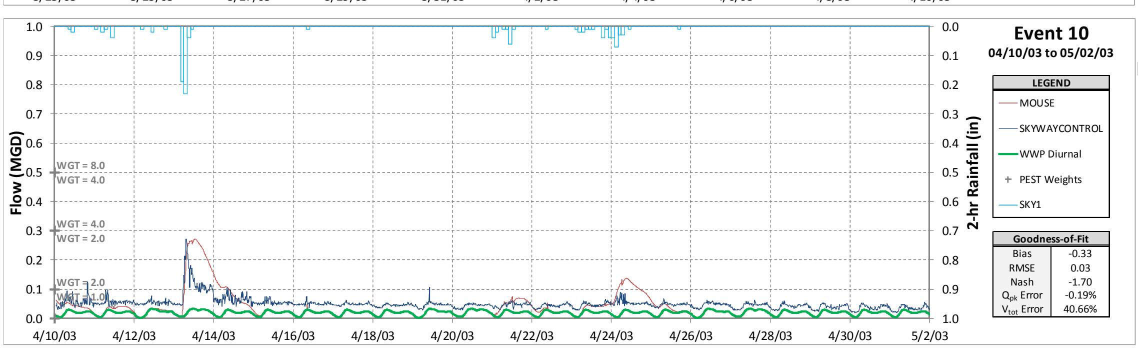
SKYWAYCONTROL Pre- I/I Pilot Project











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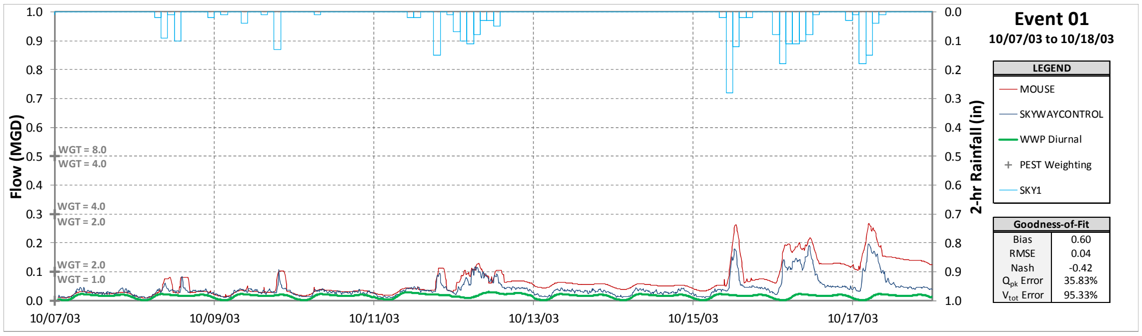
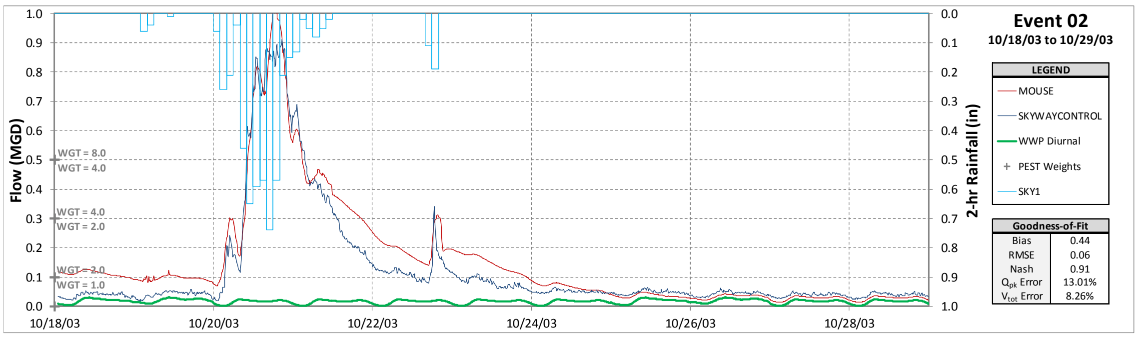
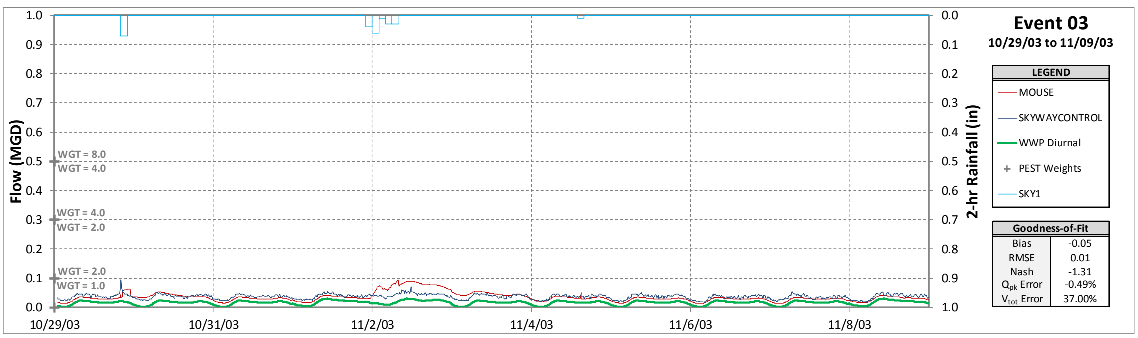
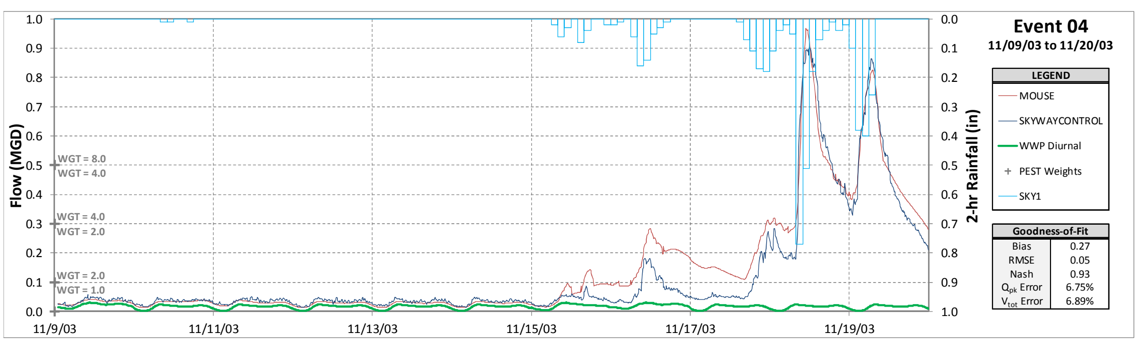
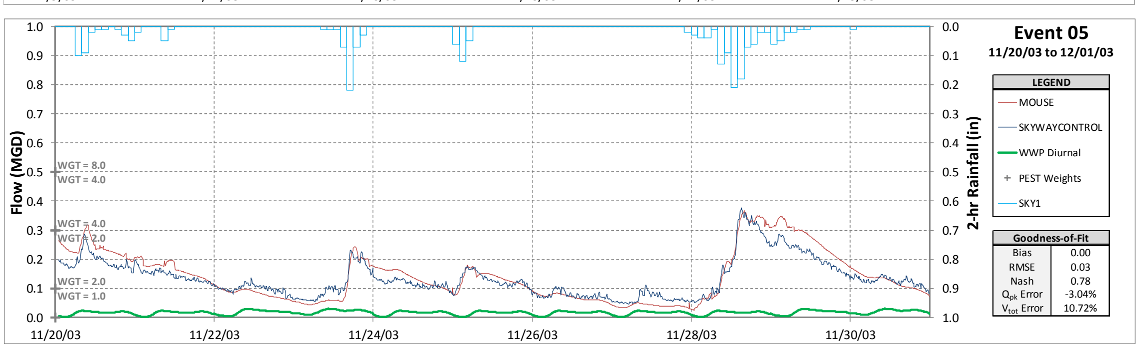


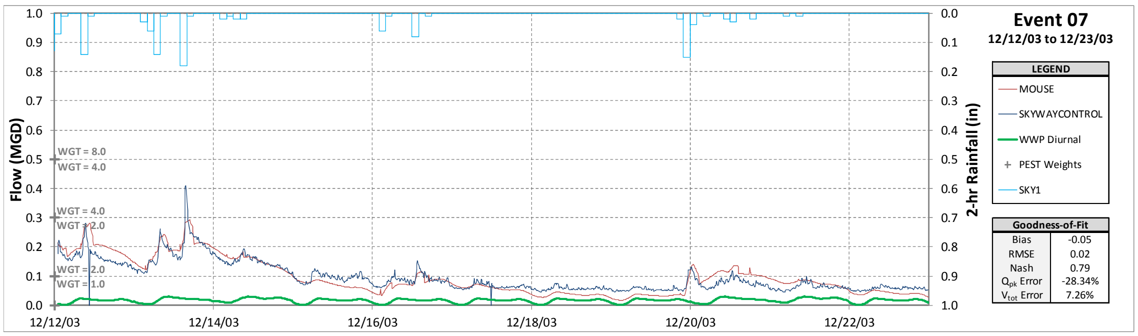


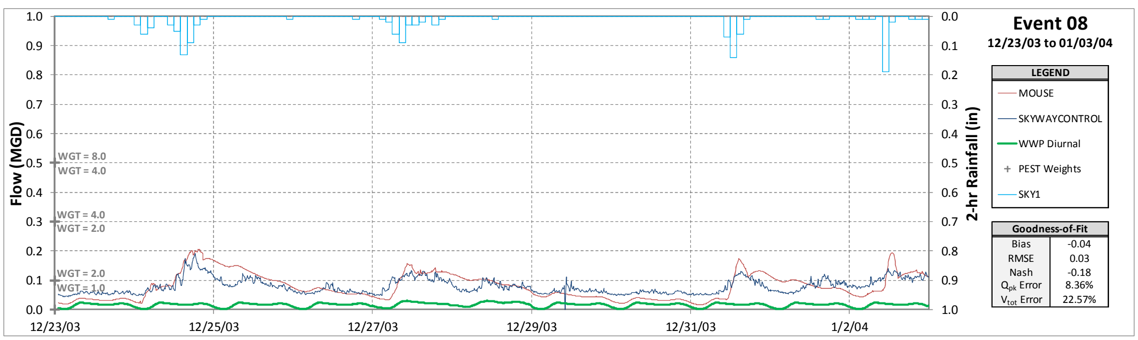


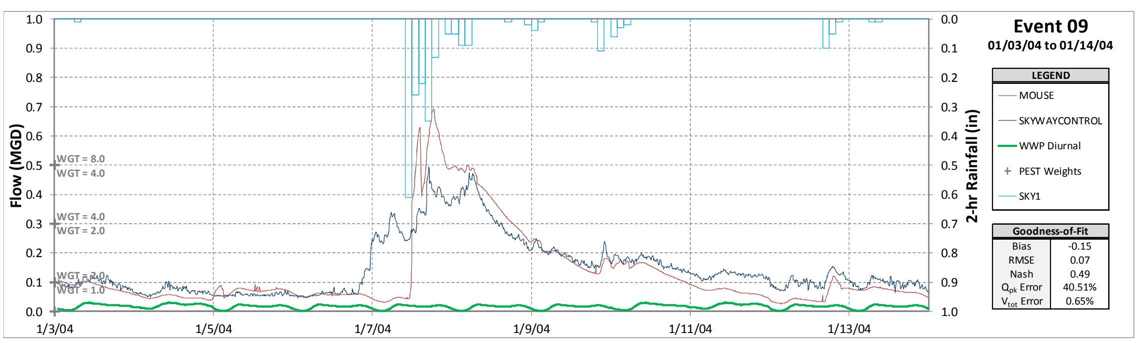


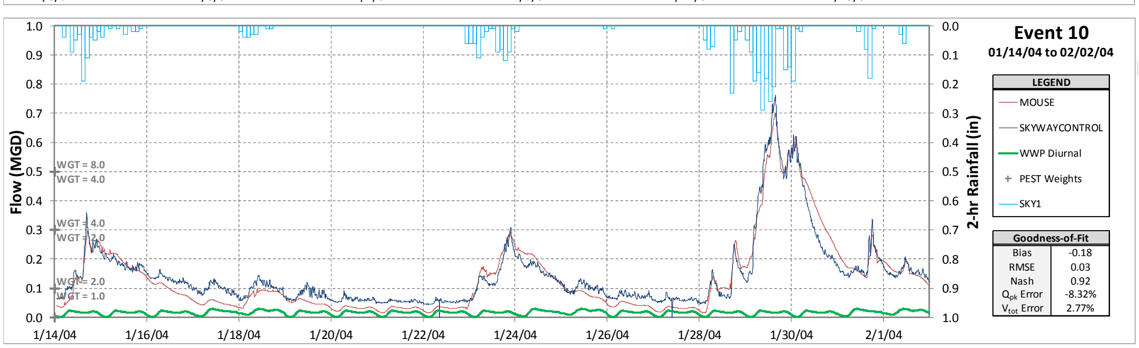


SKYWAYCONTROL Post- I/I Pilot Project









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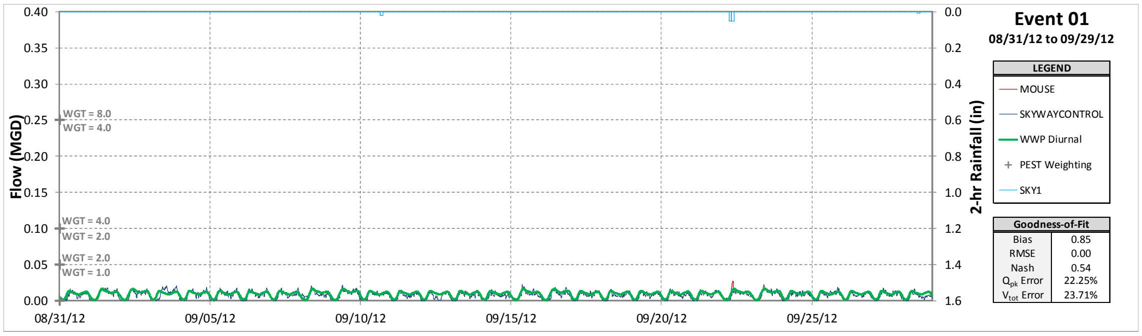

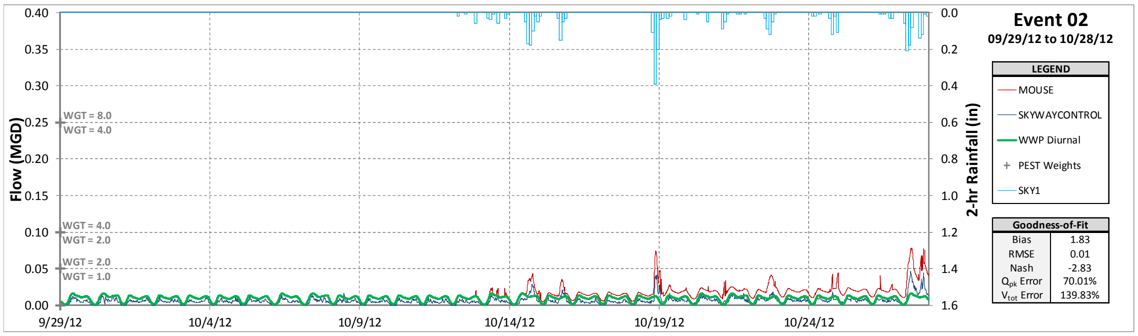

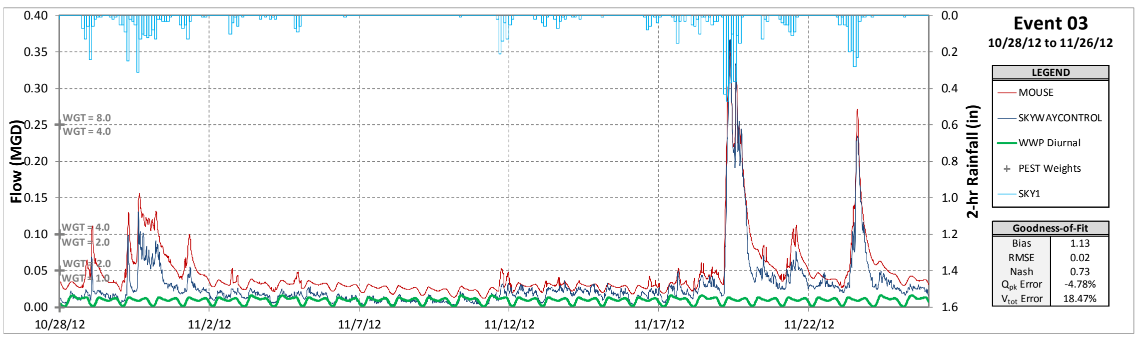

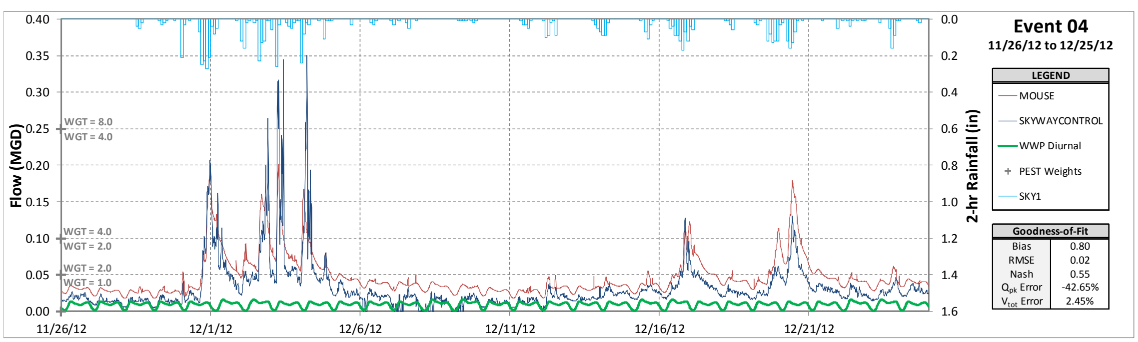

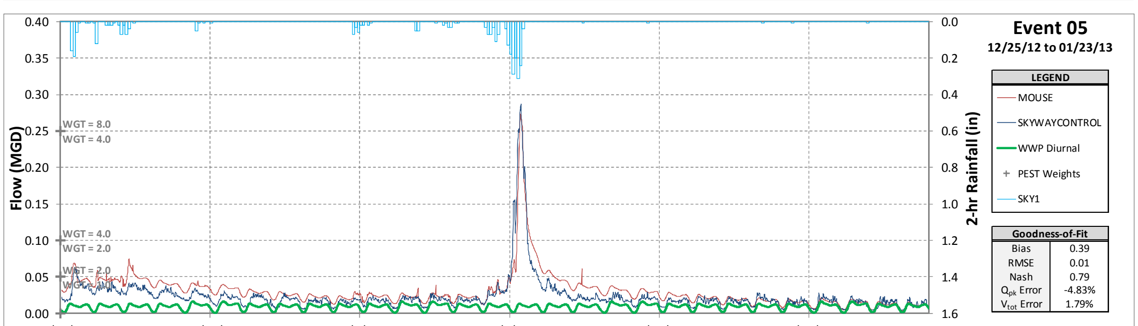

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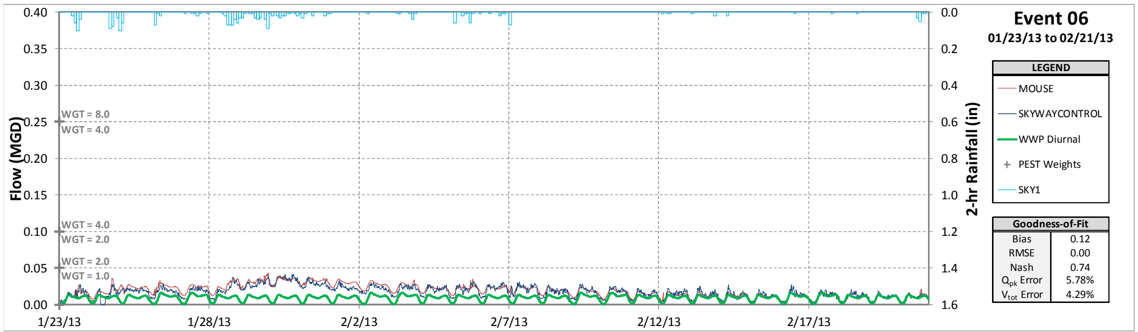
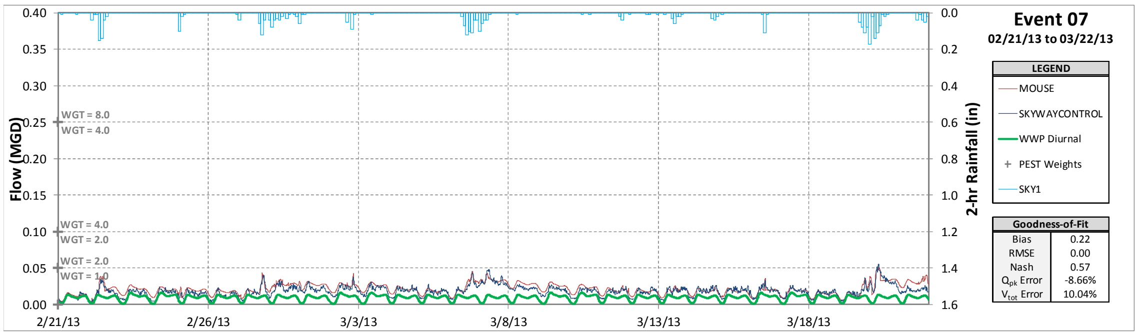
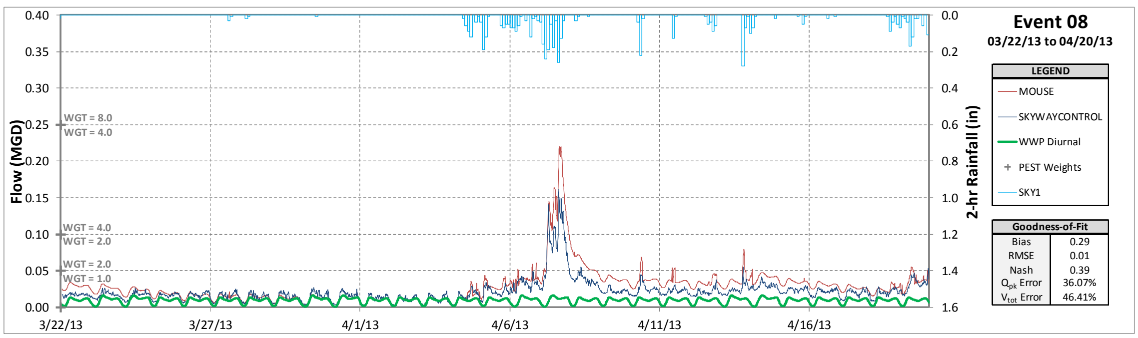
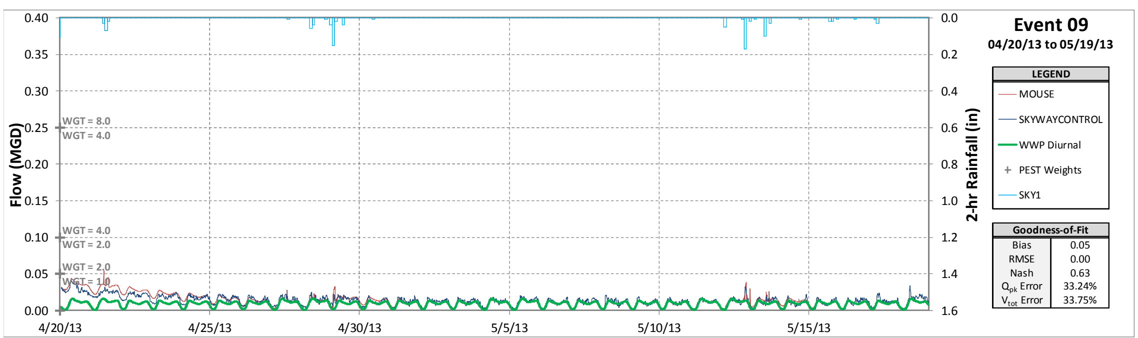
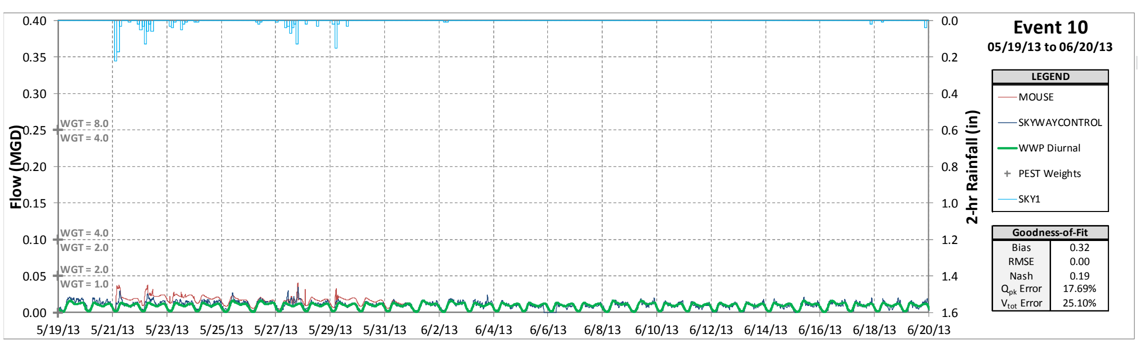


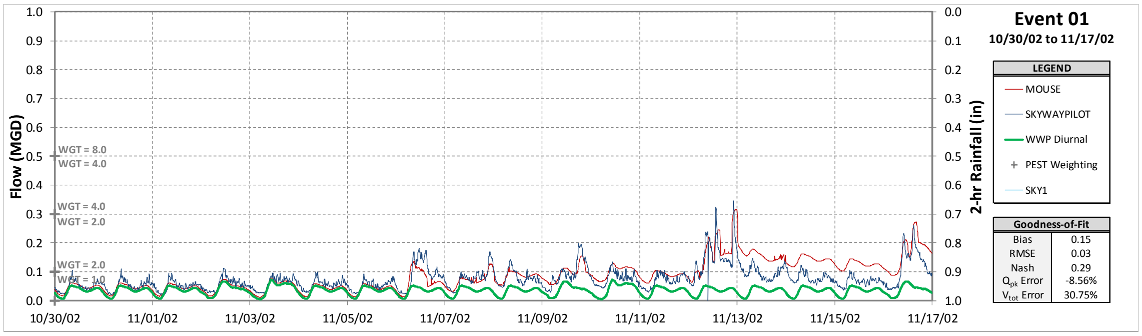


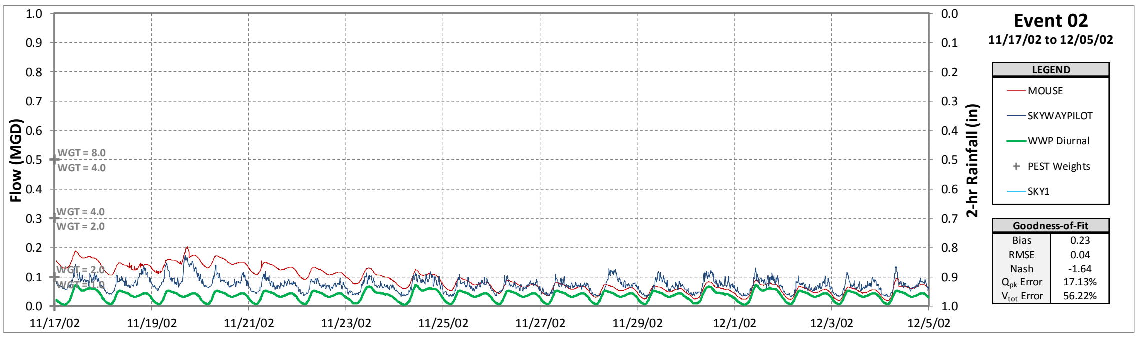


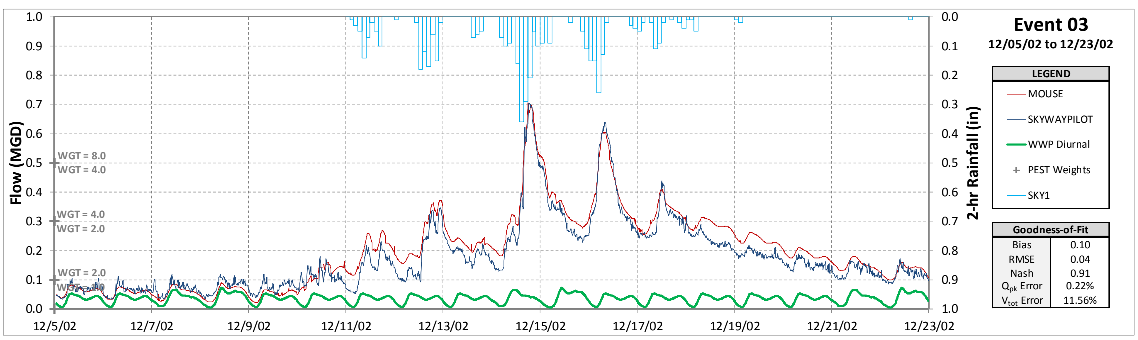


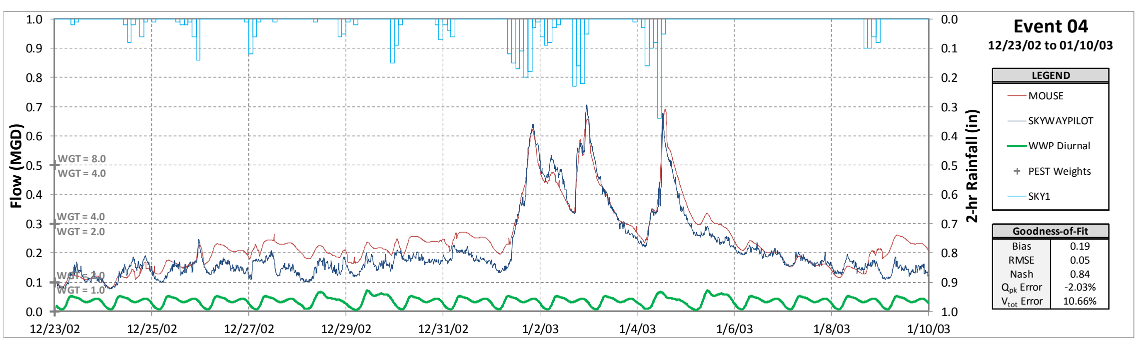


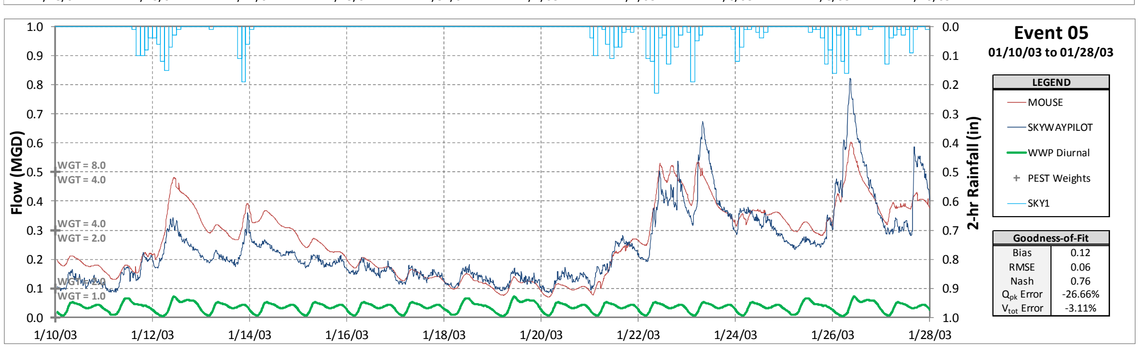
SKYWAYCONTROL Post- I/I Demonstration Project



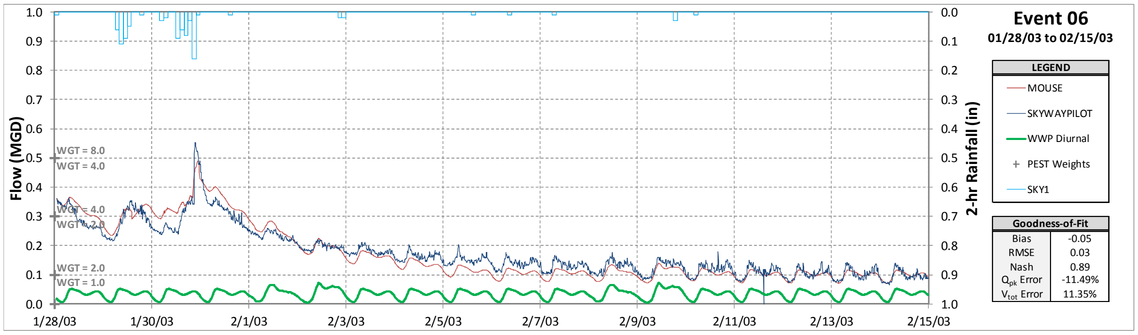


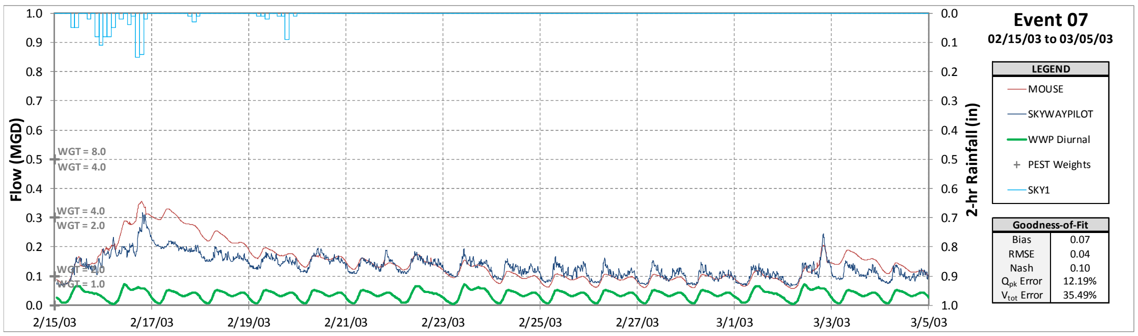


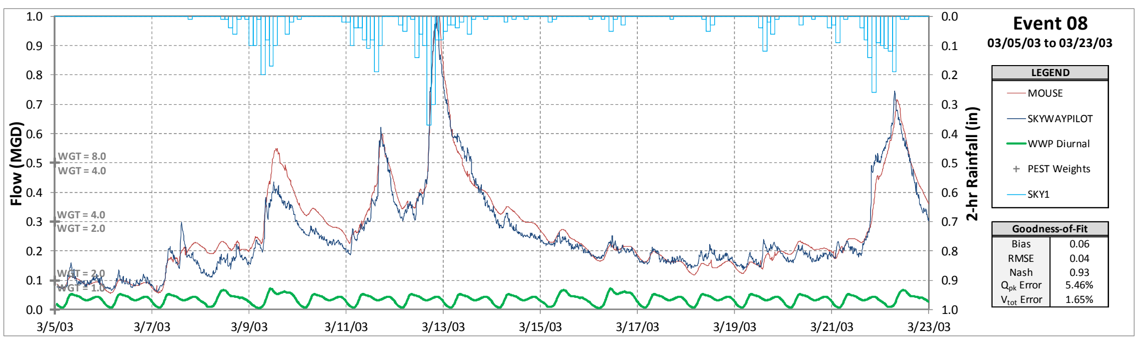


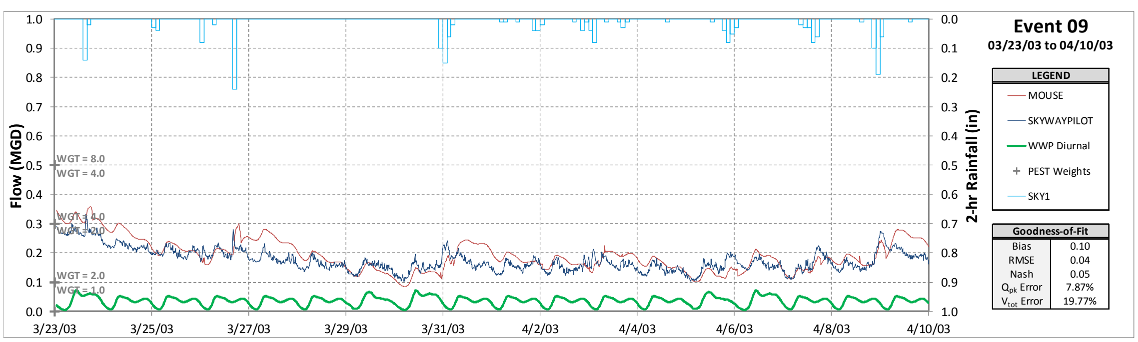


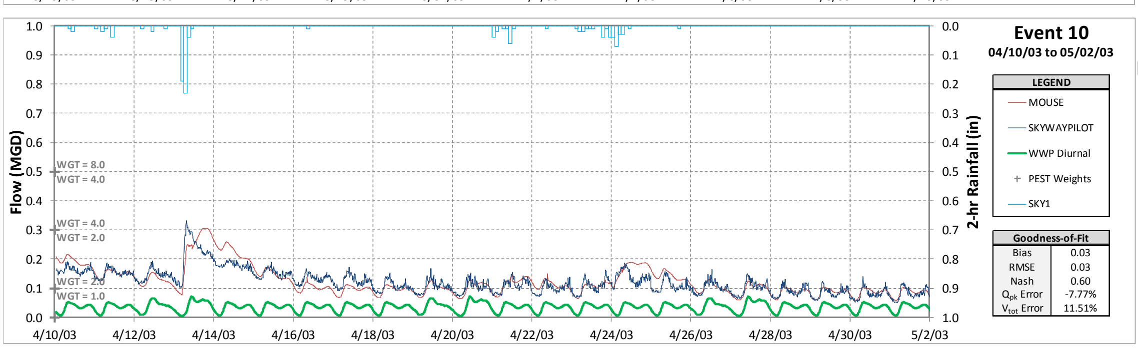
SKYWAYPILOT Pre- I/I Pilot Project











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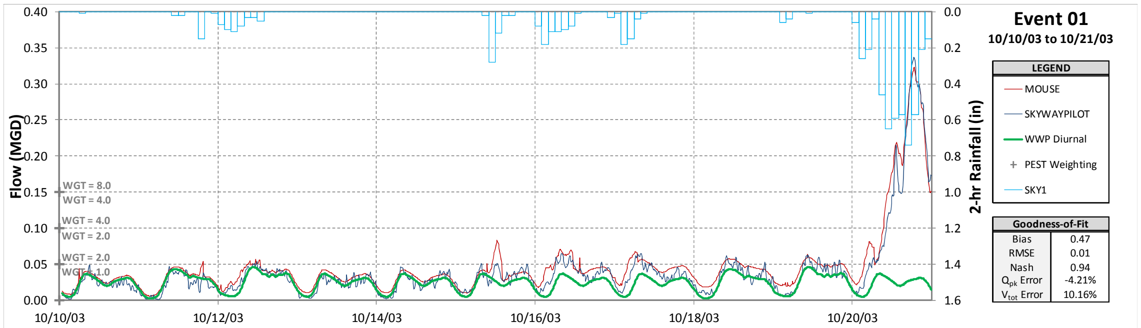
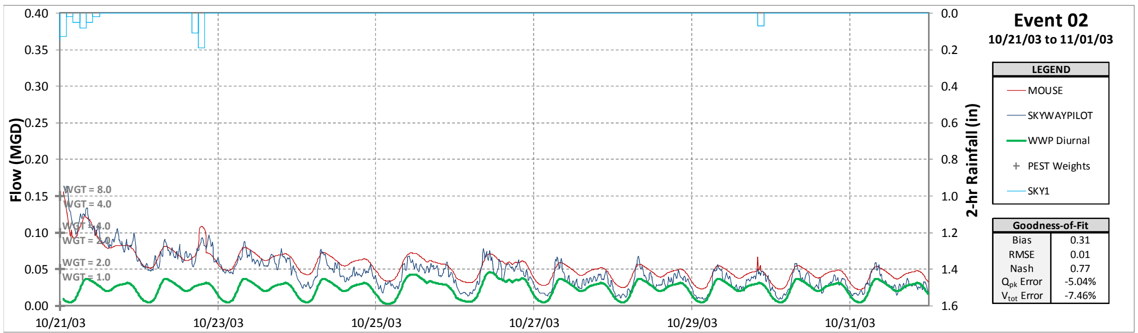
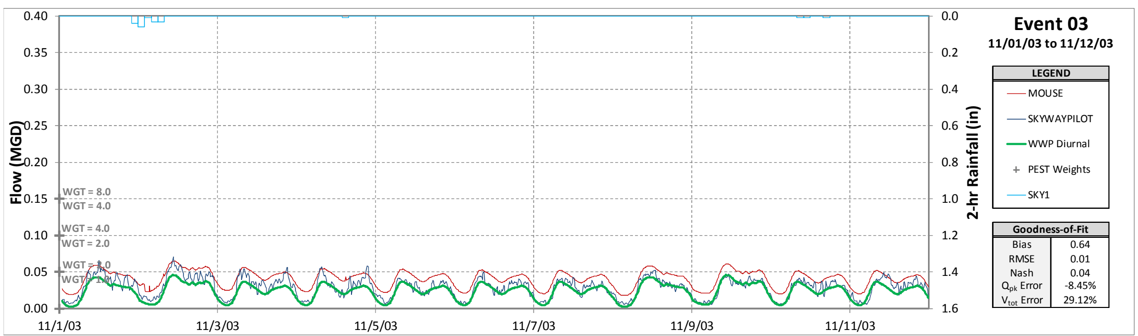
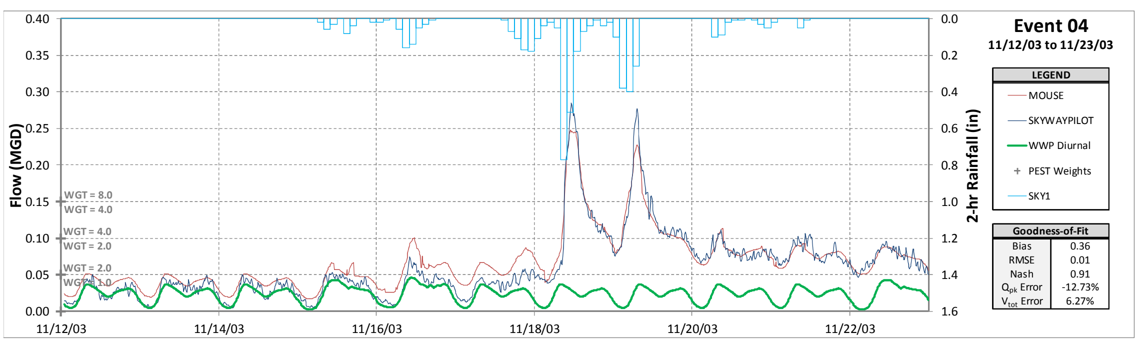
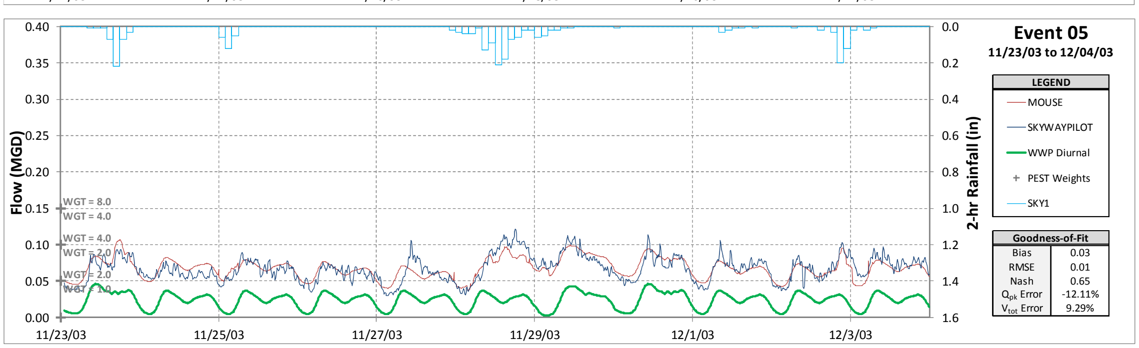


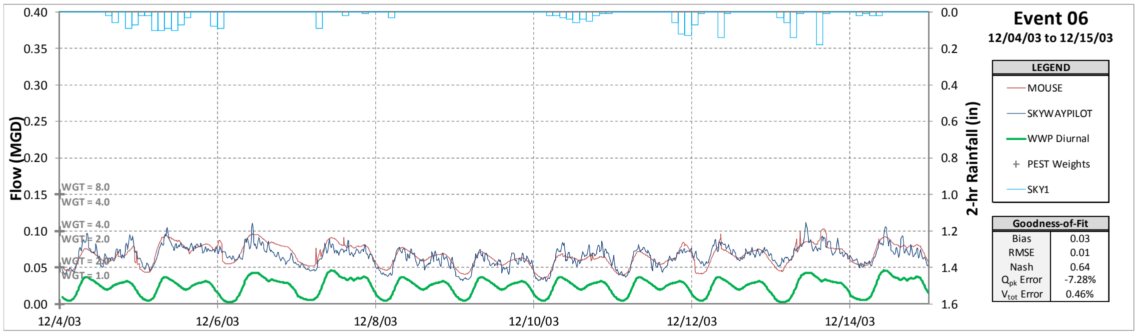


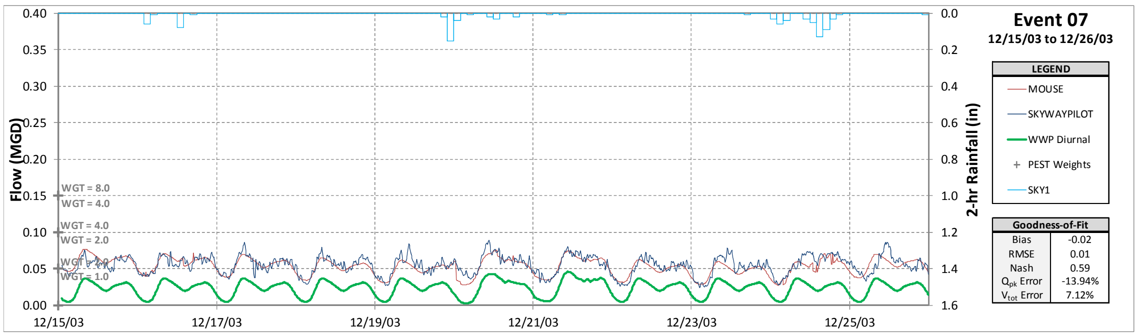


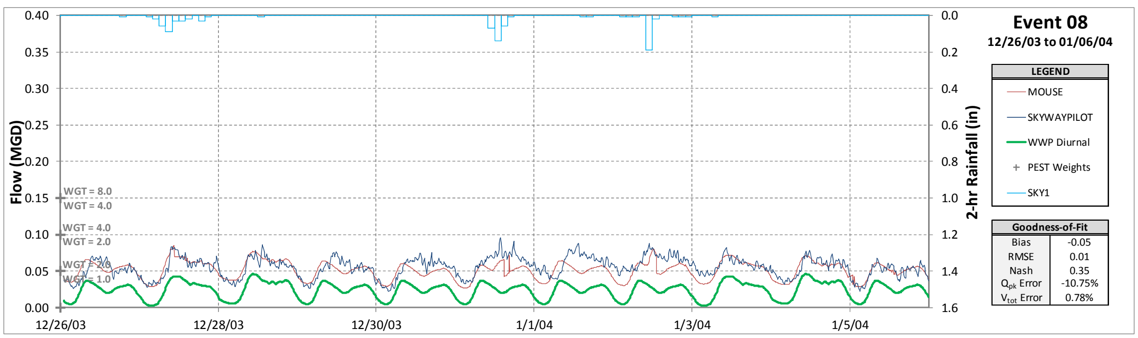


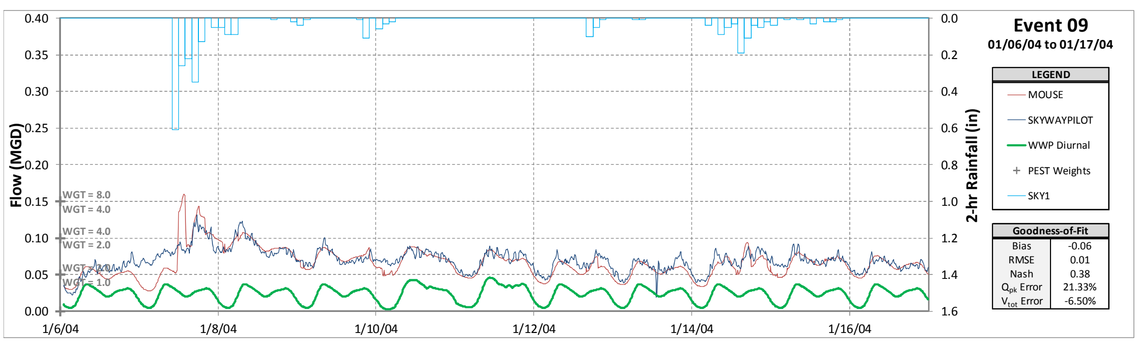


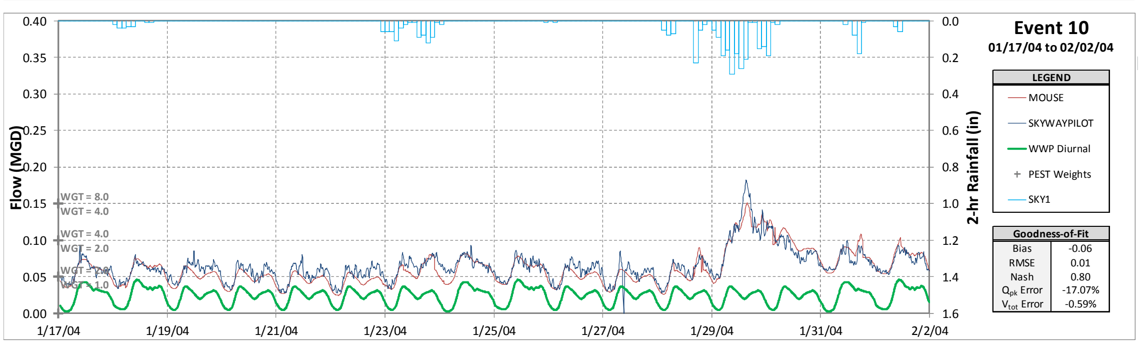
SKYWAYPILOT Post- I/I Pilot Project











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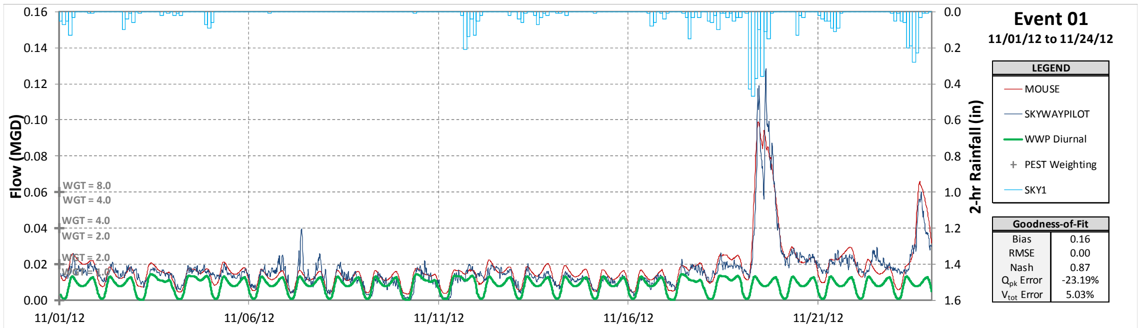
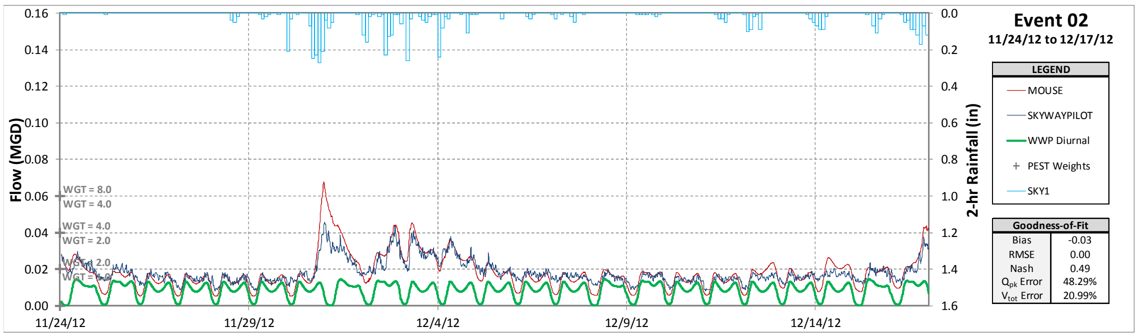
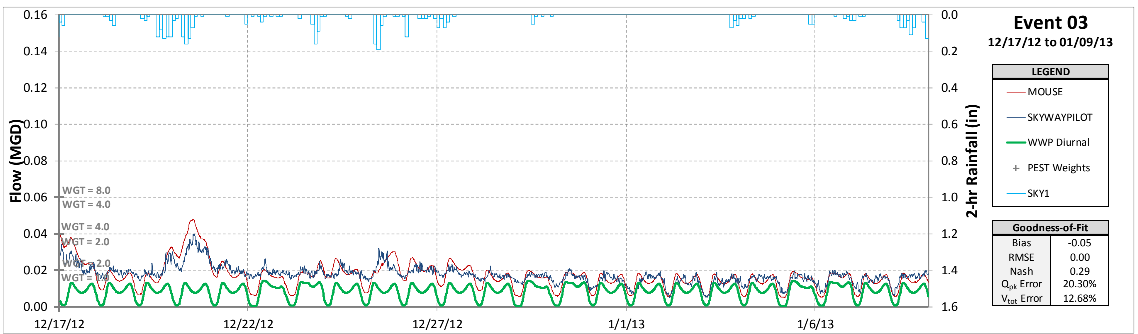
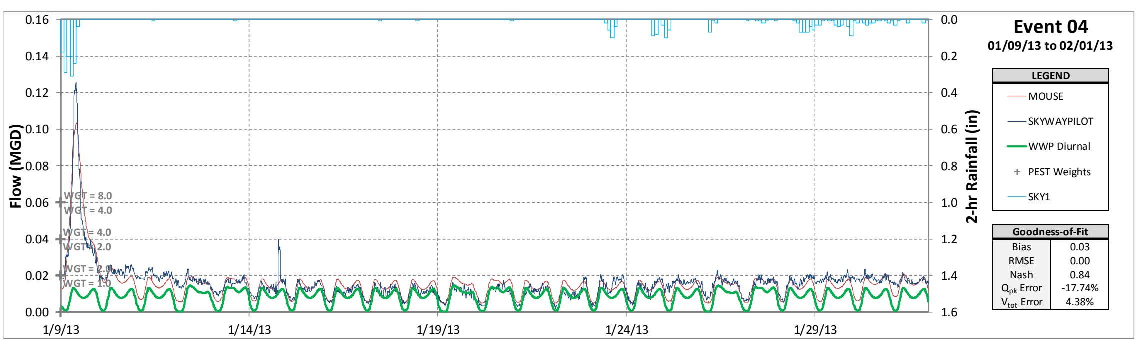
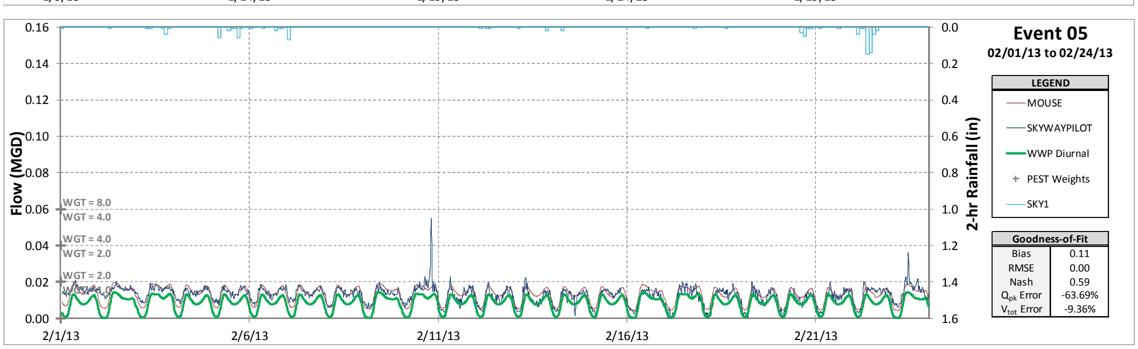


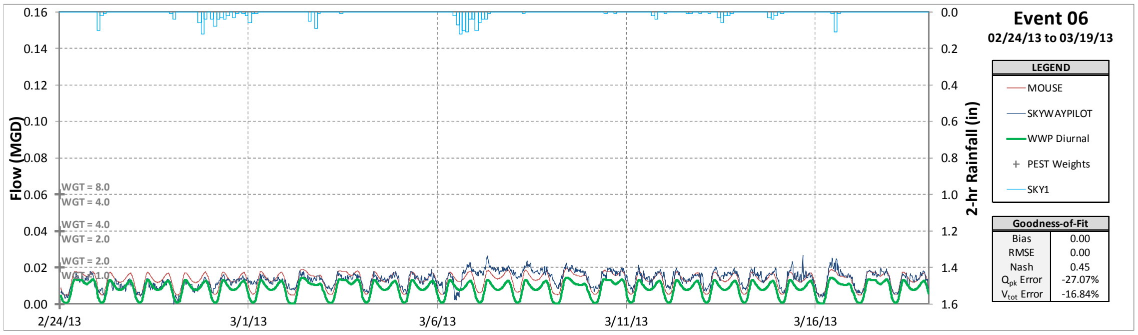


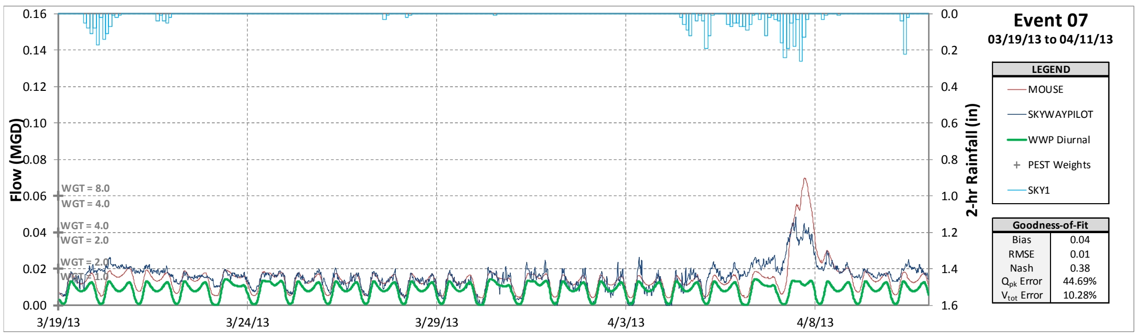


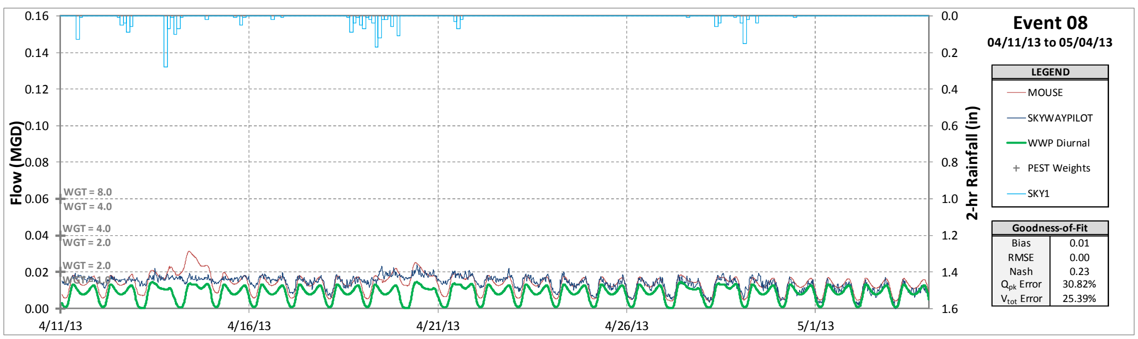


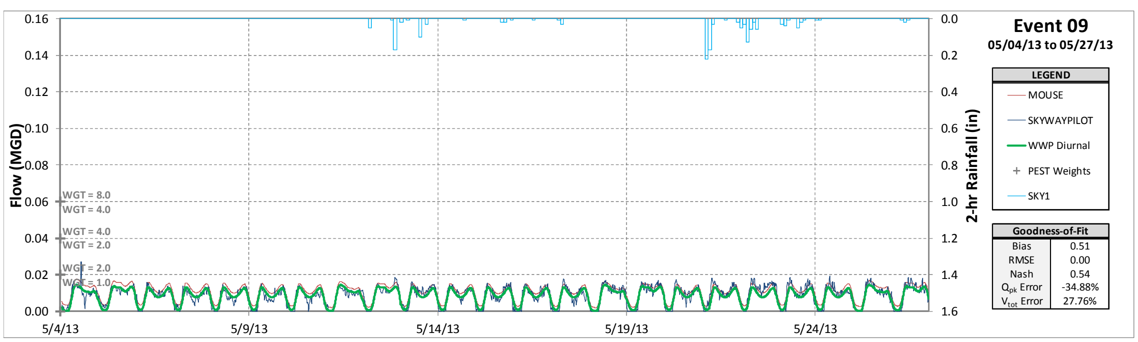


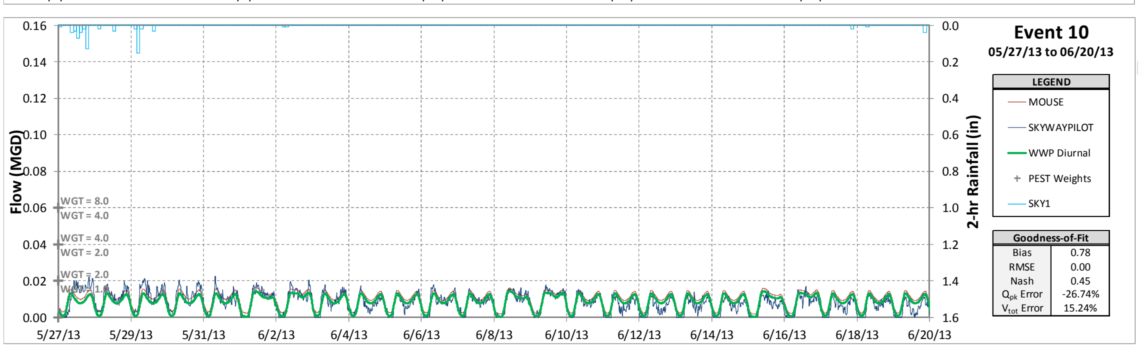
SKYWAYPILOT Post- I/I
Demonstration Project



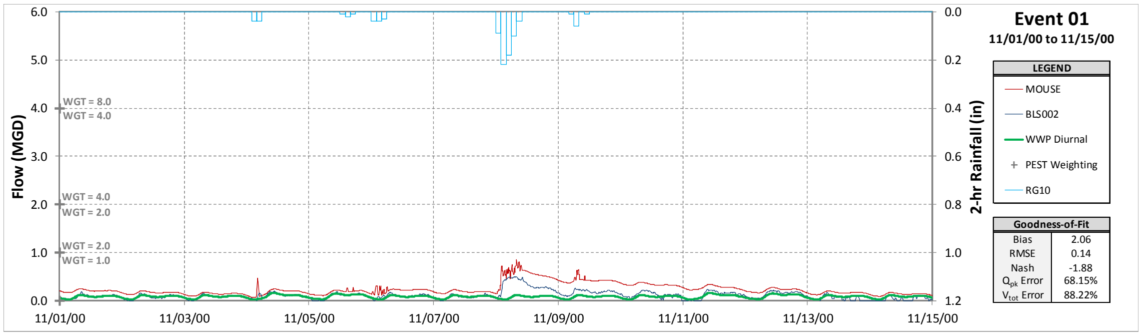


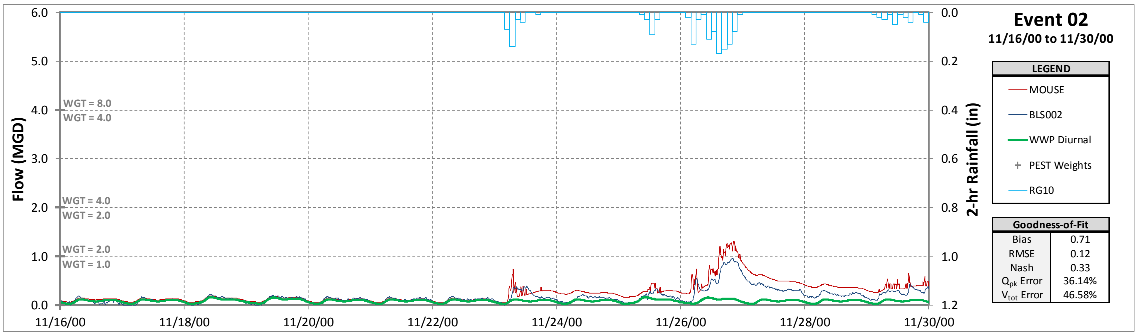


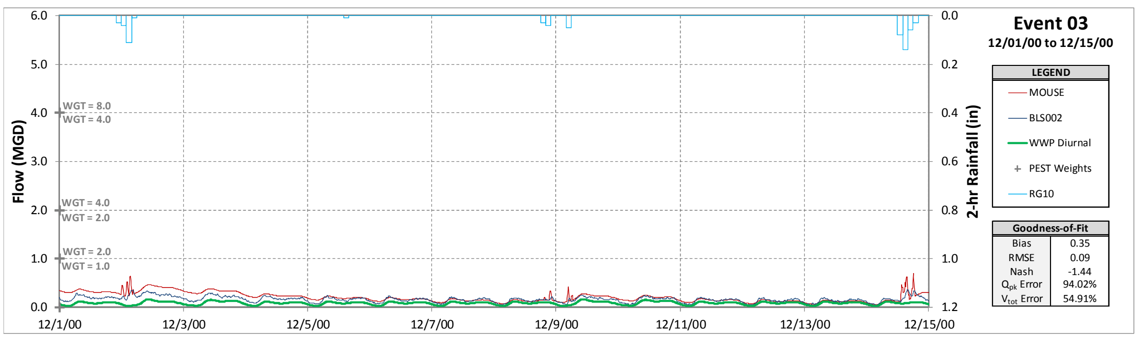


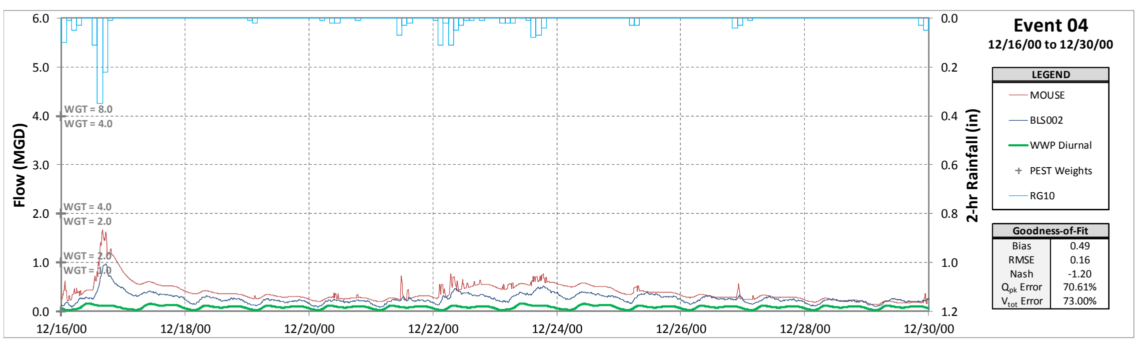


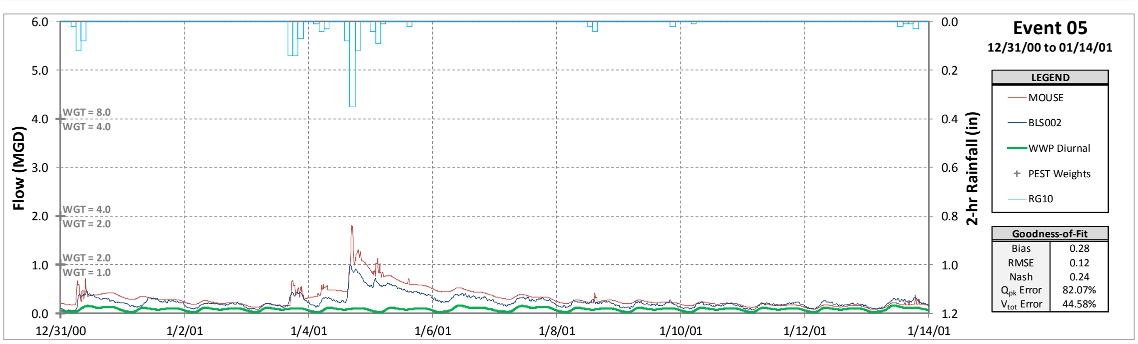
SKYWAYPILOT Post- I/I
Demonstration Project



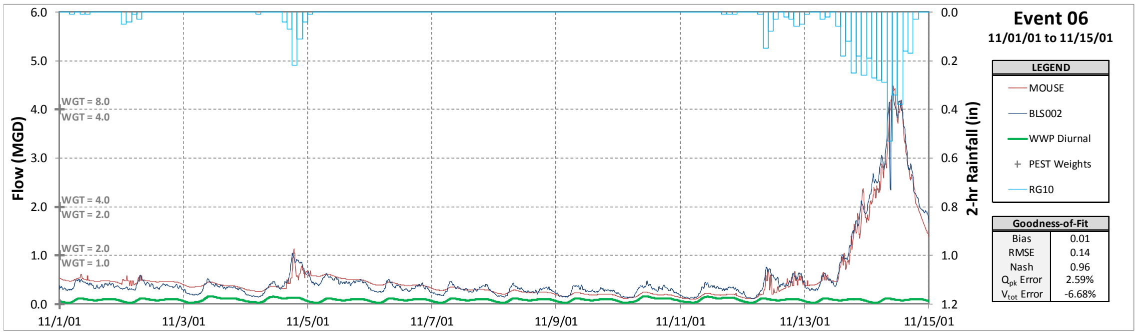








BLS002 I/I Control Program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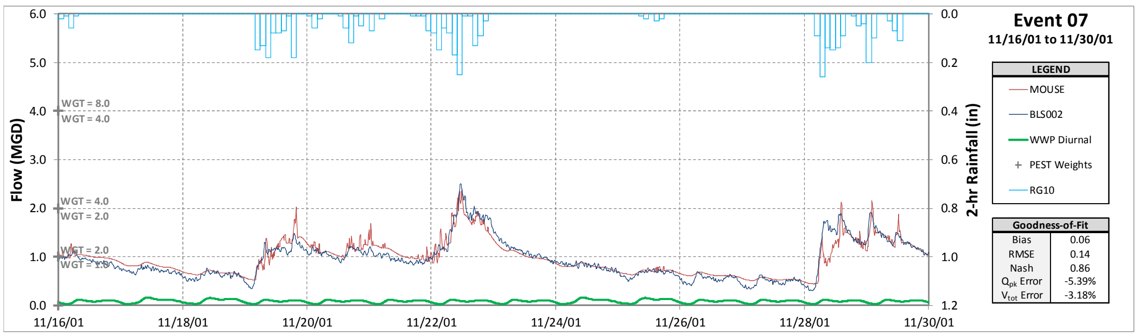
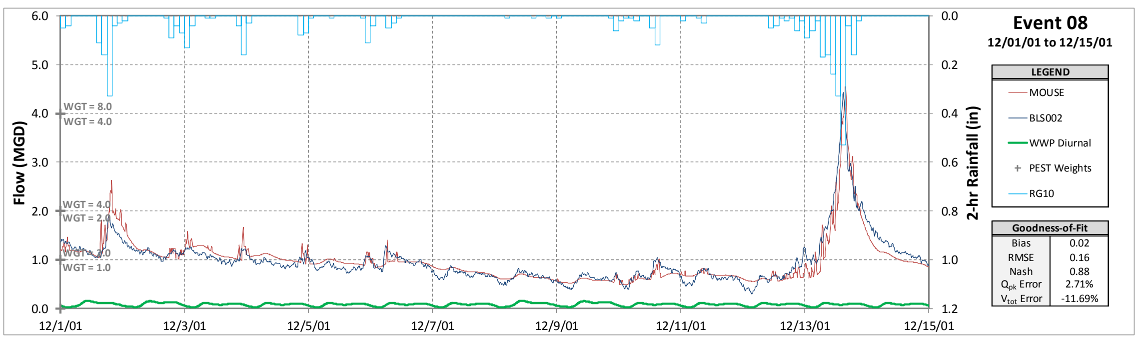
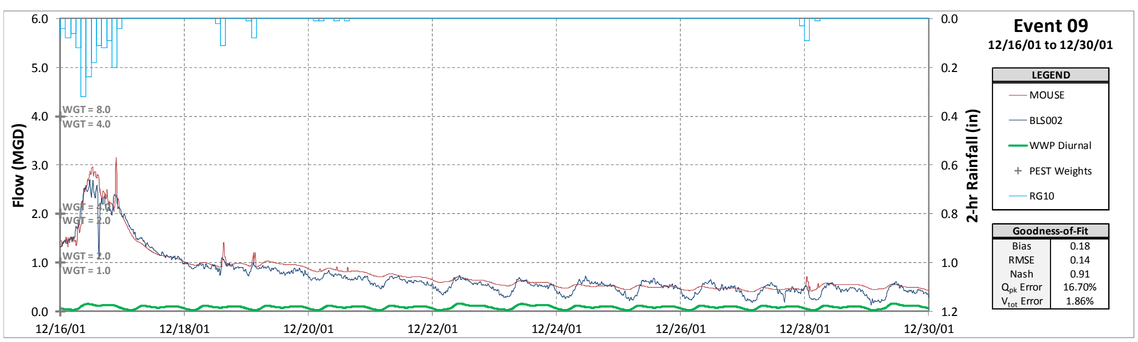
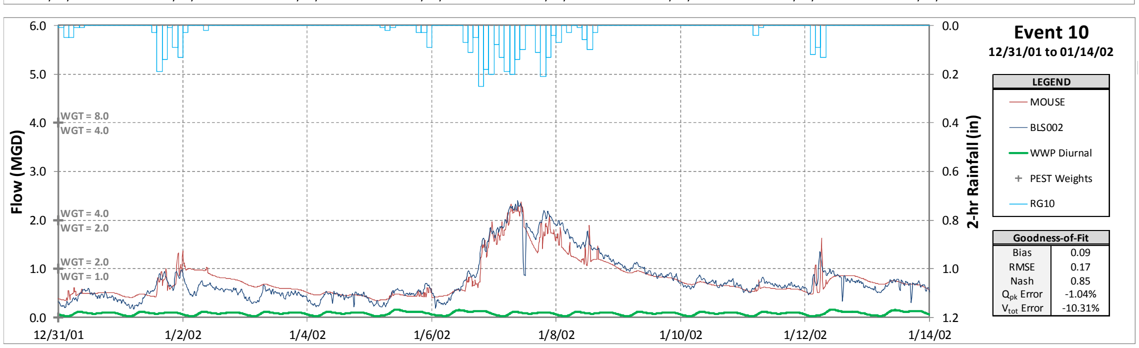
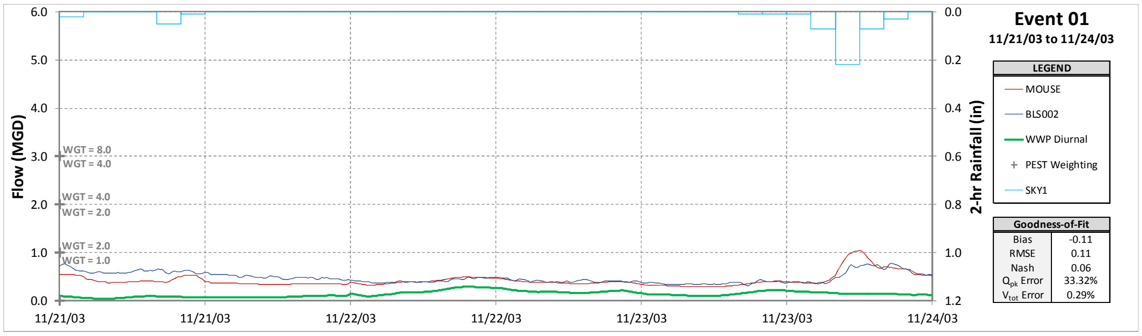
11/01/01 to 11/15/01
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
WGT = 4.0
WGT = 2.0
WGT = 2.0
WGT = 1.0
LEGEND
MOUSE
BLS002
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.01
RMSE 0.14
Nash 0.96
Q_{pk} Error 2.59%
V_{tot} Error -6.68%

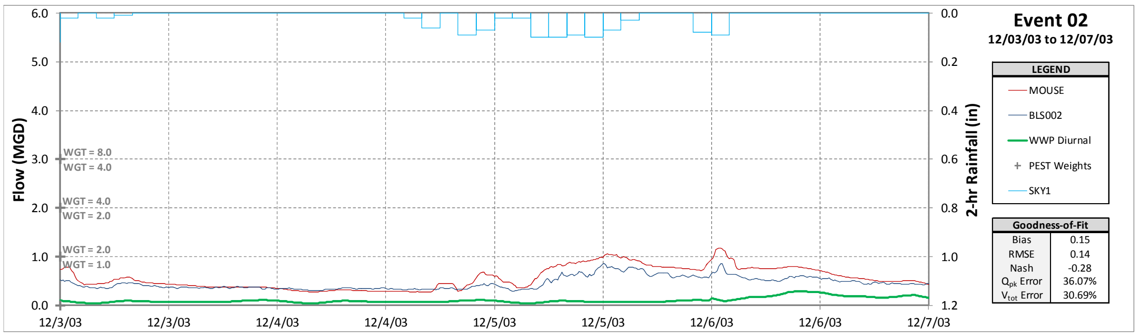

Event 07
11/16/01 to 11/30/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS002
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.06
RMSE 0.14
Nash 0.86
Q_{pk} Error -5.39%
V_{tot} Error -3.18%

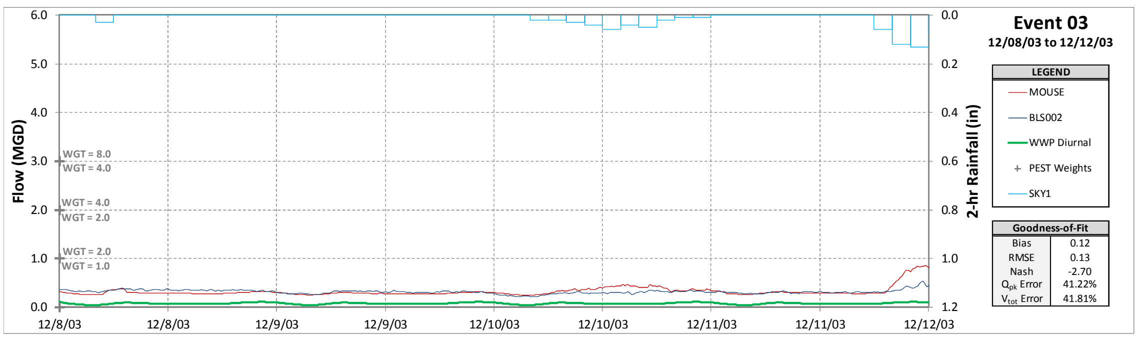

Event 08
12/01/01 to 12/15/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS002
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.02
RMSE 0.16
Nash 0.88
Q_{pk} Error 2.71%
V_{tot} Error -11.69%

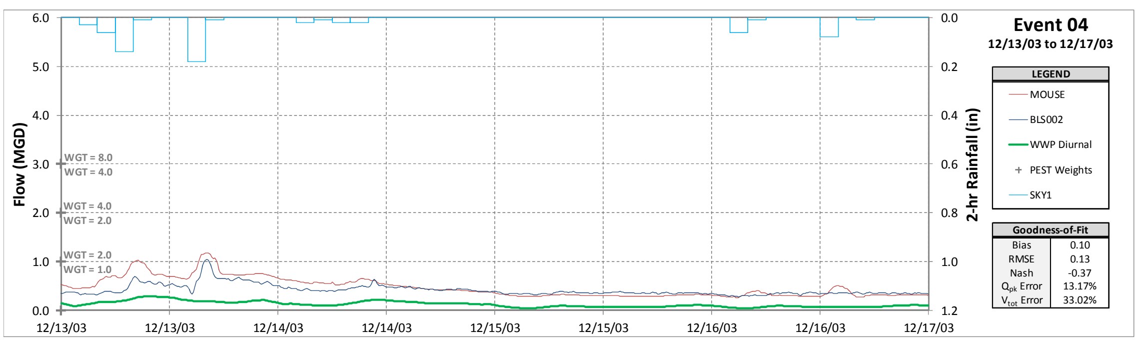

Event 09
12/16/01 to 12/30/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS002
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.18
RMSE 0.14
Nash 0.91
Q_{pk} Error 16.70%
V_{tot} Error 1.86%

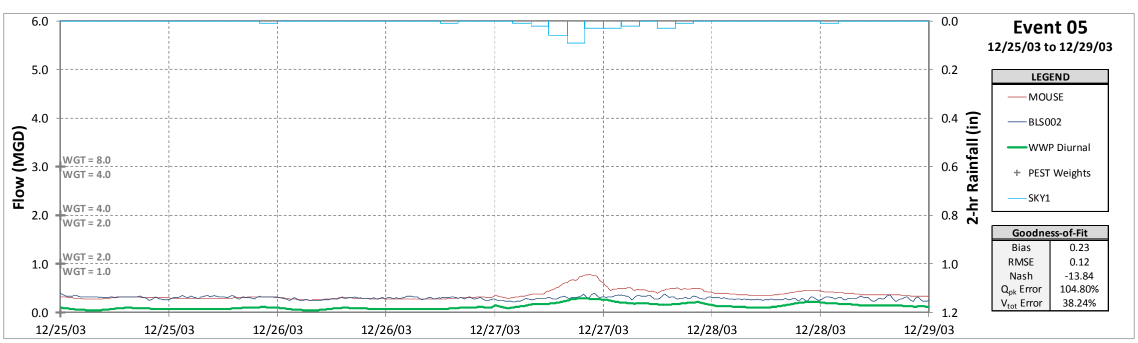

Event 10
12/31/01 to 01/14/02
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS002
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.09
RMSE 0.17
Nash 0.85
Q_{pk} Error -1.04%
V_{tot} Error -10.31%



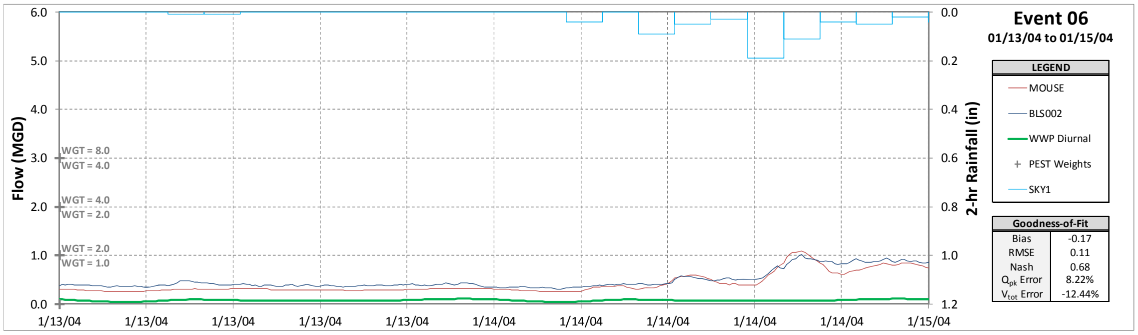


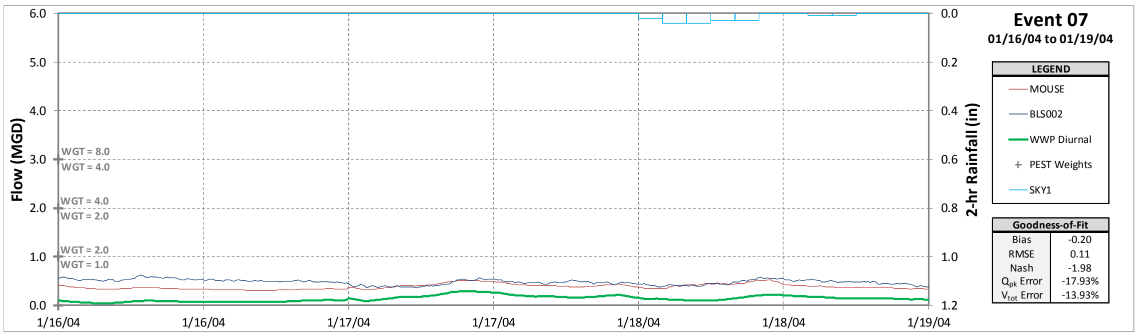


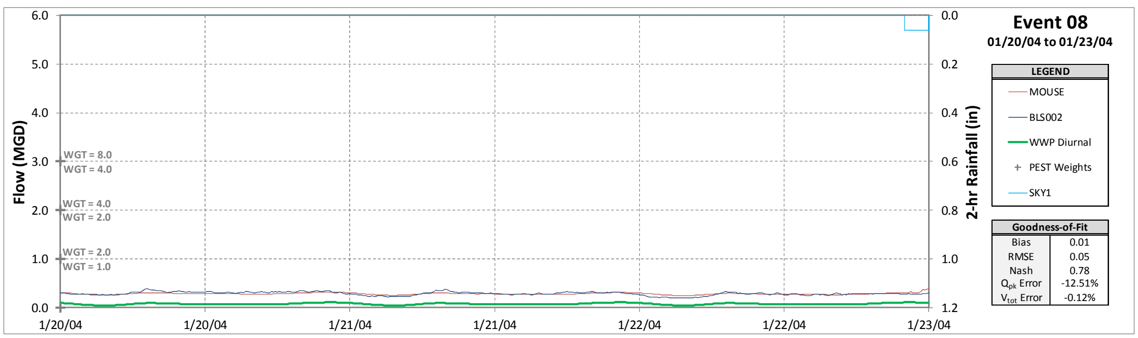


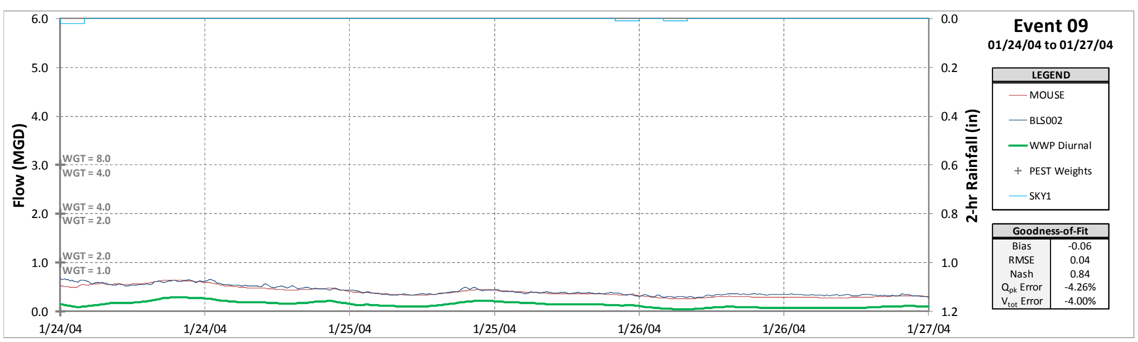


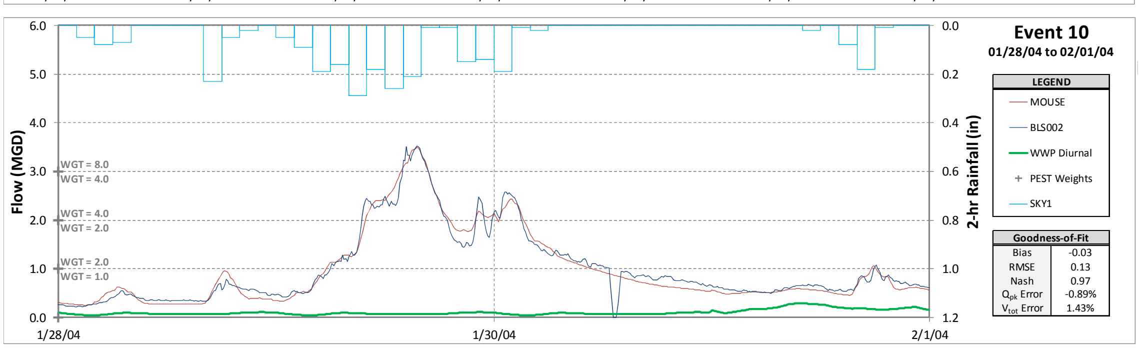
BLS002 Post- I/I Pilot Project



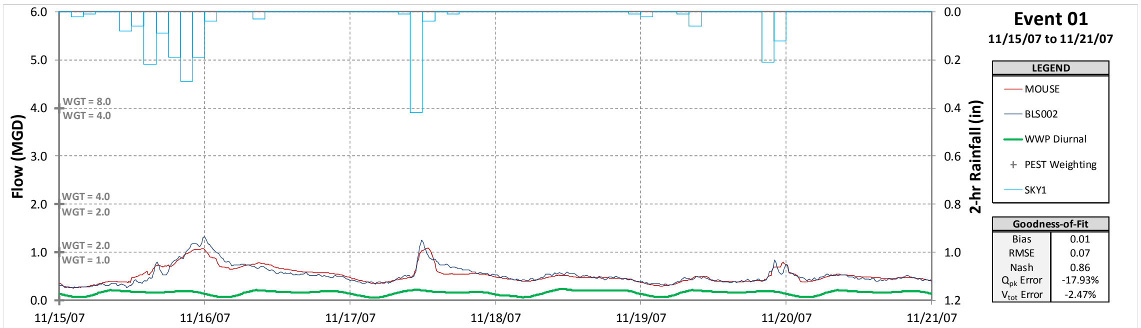


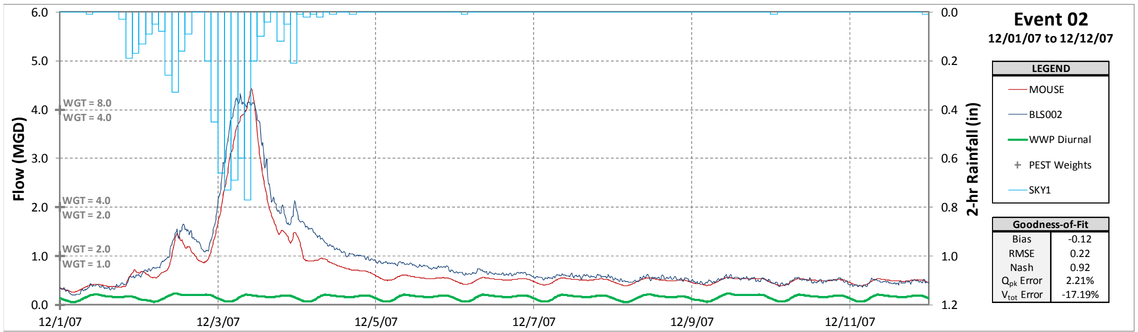


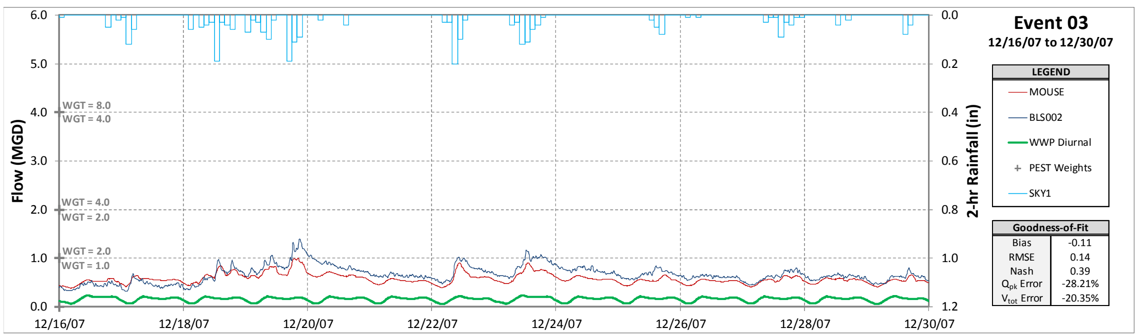


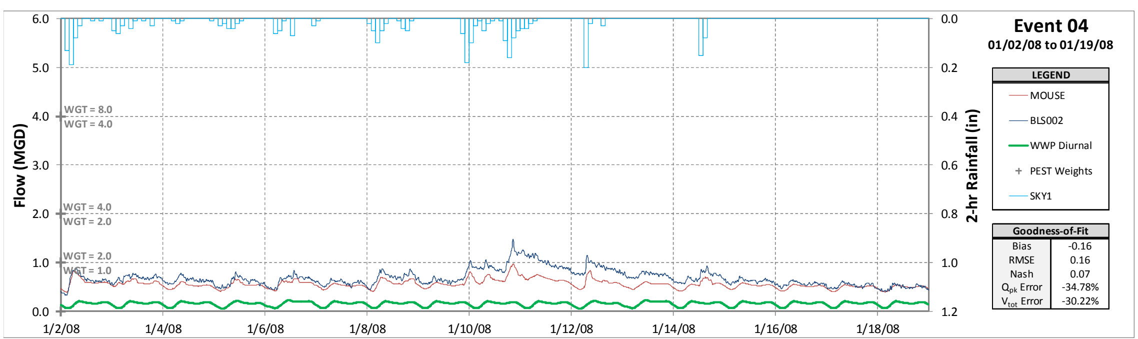


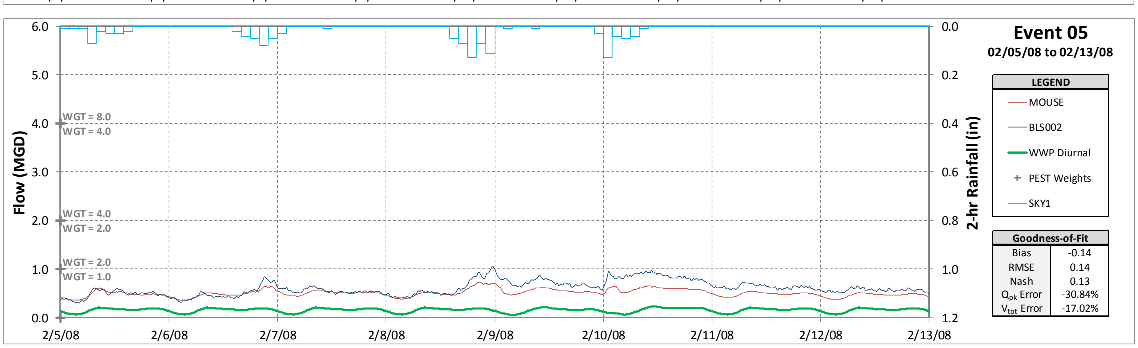
BLS002 Post- I/I Pilot Project



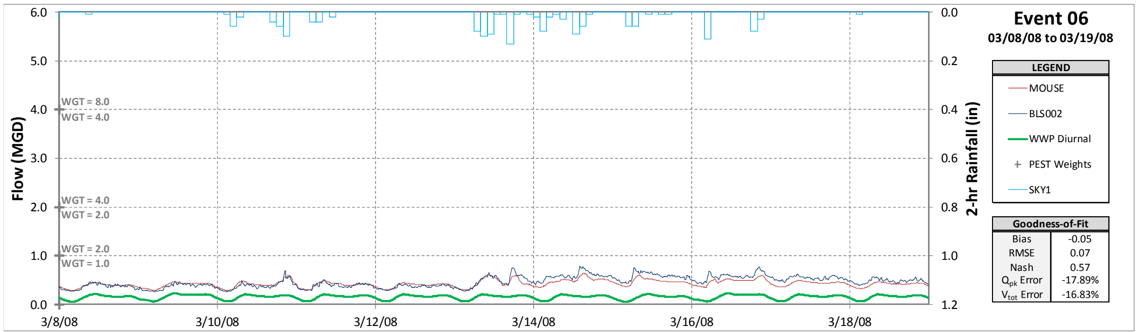


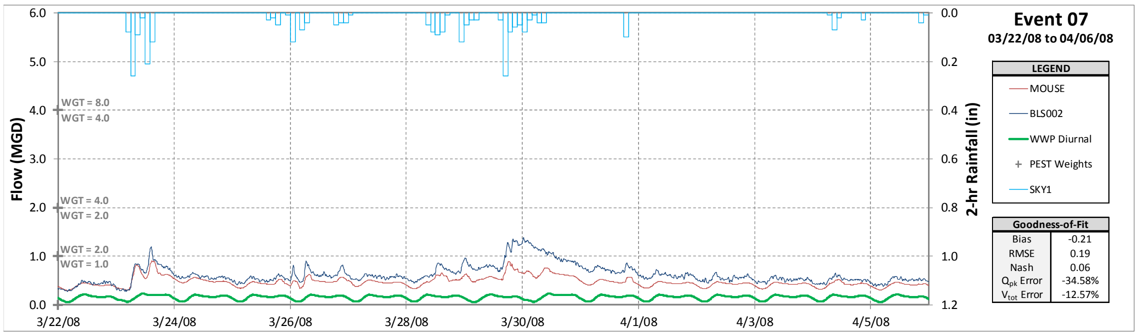


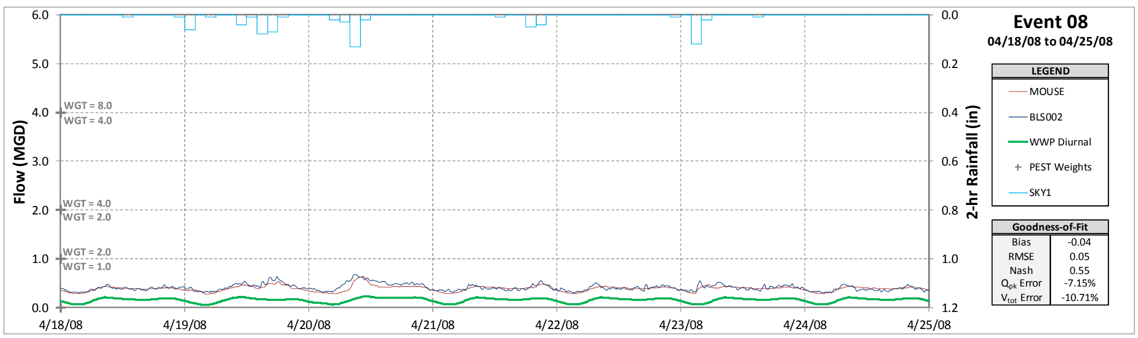


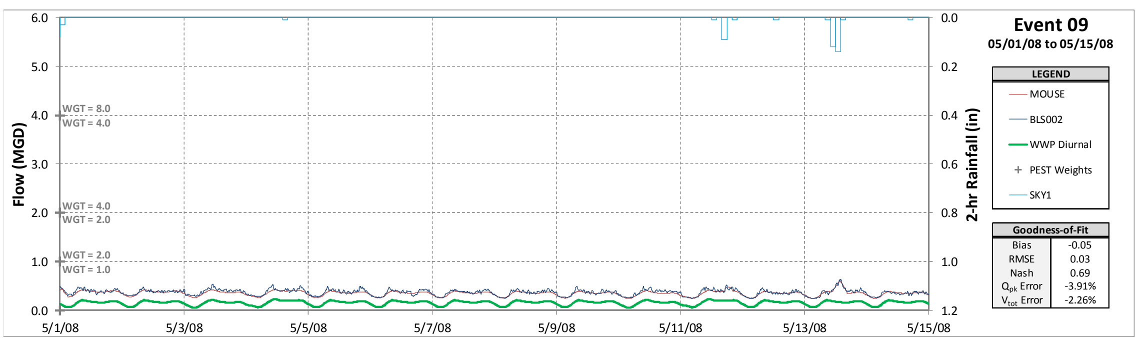


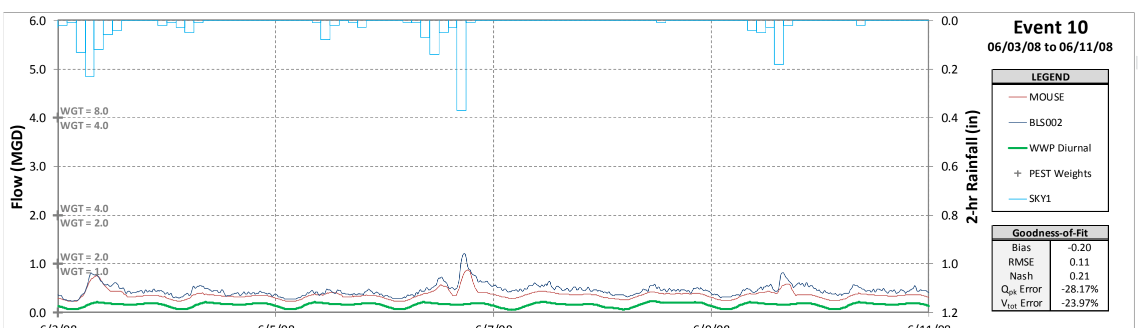
BLS002 Pre- I/I Demonstration Project



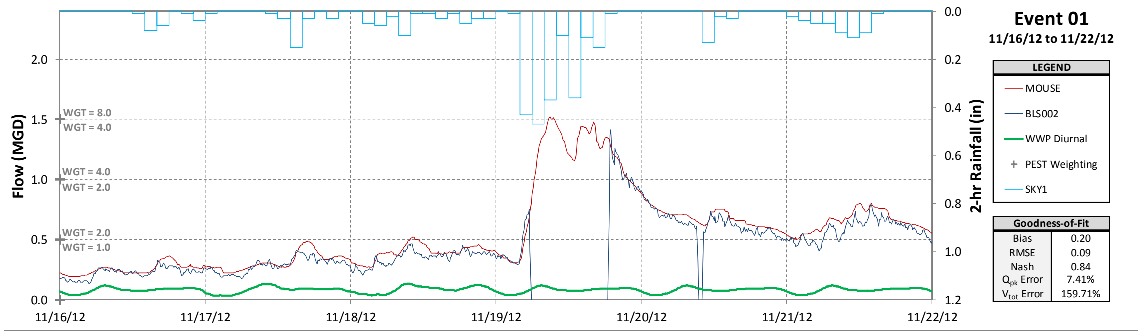


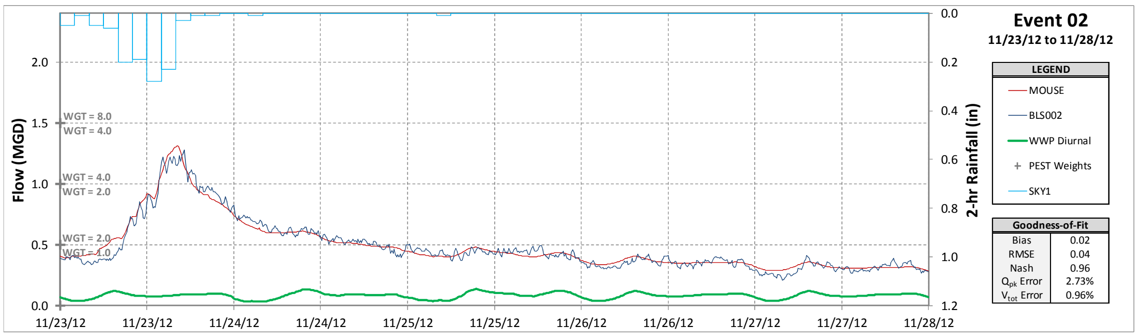


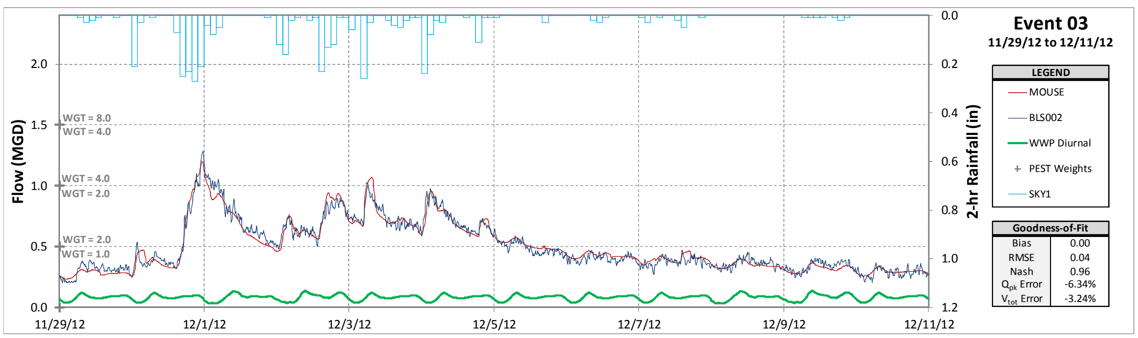


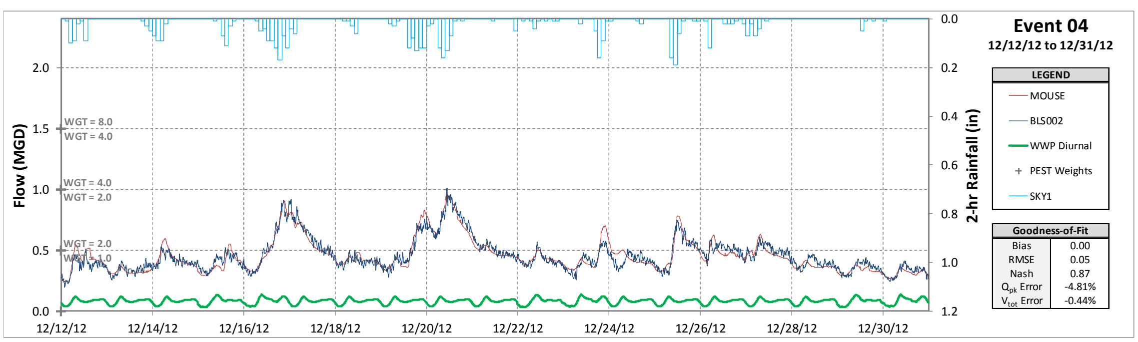


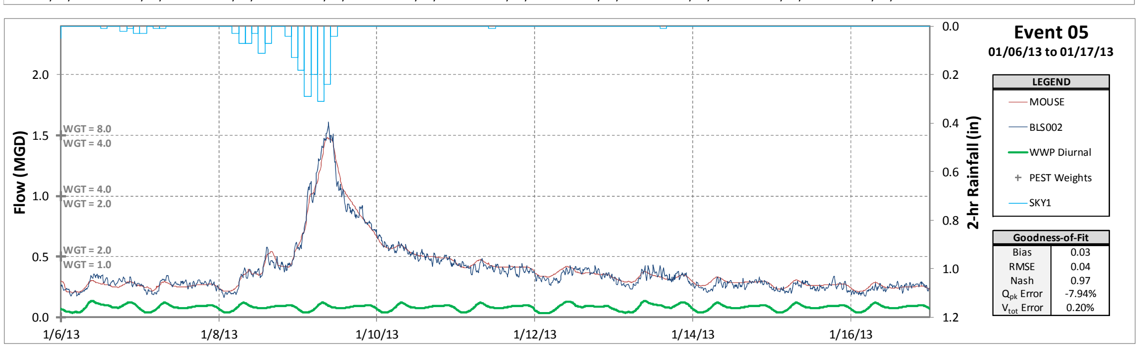
BLS002 Pre- I/I Demonstration Project



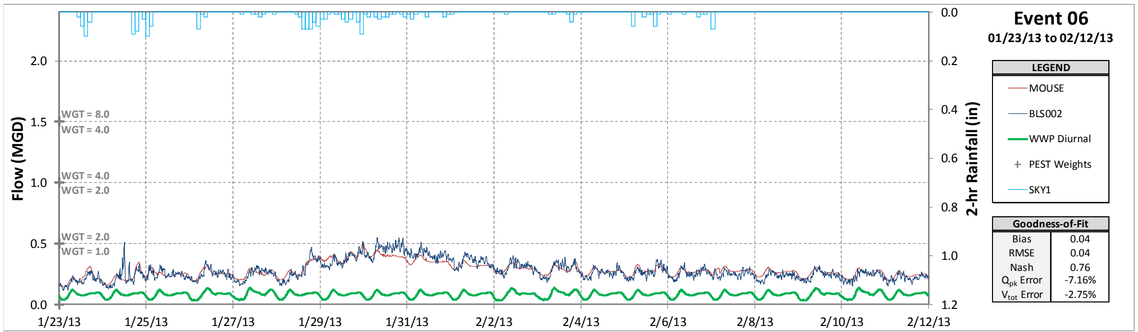


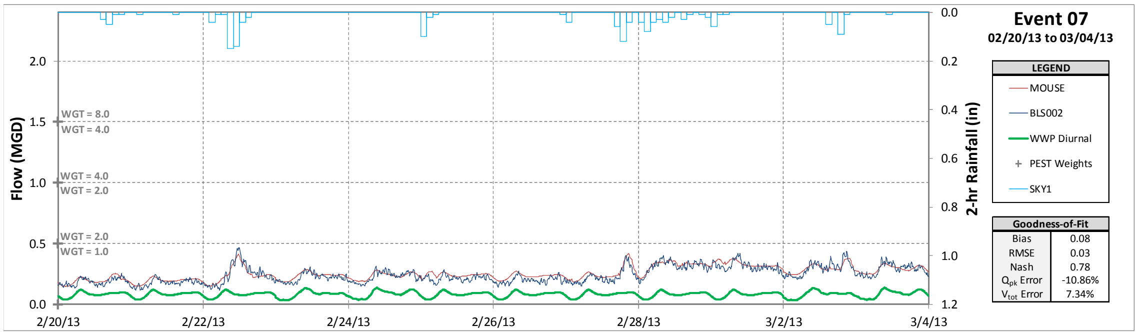


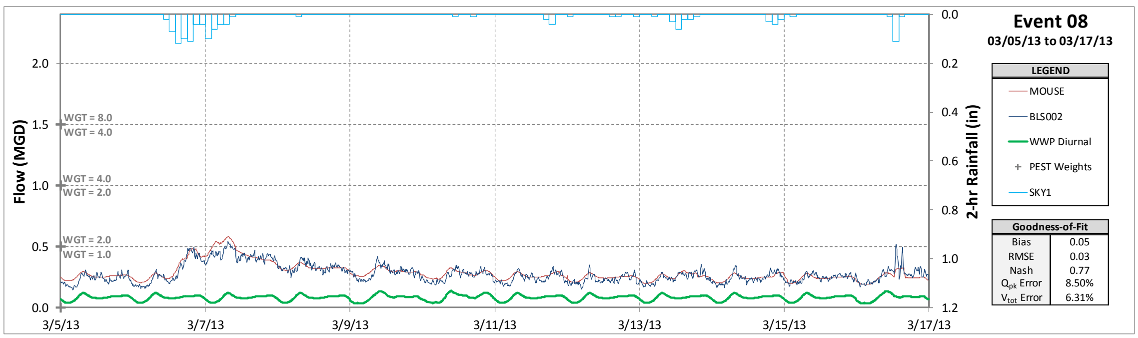


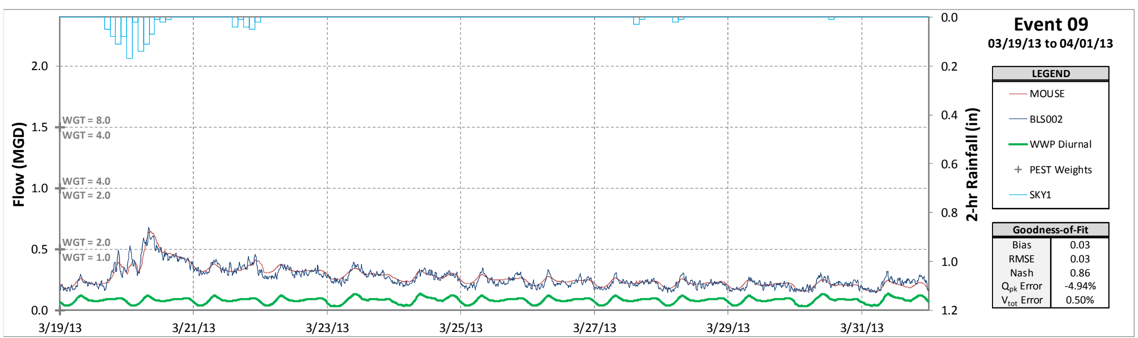


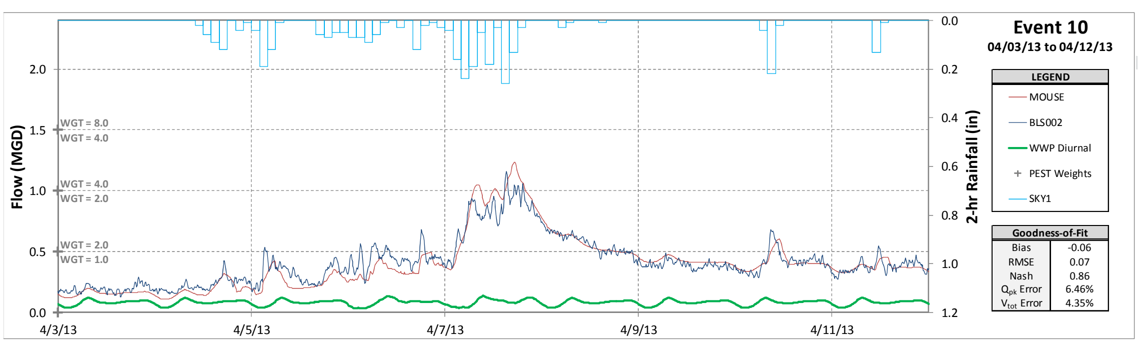
BLS002 Post- I/I Demonstration Project



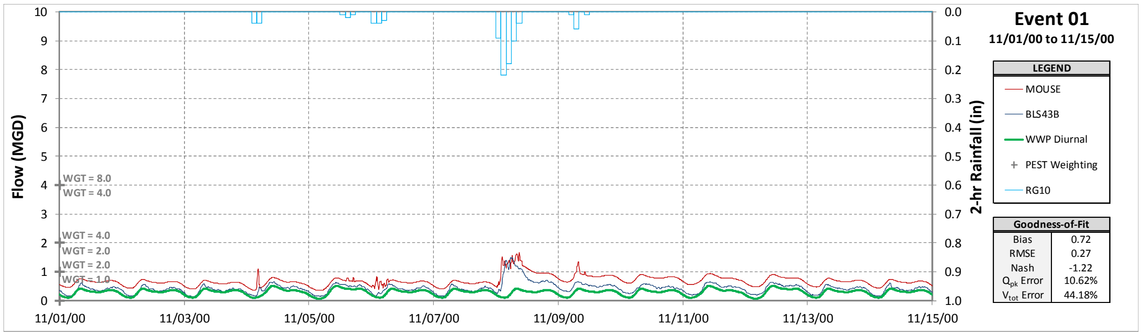


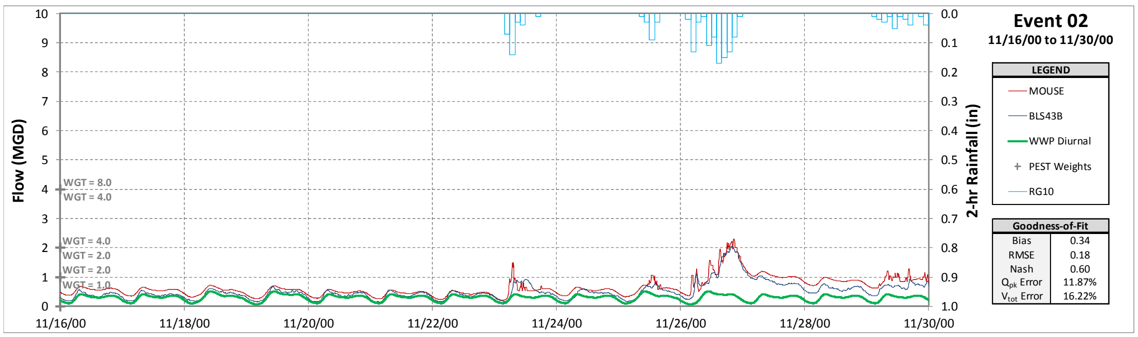


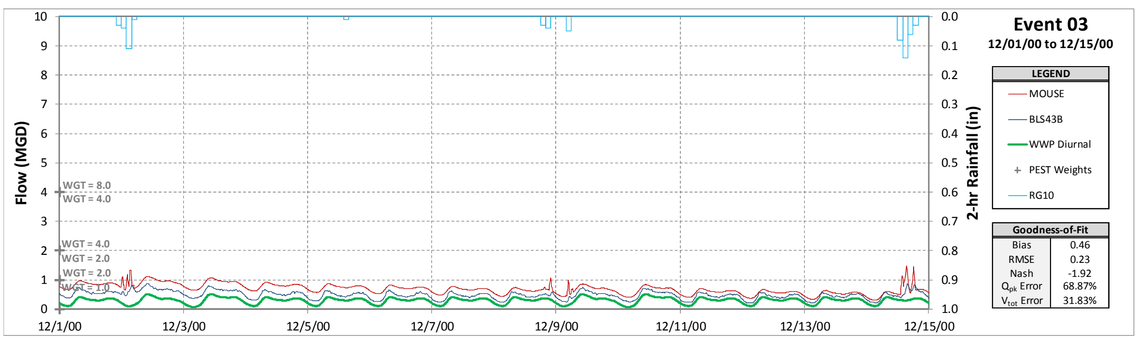


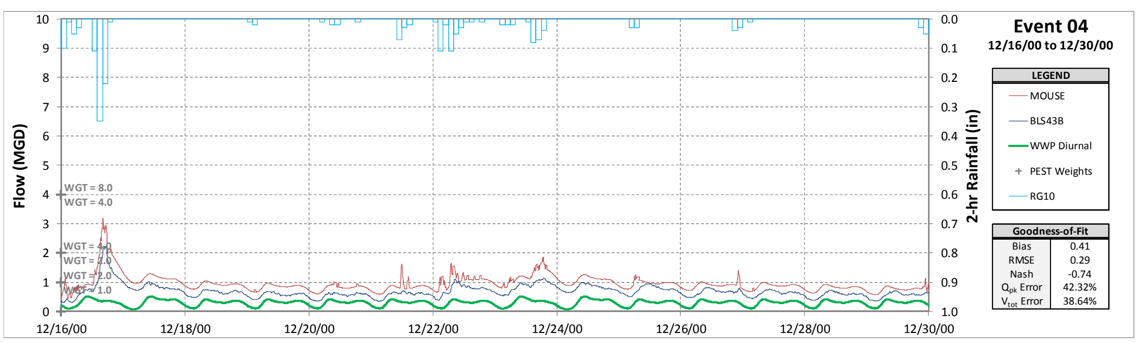


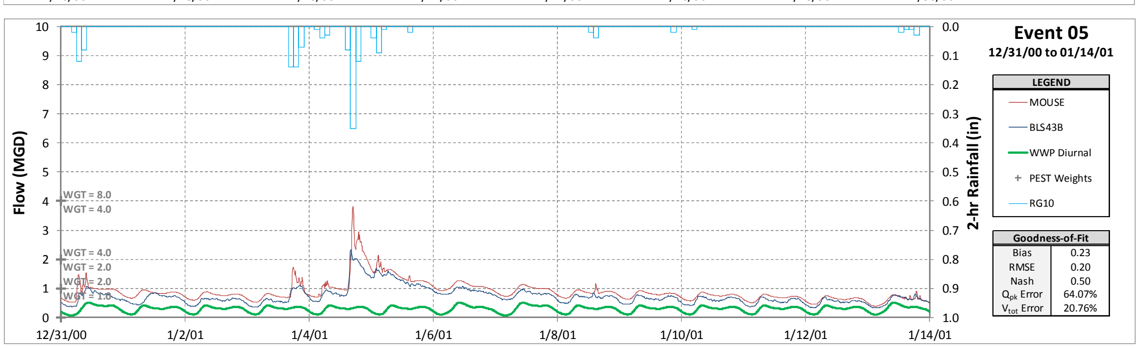
BLS002 Post- I/I Demonstration Project

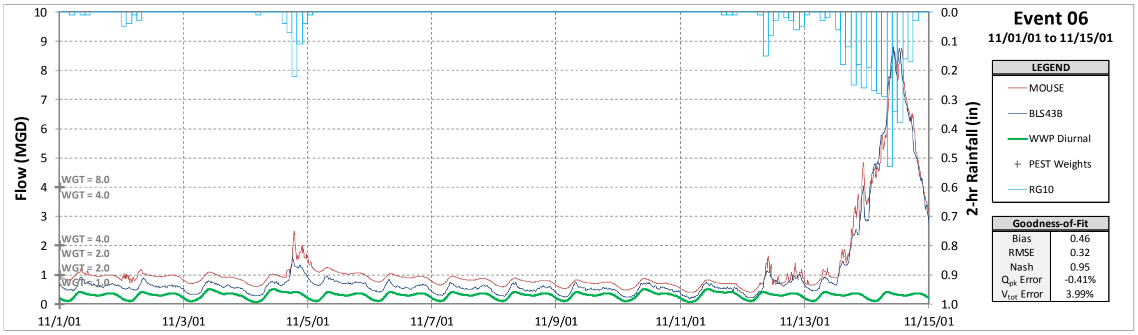

Event 01
11/01/00 to 11/15/00
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weighting
RG10
Goodness-of-Fit
Bias 0.72
RMSE 0.27
Nash -1.22
Q_{pk} Error 10.62%
V_{tot} Error 44.18%
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
WGT = 4.0
WGT = 2.0
WGT = 2.0
WGT = 1.0
11/01/00
11/03/00
11/05/00
11/07/00
11/09/00
11/11/00
11/13/00
11/15/00

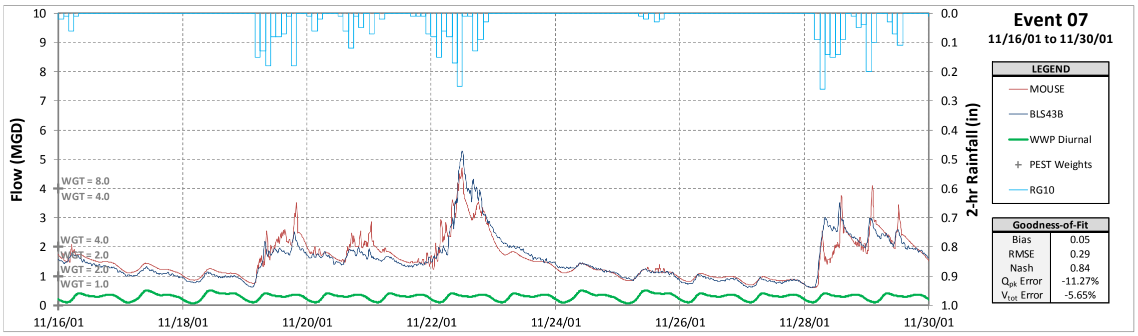

Event 02
11/16/00 to 11/30/00
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.34
RMSE 0.18
Nash 0.60
Q_{pk} Error 11.87%
V_{tot} Error 16.22%
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
WGT = 4.0
WGT = 2.0
WGT = 2.0
WGT = 1.0
11/16/00
11/18/00
11/20/00
11/22/00
11/24/00
11/26/00
11/28/00
11/30/00

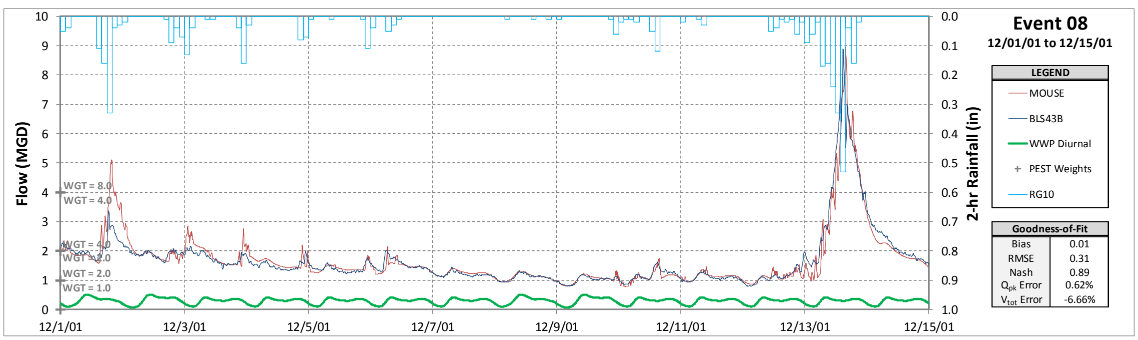

Event 03
12/01/00 to 12/15/00
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.46
RMSE 0.23
Nash -1.92
Q_{pk} Error 68.87%
V_{tot} Error 31.83%
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
WGT = 4.0
WGT = 2.0
WGT = 2.0
12/1/00
12/3/00
12/5/00
12/7/00
12/9/00
12/11/00
12/13/00
12/15/00

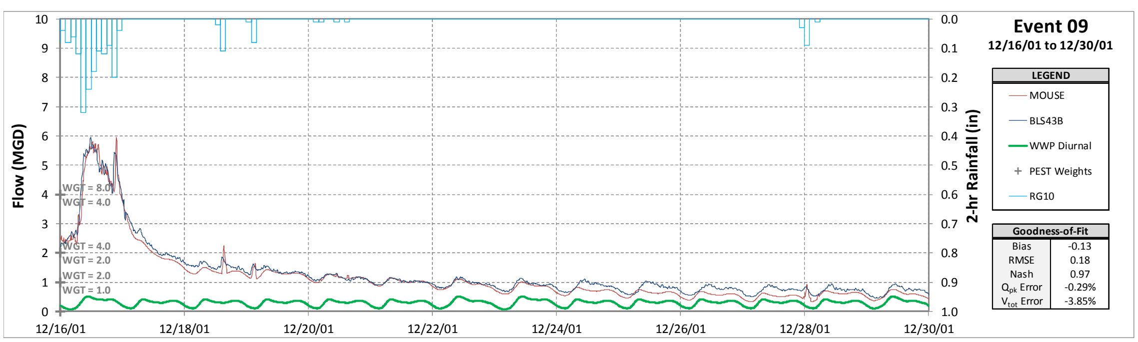

Event 04
12/16/00 to 12/30/00
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.41
RMSE 0.29
Nash -0.74
Q_{pk} Error 42.32%
V_{tot} Error 38.64%
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
12/16/00
12/18/00
12/20/00
12/22/00
12/24/00
12/26/00
12/28/00
12/30/00

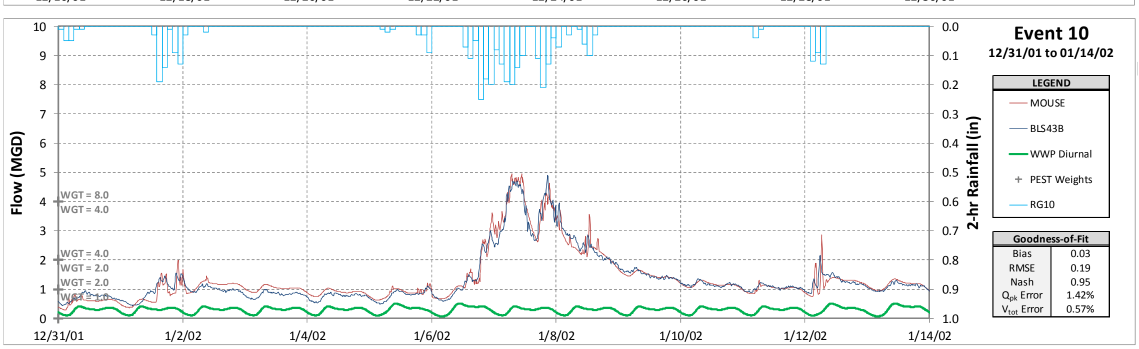

Event 05
12/31/00 to 01/14/01
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.23
RMSE 0.20
Nash 0.50
Q_{pk} Error 64.07%
V_{tot} Error 20.76%
Flow (MGD)
2-hr Rainfall (in)
WGT = 8.0
WGT = 4.0
WGT = 4.0
WGT = 2.0
12/31/00
1/2/01
1/4/01
1/6/01
1/8/01
1/10/01
1/12/01
1/14/01

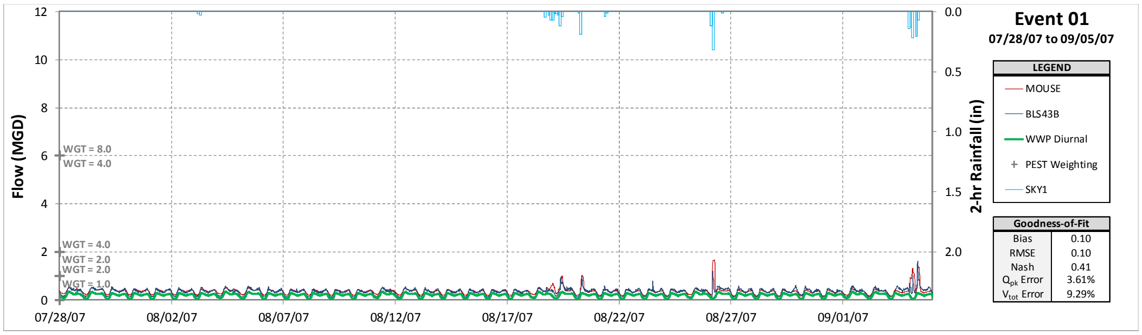

Event 06
11/01/01 to 11/15/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.46
RMSE 0.32
Nash 0.95
Q_{pk} Error -0.41%
V_{tot} Error 3.99%

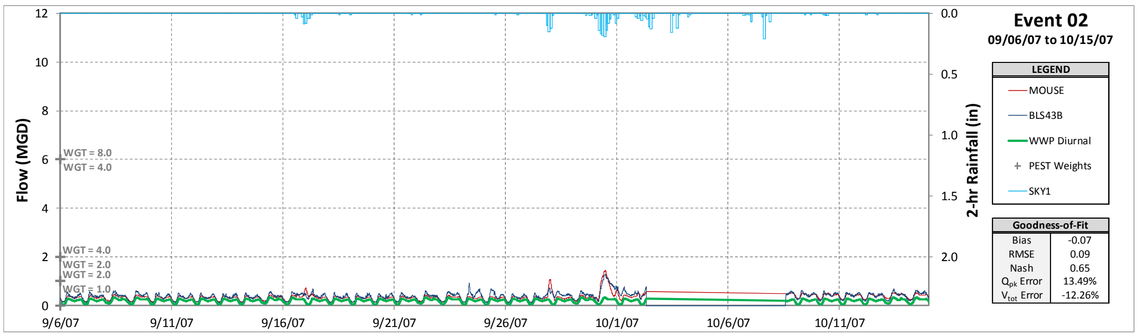

Event 07
11/16/01 to 11/30/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.05
RMSE 0.29
Nash 0.84
Q_{pk} Error -11.27%
V_{tot} Error -5.65%

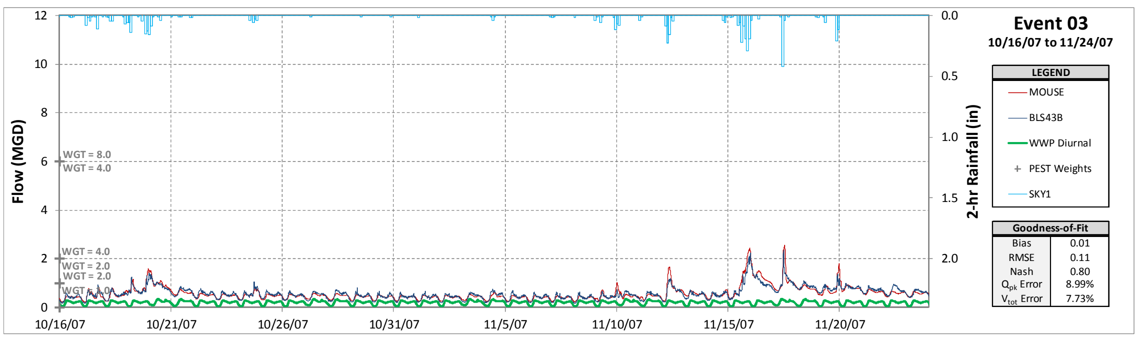

Event 08
12/01/01 to 12/15/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.01
RMSE 0.31
Nash 0.89
Q_{pk} Error 0.62%
V_{tot} Error -6.66%

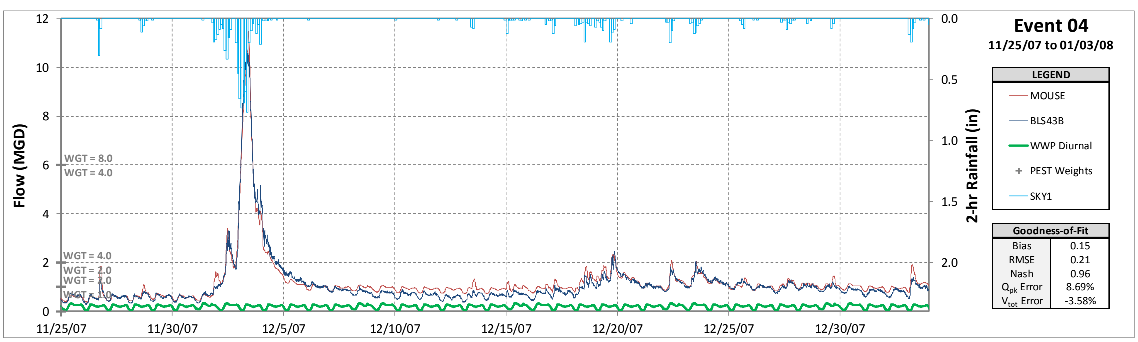

Event 09
12/16/01 to 12/30/01
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias -0.13
RMSE 0.18
Nash 0.97
Q_{pk} Error -0.29%
V_{tot} Error -3.85%

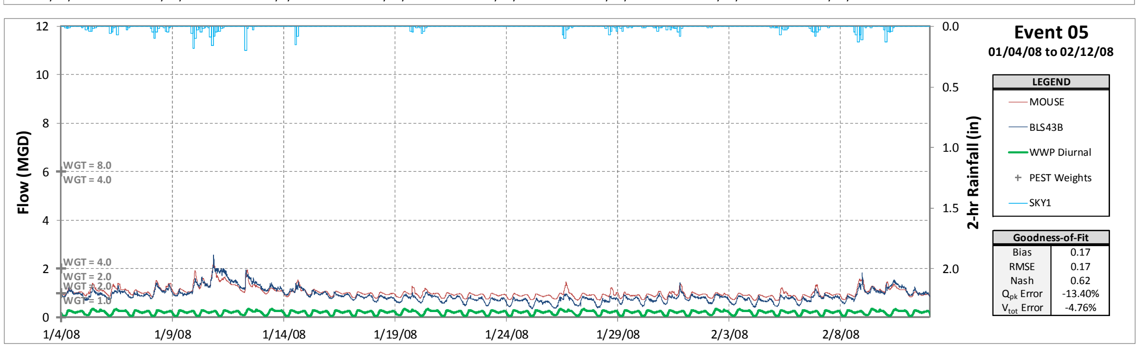

Event 10
12/31/01 to 01/14/02
Flow (MGD)
2-hr Rainfall (in)
LEGEND
MOUSE
BLS43B
WWP Diurnal
PEST Weights
RG10
Goodness-of-Fit
Bias 0.03
RMSE 0.19
Nash 0.95
Q_{pk} Error 1.42%
V_{tot} Error 0.57%



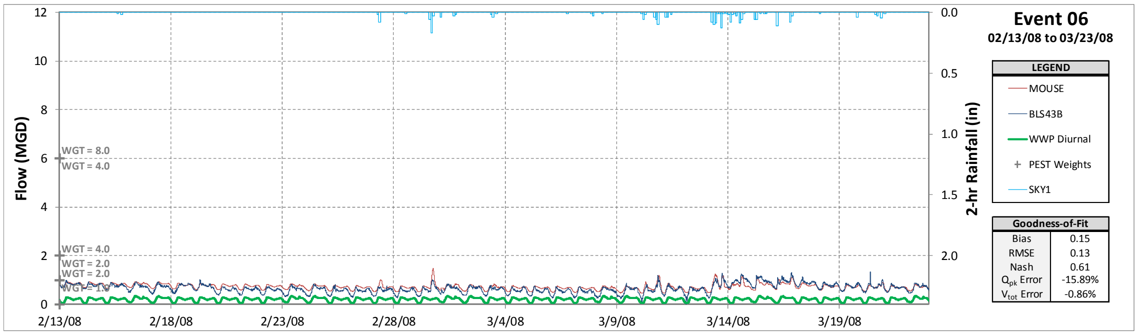


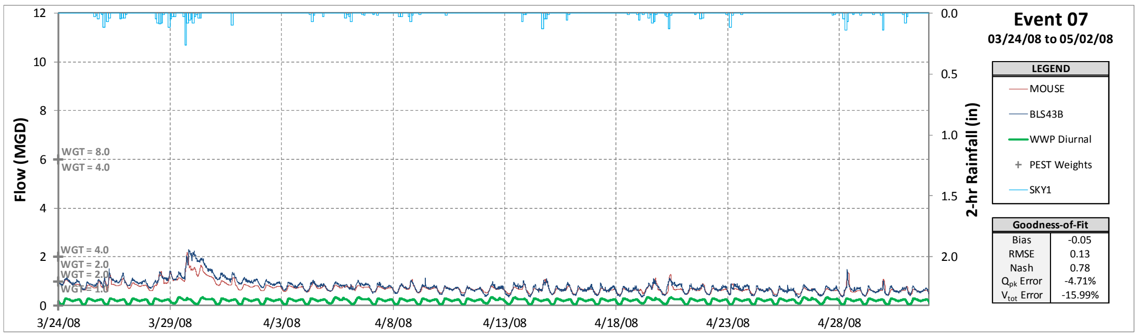


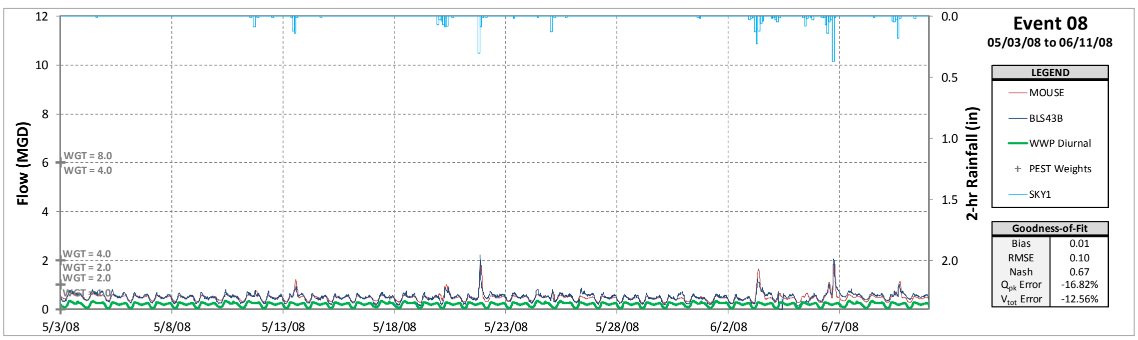


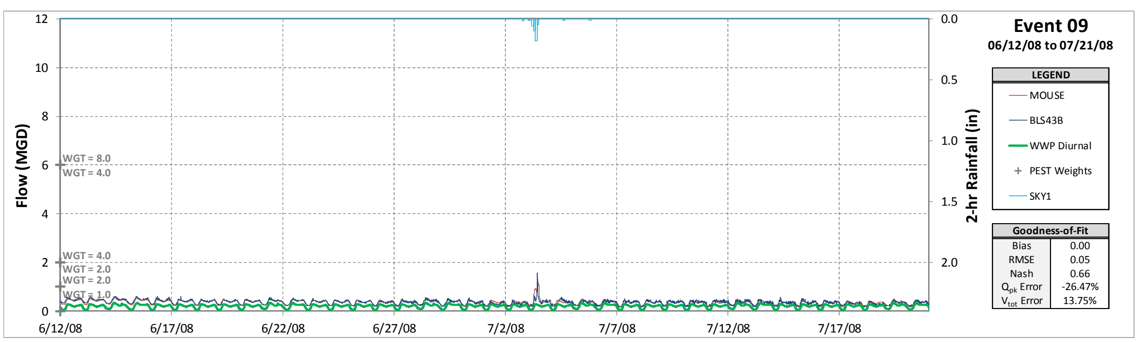


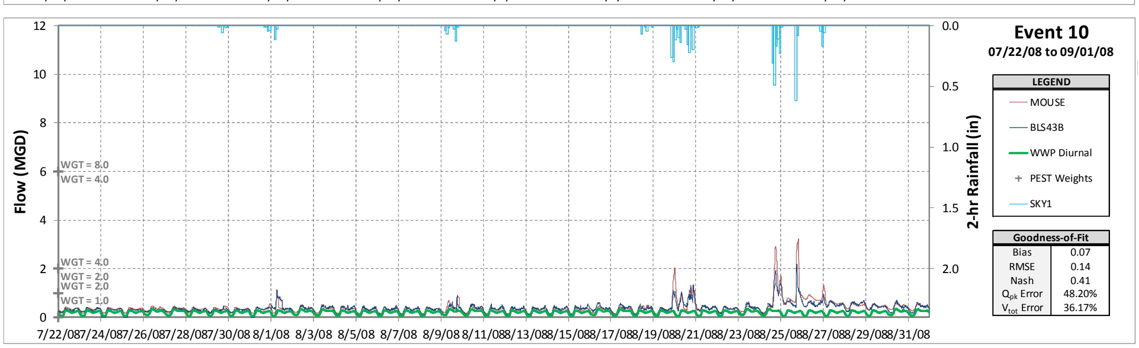
BLS43B Pre- I/I Demonstration Project



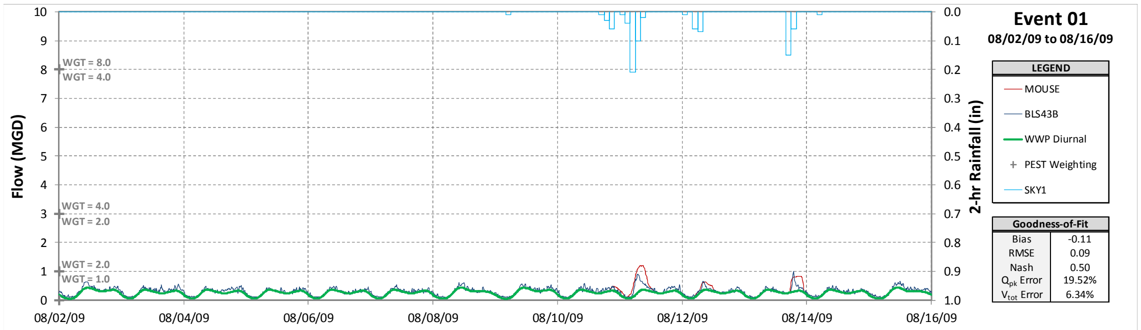


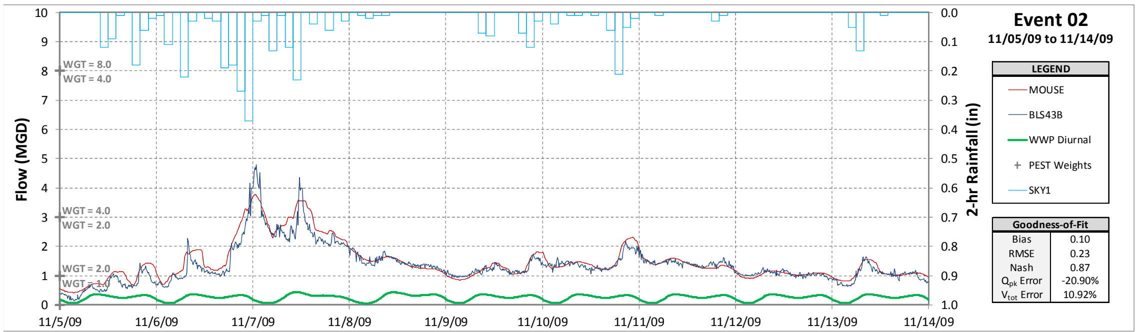


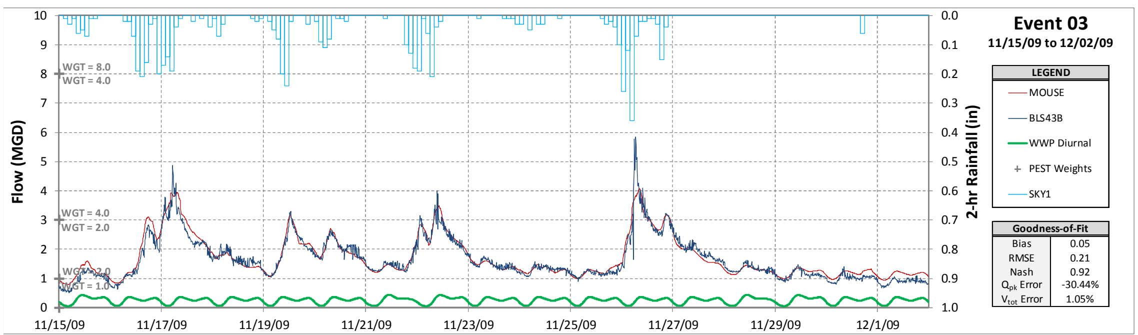


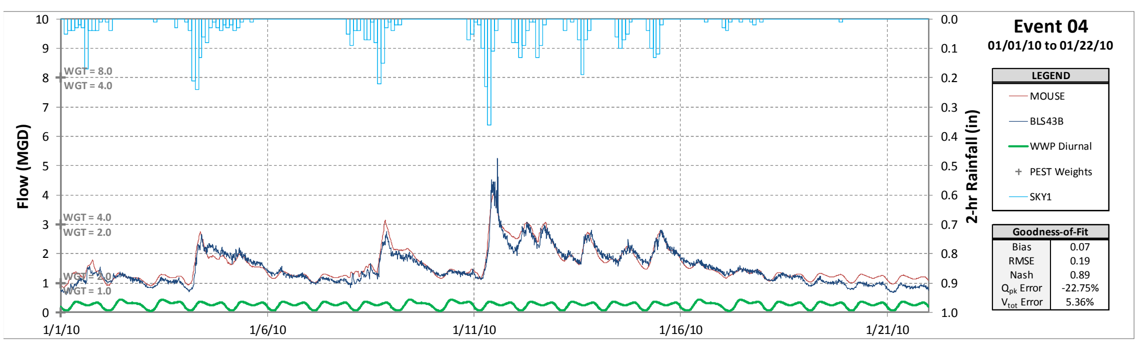


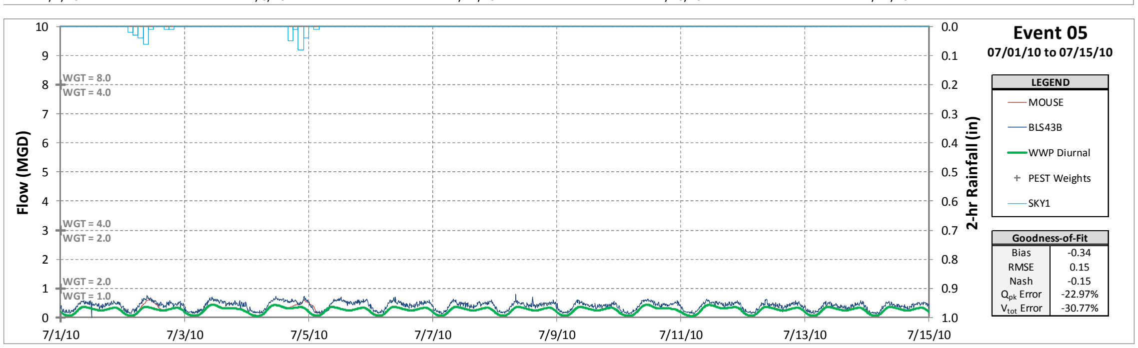
BLS43B Pre- I/I Demonstration Project



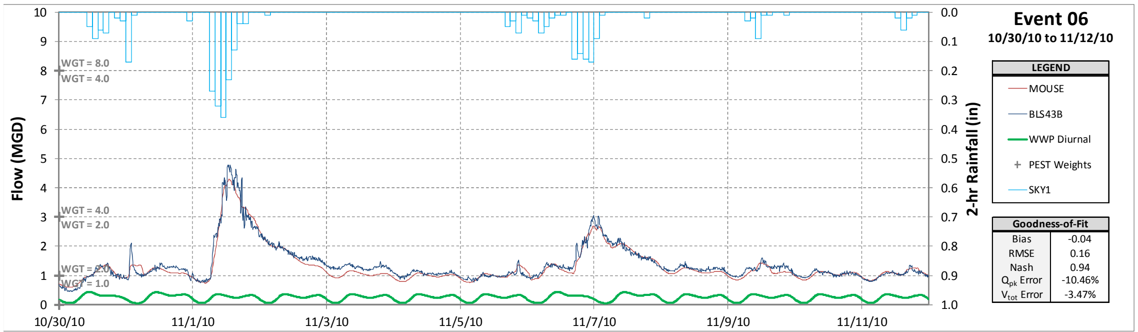






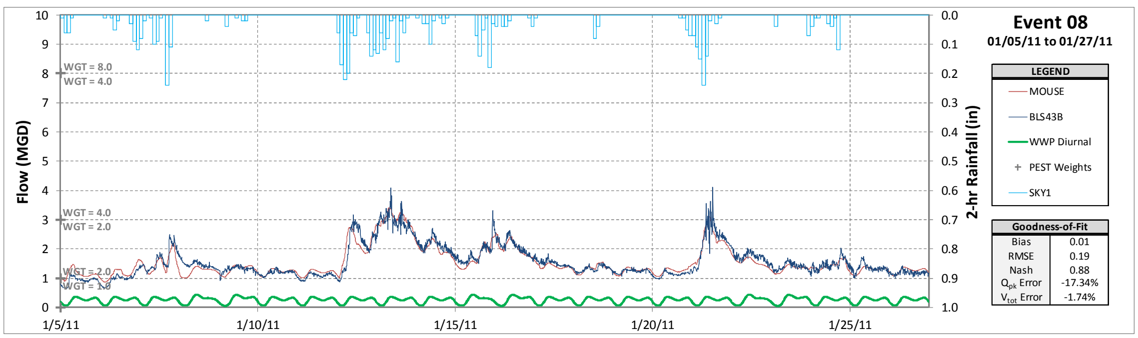


BLS43B Decennial Flow Monitoring

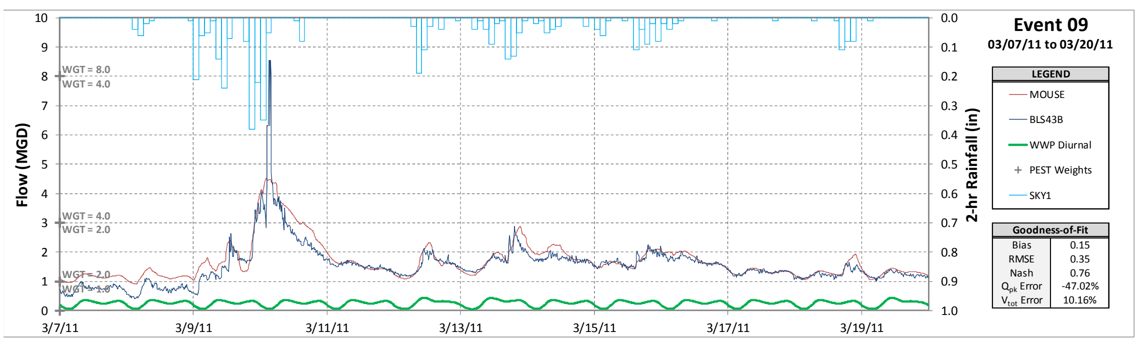


Goodness-of-Fit	
Bias	-0.04
RMSE	0.16
Nash	0.94
Q_{pk} Error	-10.46%
V_{tot} Error	-3.47%

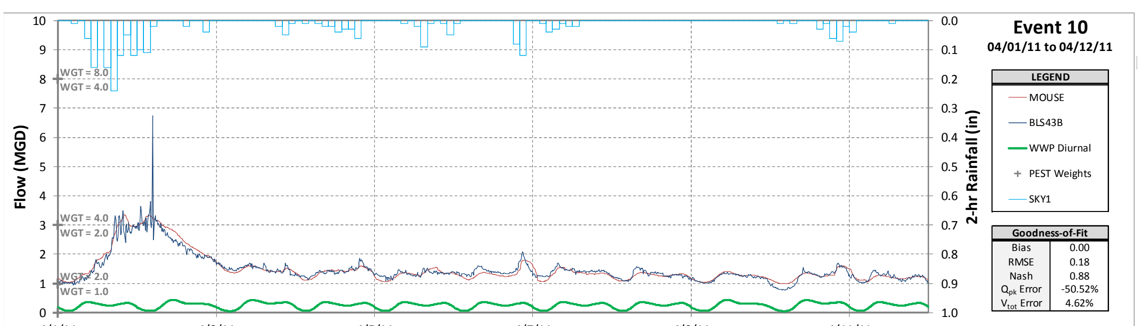
Goodness-of-Fit	
Bias	0.08
RMSE	0.33
Nash	0.96
Q_{pk} Error	5.90%
V_{tot} Error	2.30%



Goodness-of-Fit	
Bias	0.01
RMSE	0.19
Nash	0.88
Q_{pk} Error	-17.34%
V_{tot} Error	-1.74%

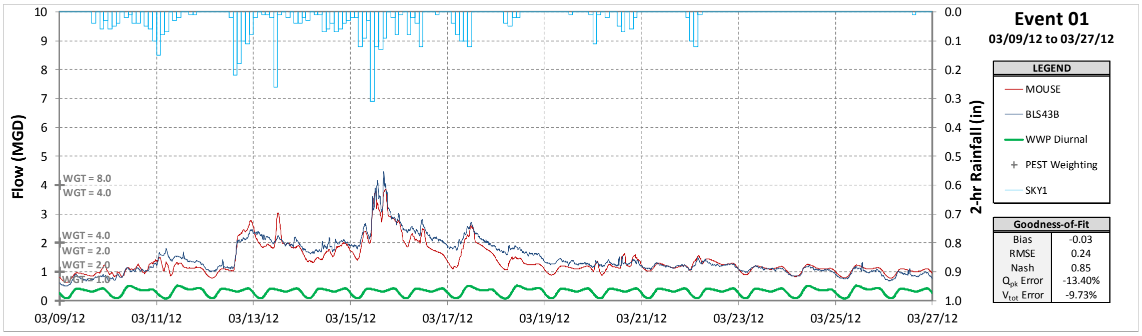


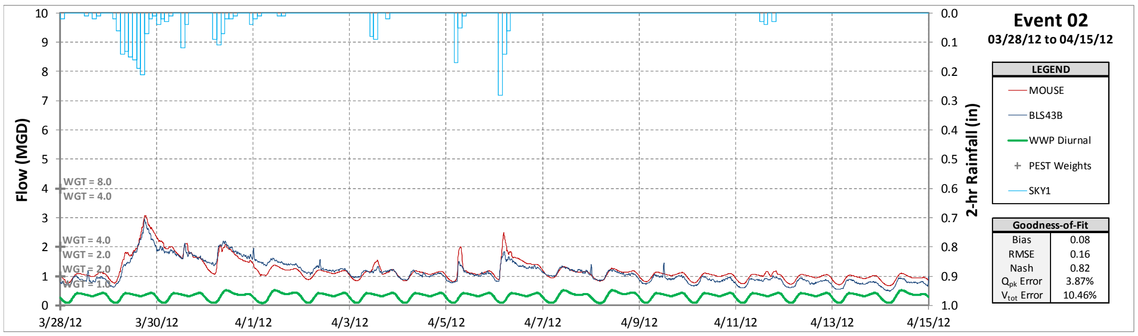
Goodness-of-Fit	
Bias	0.15
RMSE	0.35
Nash	0.76
Q_{pk} Error	-47.02%
V_{tot} Error	10.16%

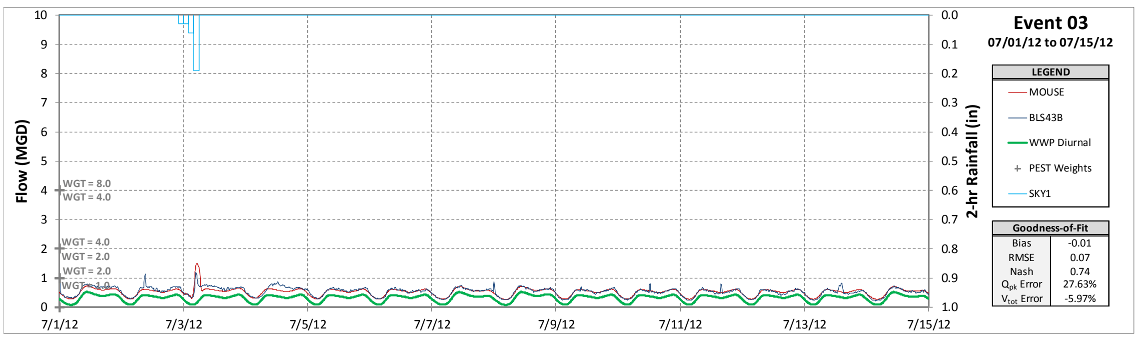


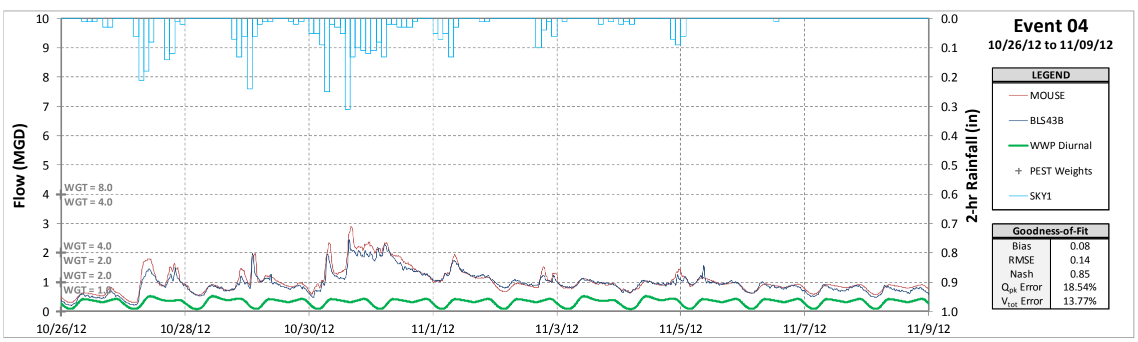
Goodness-of-Fit	
Bias	0.00
RMSE	0.18
Nash	0.88
Q_{pk} Error	-50.52%
V_{tot} Error	4.62%

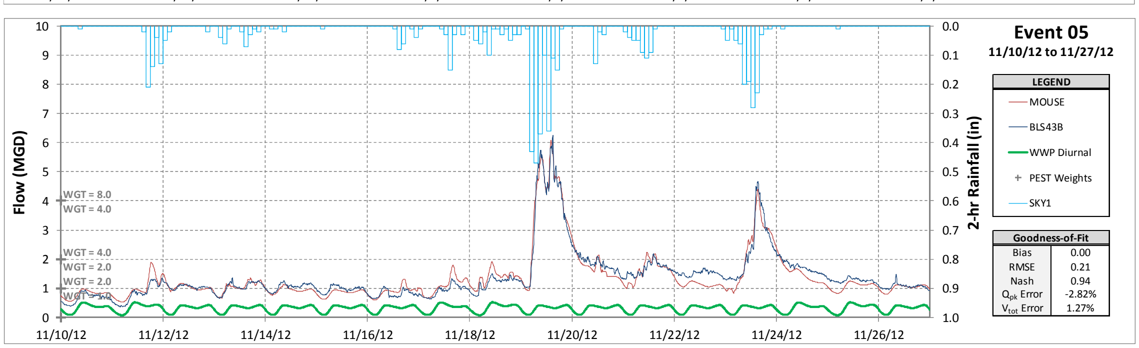
BLS43B Decennial Flow Monitoring



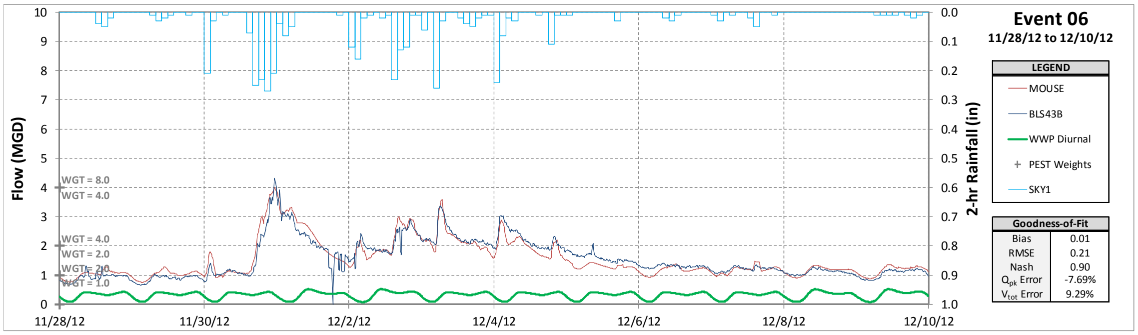


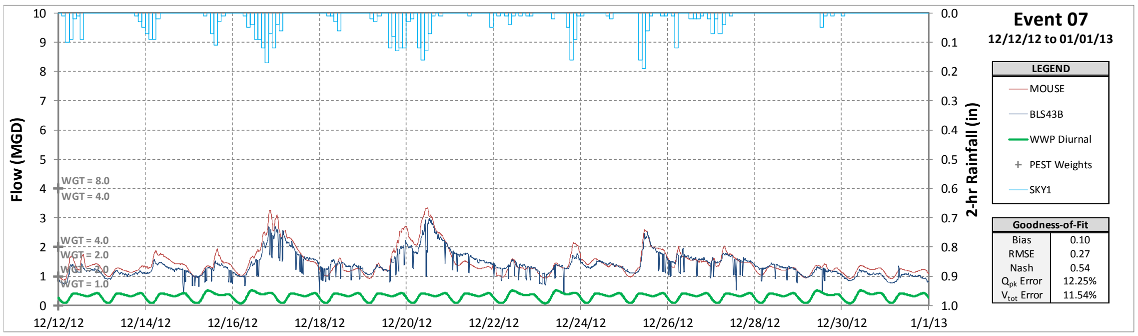


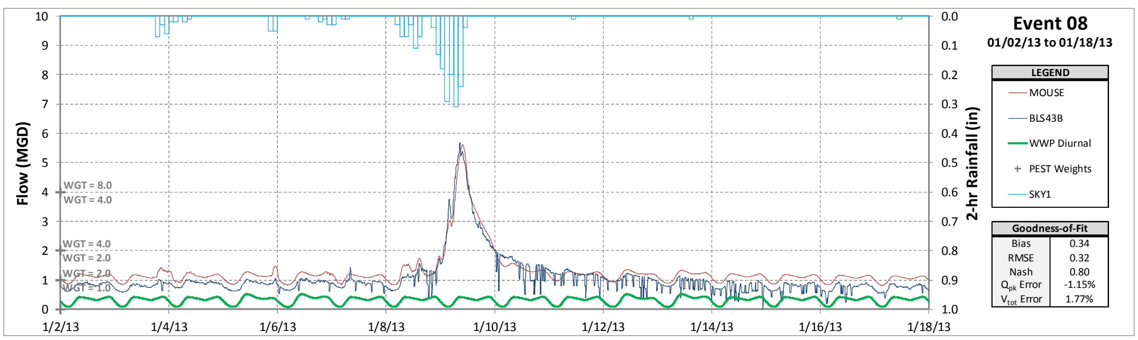


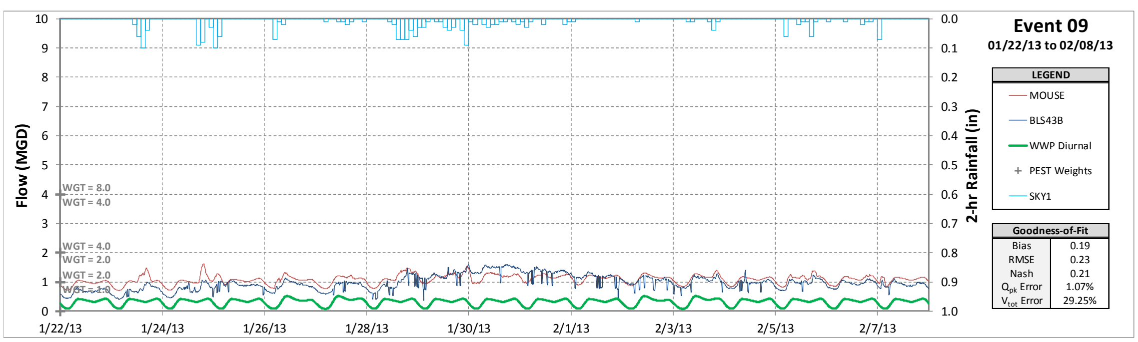


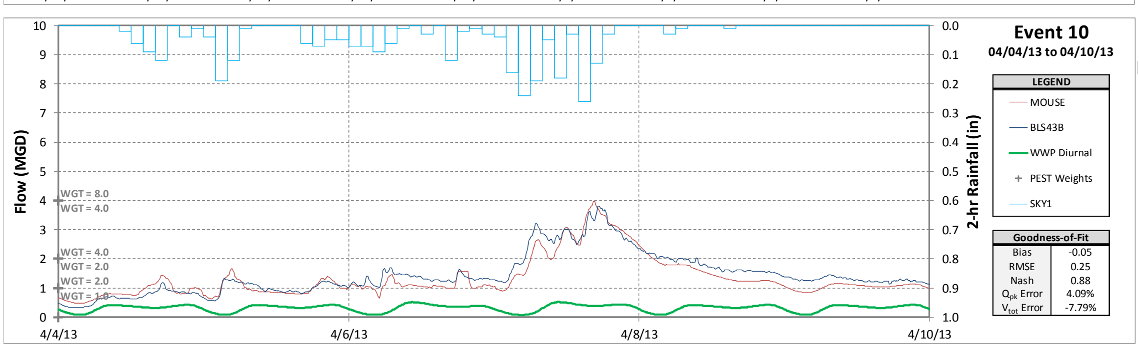
BLS43B Post- I/I Demonstration Project











BLS43B Post- I/I Demonstration Project

ATTACHMENT 4.
CALIBRATED MODEL PARAMETERS

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Table D-1 Calibrated Hydrologic Parameters by Basin and Monitoring Effort

Basin / Monitoring Effort	**AFLOW** *cfs*	**RDII_AREA** *%*	**A_IAREA** *%*	**A_CTIME** *hr*	**UMAX** *in*	**LMAX** *in*	**CQOF**	**CK** *hr*	**CKIF** *hr*	**CKBF** *hr*	**GW_CAREA**
Skyway Control											
Pre- I/I Pilot Project	0.00	55.8	4.3	173	0.48	4.09	0.123	1.5	12	10	0.26
Post- I/I Pilot Project	0.00	43.1	6.8	167	0.91	5.14	0.115	1.9	15	5158	3.67
Post- I/I Demonstration Project	0.00	16.1	1.3	95	1.33	7.10	0.254	1.3	104	11	0.87
Skyway Pilot											
Pre- I/I Pilot Project	0.00	85.2	3.9	170	0.54	4.86	0.249	3.2	38	1924	2.52
Post- I/I Pilot Project	0.00	7.9	1.2	134	1.02	5.14	0.369	4.0	47	2953	11.65
Post- I/I Demonstration Project	0.00	3.7	0.1	274	2.00	2.49	0.723	6.9	677	5803	2.55
Minibasin BLS002											
I/I Control Program	0.00	53.4	4.5	25	0.43	1.30	0.230	2.7	43	434	1.58
Post- I/I Pilot Project	0.03	38.1	7.2	143	2.98	9.89	1.000	7.0	495	2000	3.73
Pre- I/I Demonstration Project	0.17	56.5	8.9	248	0.71	9.56	0.203	12.9	499	2000	1.87
Post- I/I Demonstration Project	0.00	108.8	3.0	191	1.43	5.26	0.051	4.5	836	65	0.16
Model Basin M_BLS43B											
I/I Control Program	0.00	54.3	2.8	36	0.93	2.30	0.124	2.2	149	18	0.16
Pre- I/I Demonstration Project	0.01	24.6	3.5	176	1.02	1.21	0.290	9.6	532	2170	2.64
Decennial Flow Monitoring	0.00	62.4	4.4	284	3.55	2.47	0.229	7.3	749	1931	0.21
Post- I/I Demonstration Project	0.19	42.7	3.5	128	2.05	3.90	0.278	5.4	570	2008	0.77

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ATTACHMENT 5.
CALIBRATION EVENT GOODNESS OF FIT

Nash Coefficient

The Nash coefficient is one less the ratio of the sum of the squared differences between modeled and metered flows, and the sum of the squared differences between the metered and mean metered flows. The Nash coefficient is expressed as follows:

$$Nash = 1 - \frac{\sum_{i=1}^{m} (Q_i^{mdl} - Q_i^{mtr})^2}{\sum_{i=1}^{m} (Q_i^{mtr} - \overline{Q}_i^{mtr})^2}$$

where:

m = number of flows within the event
Q_i^{mdl} = model flow
Q_i^{mtr} = meter flow
$\overline{Q}_i^{mtr}$ = average meter flow

Nash coefficients can range from +1.0 to negative infinity, where 1.0 indicates a perfect fit. Values of 0.9 and greater indicate excellent agreement between the meter and the model.

Relative Peak Flow

The relative peak flow is the ratio of the difference between meter peak flow and model peak flow, and the meter peak flow. Although generally coincident, these peaks are not required to occur at the same time within the event. Relative Peak Flow is expressed as follows:

$$Q_{pk} = \frac{Q_{\max}^{mdl} - Q_{\max}^{mtr}}{Q_{\max}^{mtr}}$$

where:

$Q_{\max}^{mdl}$ = peak model flow
$Q_{\max}^{mtr}$ = peak meter flow

Relative peak flows can range from -1.0 to positive infinity. Values close to zero indicate excellent agreement. Positive or negative values indicate model overestimation or underestimation, respectively.

Relative Peak Volume

The relative peak volume is the ratio of the difference between model volume and meter volume, and the meter peak volume. Both model and meter volumes are coincident within the event. They measure the amount of flow one day before, and one day after, the time of the meter peak flow. Relative peak volume is expressed as follows:

$$V_{tot} = \frac{V_{tot}^{mdl} - V_{tot}^{mtr}}{V_{tot}^{mtr}}$$

where:

V_{tot}^{mdl} = two-day model volume before/after the peak meter flow
V_{tot}^{mtr} = two-day meter volume before/after the peak meter flow

Relative peak flows can range from negative 1.0 to positive infinity. Values close to zero indicate excellent agreement. Positive or negative values indicate model overestimation or underestimation, respectively.

	Pre- I/I Pilot Project			Post- I/I Pilot Project			Post- I/I Demonstration Project		
Event	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*
01	-0.6618	-0.3399	0.7820	-0.4222	0.3583	0.9533	0.5393	0.2225	0.2371
02	-4.7262	0.3639	1.0999	0.9123	0.1301	0.0826	-2.8281	0.7001	1.3983
03	0.7902	0.0116	0.2184	-1.3061	-0.0049	0.3700	0.7342	-0.0478	0.1847
04	0.8063	-0.1853	0.1237	0.9328	0.0675	0.0689	0.5479	-0.4265	0.0245
05	0.6570	-0.2694	-0.0858	0.7802	-0.0304	0.1072	0.7903	-0.0483	0.0179
06	0.6844	-0.3557	0.0265	0.7856	-0.1695	0.1507	0.7419	0.0578	0.0429
07	-4.2332	0.1949	1.0902	0.7880	-0.2834	0.0726	0.5684	-0.0866	0.1004
08	0.8683	-0.0589	0.0593	-0.1776	0.0836	0.2257	0.3916	0.3607	0.4641
09	-2.1507	0.0147	0.3369	0.4852	0.4051	0.0065	0.6331	0.3324	0.3375
10	-1.7049	-0.0019	0.4066	0.9243	-0.0832	0.0277	0.1905	0.1769	0.2510

Table E-1. Skyway Control Basin

	Pre- I/I Pilot Project			Post- I/I Pilot Project			Post- I/I Demonstration Project		
Event	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*
01	0.2925	-0.0856	0.3075	0.9395	-0.0421	0.1016	0.8684	-0.2319	0.0503
02	-1.6437	0.1713	0.5622	0.7676	-0.0504	-0.0746	0.4860	0.4829	0.2099
03	0.9133	0.0022	0.1156	0.0364	-0.0845	0.2912	0.2913	0.2030	0.1268
04	0.8384	-0.0203	0.1066	0.9067	-0.1273	0.0627	0.8397	-0.1774	0.0438
05	0.7568	-0.2666	-0.0311	0.6458	-0.1211	0.0929	0.5928	-0.6369	-0.0936
06	0.8908	-0.1149	0.1135	0.6372	-0.0728	0.0046	0.4475	-0.2707	-0.1684
07	0.0994	0.1219	0.3549	0.5911	-0.1394	0.0712	0.3839	0.4469	0.1028
08	0.9286	0.0546	0.0165	0.3539	-0.1075	0.0078	0.2342	0.3082	0.2539
09	0.0528	0.0787	0.1977	0.3806	0.2133	-0.0650	0.5380	-0.3488	0.2776
10	0.5994	-0.0777	0.1151	0.8039	-0.1707	-0.0059	0.4472	-0.2674	0.1524

Table E-2. Skyway Pilot Basin

Table E-3. Minibasin BLS002

	I/I Control Program			Post- I/I Pilot Project			Pre- I/I Demonstration Project			Post- I/I Demonstration Project		
Event	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*
01	-1.8766	0.6815	0.8822	0.0576	0.3558	0.0058	0.5280	0.0911	0.1057	0.8386	0.0741	1.5971
02	0.3261	0.3614	0.4658	-0.2998	0.3501	0.3114	0.9765	0.0382	-0.0082	0.9572	0.0273	0.0096
03	-1.4396	0.9402	0.5491	-2.7427	0.3989	0.4186	0.6333	0.0380	-0.0258	0.9557	-0.0634	-0.0324
04	-1.1954	0.7061	0.7300	-0.4481	0.1222	0.3415	0.6787	-0.0658	-0.1120	0.8731	-0.0481	-0.0044
05	0.2445	0.8207	0.4458	-13.9454	1.0715	0.3784	0.6633	-0.0091	0.0210	0.9737	-0.0794	0.0020
06	0.9619	0.0259	-0.0668	0.6740	0.0914	-0.1280	0.5810	0.0813	0.1310	0.7612	-0.0716	-0.0275
07	0.8614	-0.0539	-0.0318	-2.0132	-0.1725	-0.1429	0.6816	-0.0326	-0.1879	0.7814	-0.1086	0.0734
08	0.8823	0.0271	-0.1169	0.7824	-0.1121	0.0058	0.0082	0.2017	0.0698	0.7742	0.0850	0.0631
09	0.9117	0.1670	0.0186	0.8170	-0.0500	-0.0476	0.5255	0.3140	0.0881	0.8647	-0.0494	0.0050
10	0.8529	-0.0104	-0.1031	0.9695	-0.0084	0.0112	0.4352	-0.0008	-0.0101	0.8566	0.0646	0.0435

Table E-4. Model Basin M_BLS43B

	I/I Control Program			Pre- I/I Demonstration Project			Decennial Flow Monitoring			Post- I/I Demonstration Project		
Event	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*	*Nash*	*Qpk*	*Vol*
01	-1.2210	0.1062	0.4418	0.4076	0.0361	0.0929	0.5041	0.1952	0.0634	0.8461	-0.1340	-0.0973
02	0.6039	0.1187	0.1622	0.6482	0.1349	-0.1226	0.8735	-0.2090	0.1092	0.8243	0.0387	0.1046
03	-1.9199	0.6887	0.3183	0.8010	0.0899	0.0773	0.9180	-0.3044	0.0105	0.7365	0.2763	-0.0597
04	-0.7440	0.4232	0.3864	0.9643	0.0869	-0.0358	0.8921	-0.2275	0.0536	0.8542	0.1854	0.1377
05	0.5035	0.6407	0.2076	0.6220	-0.1340	-0.0476	-0.1530	-0.2297	-0.3077	0.9394	-0.0282	0.0127
06	0.9515	-0.0041	0.0399	0.6087	-0.1589	-0.0086	0.9386	-0.1046	-0.0347	0.8969	-0.0769	0.0929
07	0.8370	-0.1127	-0.0565	0.7831	-0.0471	-0.1599	0.9553	0.0590	0.0230	0.5380	0.1225	0.1154
08	0.8883	0.0062	-0.0666	0.6719	-0.1682	-0.1256	0.8769	-0.1734	-0.0174	0.7996	-0.0115	0.0177
09	0.9657	-0.0029	-0.0385	0.6627	-0.2647	0.1375	0.7620	-0.4702	0.1016	0.2121	0.0107	0.2925
10	0.9459	0.0142	0.0057	0.4133	0.4820	0.3617	0.8800	-0.5052	0.0462	0.8758	0.0409	-0.0779