DISCHARGE CHARACTERISTICS AT BIOSWALE INSTALLATION SITES ALONG I-294 IN NORTHERN COOK COUNTY, ILLINOIS

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EXECUTIVE SUMMARY

In a seven-year study, ISGS monitored the quantity and quality of roadway runoff in the highway drainage system of I-294 in northern Cook County, Illinois, to evaluate the effectiveness of bioswales installed for treatment of runoff. Four bioswale areas were monitored prior to installation and for five years after bioswale construction. Two different types of bioswales were monitored to determine if design factors influenced performance: wet bioswales that detain runoff on land surface and dry bioswales that are designed to infiltrate runoff. Discharges were characterized to identify output volume reductions between bioswale inputs versus outputs and document slowing of runoff flow to allow for additional retention and treatment times in the bioswale areas. Discharges calculated here are also used in a companion report to calculate mass loadings. This report details methods and results of discharge volume measurements and runoff flow analyses in two wet bioswales and two dry bioswales at nine monitored input and output locations.

Annual discharge volumes were calculated with rating curve models at three input and six output monitoring locations. Discharge totals were used to evaluate volume reductions between bioswale inputs and outputs. Measured bioswale input volumes were similar to precipitation volumes that fell on contributing roadway areas, ranging between 91% and 112% of roadway volumes. Measured bioswale output volumes varied with precipitation rates, ranging between 68% and 120% of roadway volumes. Because of a wide variability in annual precipitation totals during the project, a combined post-construction discharge total was used to determine a composite discharge for each site, and was used to evaluate volume reductions between inputs and outputs. One wet bioswale had a higher degree of infiltration than the other three monitored sites. At this site, post-construction output discharge averaged 68% of roadway volumes, compared to inputs averaging 98% of roadway volumes, indicating a total output volume reduction of 31%. The second wet bioswale and two dry bioswales likely had local groundwater input contributions, creating higher output volumes averaging between 111% and 120% of roadway volumes.

Slowing of runoff flow with the installation of bioswale check dams was evaluated by determining runoff travel times through the bioswales with hydrograph analyses of event peak travel times between input and output locations. Hydrograph analyses, made at the only bioswale with continually monitored inputs, showed an increase in travel times of discharge peaks from inlet to outlet after bioswale installation. Average travel times for event hydrograph peaks increased by 0.22 hours, ranging from 0.44 hours before installation to 0.88 hours after bioswale construction. Selected isolated single-peak event volume travel times increased from 0.56 hours before construction to 2.42 hours after installation, showing an increase of 1.86 hours. Isolated single-peak event travel times are likely greater than travel times including all events due to drier average antecedent moisture conditions for the isolated events.

In general, output volumes after bioswale installation varied with annual precipitation totals, bioswale type, and hydrologic setting. Dry bioswales were less likely than wet bioswales to reduce output volumes, as most infiltrated water was collected by the dry bioswale underdrain and piped directly through to a surface outlet with little time to enter the surrounding groundwater. Both dry bioswales also likely had groundwater contributing to output volume totals because the underdrain pipes were located below the water table at least seasonally. Similarly, the wet bioswale located next to a lake was likely in a location with a higher water table, especially in years with greater precipitation amounts, creating less infiltration to the local groundwater regime and possible groundwater inputs to the bioswale, and resulting in higher bioswale output volumes. The bioswale with the best performance at reducing output volumes was the wet bioswale located in a drier area adjacent to a forest, which allowed for increased runoff retention times with check dam installation and more infiltration of runoff into the local groundwater regime. Slowing of runoff flow in wet bioswales with the installation of check dams, as indicated by the hydrograph analyses, would also increase settling time for suspended solids and allow more time for dilution of output flows with additional rainfall, resulting in decreased constituent concentrations in output waters.

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INTRODUCTION

In 2007, the Illinois State Geological Survey (ISGS) was contracted by the Illinois State Toll Highway Authority (Illinois Tollway) to monitor the effectiveness of bioswales to be installed during reconstruction and expansion of I-294 in northern Cook County, Illinois, USA. Bioswales are wide, gently sloping ditches that reduce the quantity and improve the quality of runoff by slowing or infiltrating water and fostering contact of runoff with soils and vegetation (Mazer et al. 2001). From February 2008 through August 2010, the ISGS monitored the quantity and quality of runoff from I-294 in the existing roadside ditch system where bioswales were to be constructed. In 2010, the bioswales were constructed (Figure 1), and were monitored through August 2015. This report contains data and analyses from all monitoring years and supersedes all previous reports due to new methodologies developed during post-construction monitoring and subsequent recalculation of previously reported results.

This report was prepared under contract #ITHA RR-07-9918 and #ITHA 2015-01230 MINER, and is limited to activities regarding bioswale construction and monitoring along the I-294 corridor between Touhy Avenue and Lake-Cook Road, and does not address other activities contained within the above-referenced contracts.

PURPOSE AND SCOPE

The purpose and scope of the larger project are detailed in Miner et al. (2012a, 2012b). In summary, the quantity and quality of runoff discharging from four bioswales were monitored, and effectiveness of the bioswale installations in treating roadway runoff was determined by comparison of discharge measured at inputs versus outputs, as well as before and after bioswale construction. Additional separate reports discuss bioswale data and analyses regarding reductions in mass of contaminants in surface water (Miner et al. 2016), datalogged surface-water quality (Ackerman et al. 2016), impacts to groundwater quality and groundwater levels (Carr et al. 2016), and total recoverable metals in bioswale soils (Plankell et al. 2016).

The main purpose of this report is to present the methods used to calculate discharge entering and exiting the bioswales to compare discharge volumes before and after bioswale construction. The input and output volume data are also used in a companion report (Miner et al. 2016) to calculate mass loadings and total analytes in bioswale waters using water quality samples collected during the study.

This report focused on runoff characteristics of two types of bioswales to evaluate runoff volumes and retention times. Two wet bioswale sites and two dry bioswale sites were monitored. Wet bioswales have check dam impoundments and surface outputs to treat runoff by slowing discharge, facilitating deposition of suspended solids and creating increased interaction with plants and substrate materials in a ponded anaerobic environment. Dry bioswales have an underdrain emplaced below a sand bed, promoting treatment of runoff through rapid infiltration and filtering of suspended solids and associated adsorbed metals through the sand and earthen substrate materials.

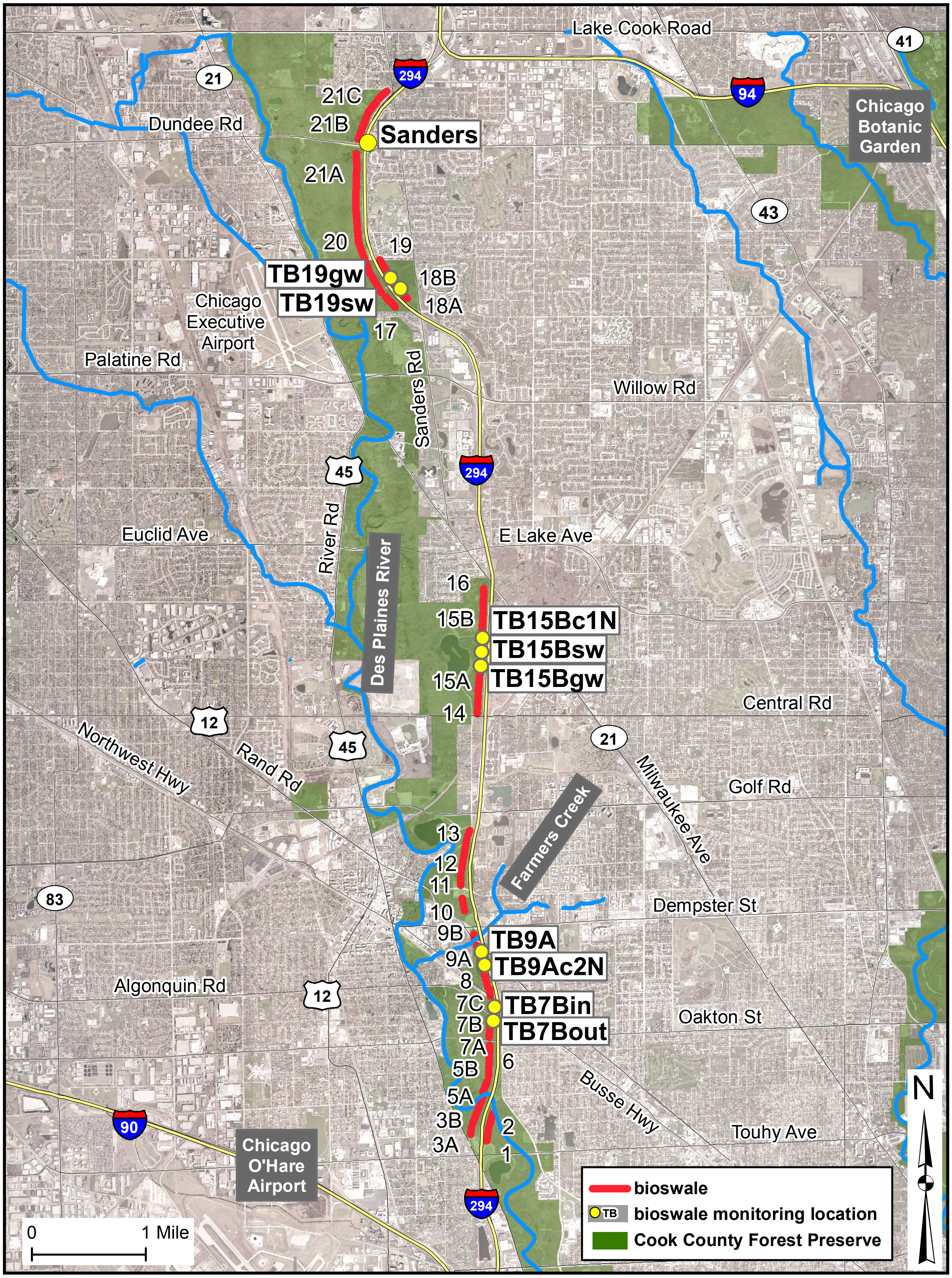


Figure 1. Location map of all bioswales

Discharge characteristics were used to investigate changes in runoff retention times in the bioswales, indicated by a decrease in output volumes and longer duration of output runoff event hydrographs. The main discharge characteristics considered in this report are total runoff volumes at bioswale inputs and outputs, event peak travel times, and duration of runoff flow through the bioswales.

METHODS

FIELD SITES AND INSTRUMENTATION

Four bioswale sites were monitored for this project. Two wet bioswales (TB7B and TB9A) and two dry bioswales (TB15B and TB19) were monitored before and after bioswale construction to measure discharge volume characteristics. Sites were chosen to minimize backwater conditions and inputs from non-roadway sources. Pre-construction monitoring was from 2/21/08-8/15/10. Post-construction monitoring continued for 5 years, starting with Year 1 on 8/16/10 and ending with Year 5 on 8/15/15. The installation timeline for all monitoring locations is shown in Figure 2.

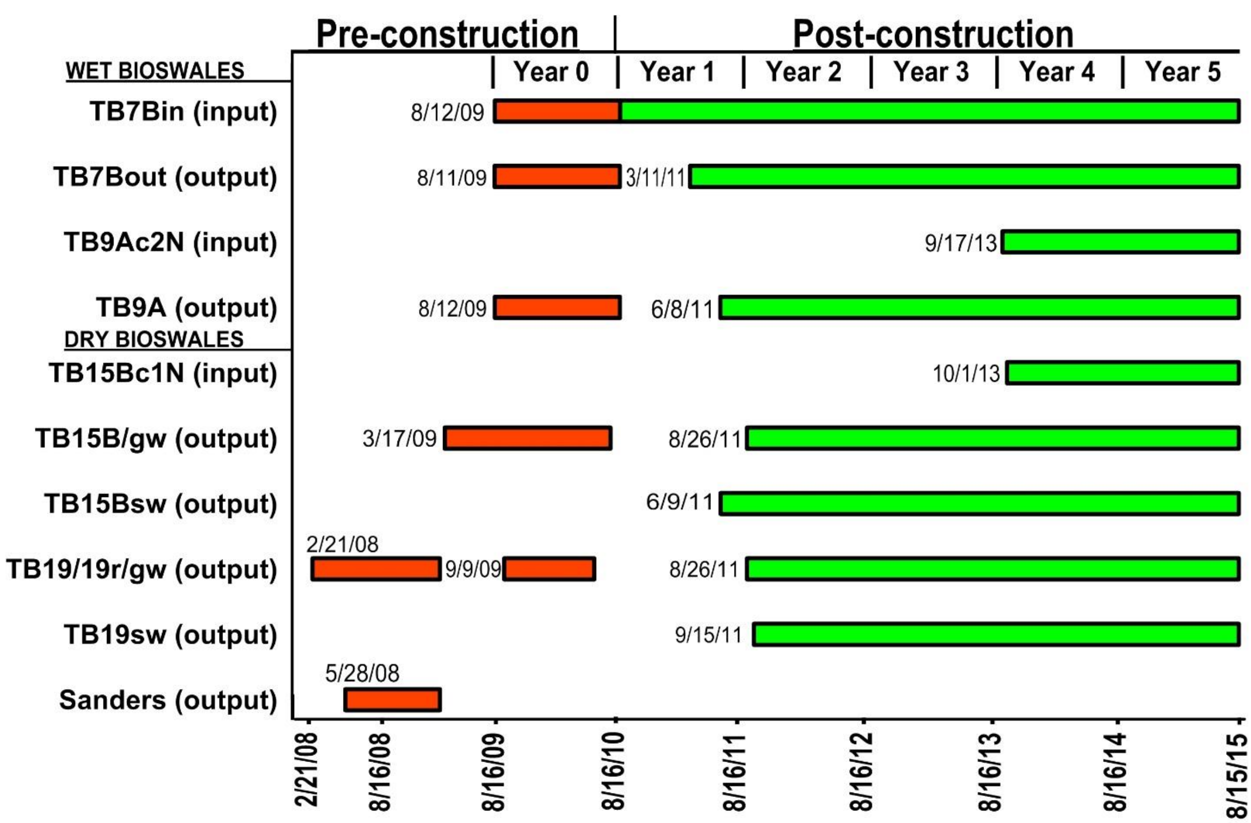


Figure 2. Bioswale monitoring timeline

Output locations were monitored at all four bioswale sites during pre- and post-construction phases. Three bioswale inputs were monitored at TB7Bin, TB9Ac2N, and TB15Bc1N. No discrete input locations were monitored at TB19. The input location at TB7Bin was monitored continuously starting in August 2009 in the pre-construction phase through to the end of the post-construction phase in August 2015. Input monitoring at TB9Ac2N and TB15Bc1N was started in Year 4 to supplement input runoff data. Discharge calculation methods for these two sites are presented, but insufficient data were collected for representative comparisons and conclusions to be made.

Three additional locations were monitored during the early pre-construction phase for method development purposes. The Sanders site was monitored for discharge volumes and water quality between May 2008 and March 2009, mainly to develop discharge measurement methods. There was no bioswale built at the site, and the pre-construction data are included here but not used for comparisons in later reports. TB5 and TB20 were discontinued because of highly unsteady flow or the predominance of backwater conditions in the channels, and data for these sites are not presented.

Wet Bioswale Site Descriptions

Both wet bioswales are located at the bottom of steep roadway embankments. One or more input culverts drain directly off the highway from the roadway gutter. Runoff input descends directly downward from the roadway to catch basins, and exits to the bioswales via a low-sloped culvert pipe. Runoff enters the bioswale area, filling individual ponded segments separated by check dams and exits through the monitored output location.

TB7B

TB7B was a short, 360-ft long bioswale at the bottom of a 35-ft high roadway embankment, bordered by Algonquin Road to the south and a railroad right-of-way to the north (Figure 3). This bioswale had the most direct input and output discharge correlations, having a single input pipe directly from the elevated roadway and a single output monitoring location in a relatively well-defined drainage area. The input monitoring location at TB7Bin was located in a 1.5-ft diameter culvert at the north end of the bioswale during both pre- and post-construction monitoring (Figure 3a-b). The output monitoring station at TB7Bout was located in a 2-ft diameter culvert that extended under Algonquin Road at the south end of the bioswale during pre-construction and Years 1 and 2 of post-construction monitoring (Figure 3c). To improve capture of measured runoff, the output monitoring location was moved at the end of Year 3 from the 2-ft diameter culvert pipe to a location just upstream in the southernmost concrete check dam (Figure 3d). This site also had the only continuously monitored input location in the study, which provided runoff data channeled directly from a roadway area and was used to evaluate bioswale outputs at all study locations.

The pre-construction site was a vegetated ditch that had ponding at the input culvert location and debris damming in the main channel. Continuous ponding over the TB7Bin monitoring instruments occurred between a 0.2’ and 0.3’ depth, while the output location was often dry and only flowed during larger precipitation events.

The post-construction bioswale was widened and deepened, and two check dams were installed to impound runoff. Erosion control mats and fill material were placed under the input pipe to reduce scouring and ponding. These erosion control measures were reinforced in Year 2, and were effective until ponding started to increase again in Years 4 and 5 due to scouring and accumulation of sediment near the TB7Bin inlet pipe.

3a. Pre-construction inlet - view to south

3b. Post-construction inlet - view to north

3c. Pre-construction outlet - view to south

3d. Post-construction outlet - view to north

3e. Bioswale site TB7B

Figure 3. TB7B monitoring site locations (Aerial photo: Google Earth)

TB9A

TB9A was the longest bioswale monitored, and had the largest roadway area contributing runoff. The monitored bioswale was 2,060-ft long and consisted of three connected bioswale areas: 7C, 8, and 9A (Figure 4). The bioswale contained numerous check dams and ponded segments, and was located between a steep, 25-ft high roadway embankment and Belleau Lake. The bioswale drained into Farmers Creek about 0.65 miles upstream from its confluence with the Des Plaines River. Five input culverts entered the bioswale from the elevated roadway. One input culvert was monitored post-construction (TB9Ac2N), and one output area was monitored before and after bioswale construction (TB9A) approximately 670 ft upstream from Farmers Creek.

The pre-construction site was a vegetated ditch that had occasional high backwater conditions during large precipitation events due to backups from Farmers Creek. No input culverts were monitored, and one output location (TB9A) was monitored, which was an unlined earthen ditch.

The post-construction bioswale was widened and eleven check dams were installed. The site continued to have occasional backwater conditions near the monitored outlet. The output monitoring instruments (TB9A) were located in the ninth check dam north of Busse Highway (Figure 4b). The area downstream from the TB9A monitoring point was re-graded after bioswale installation in October 2013 in an attempt to reduce minor backwater conditions and ponding during smaller precipitation events. One input culvert, TB9Ac2N (culvert 2 North - the second culvert north of Busse Highway), was monitored during Years 4 and 5 (Figure 4a) in an attempt to verify similarities with the TB7B bioswale input location (TB7Bin), which was a similar culvert draining directly from an adjacent section of elevated roadway.

Dry Bioswale Site Descriptions

Both dry bioswales were located next to the roadway at the base of low 5- to 10-ft embankments. The main inputs to the bioswales were culverts plus direct but diffuse runoff from the roadway shoulders. Runoff enters the bioswale area and rapidly infiltrates through a coarse sand bed to an 8” underdrain output pipe that exits at the downstream end of each monitored bioswale. Surface flow that did not infiltrate into the subsurface underdrain exited the swale area through a surface check dam located near the downstream end of each dry bioswale.

TB15B

TB15B was located along a straight stretch of roadway at the bottom of a short embankment. Three discrete culvert inputs drained into the approximately 1400-ft long bioswale augmented by direct runoff from the roadway shoulder (Figure 5).

The pre-construction site was a vegetated ditch that was regularly mowed (Figure 5a). No input culverts were monitored before bioswale construction, and one output location (TB15B) was monitored in the open ditch.

4a. Post-construction inlet TB9Ac2N, view to north

4b. Post-construction outlet TB9A, view to south

4c. Bioswale site TB9A

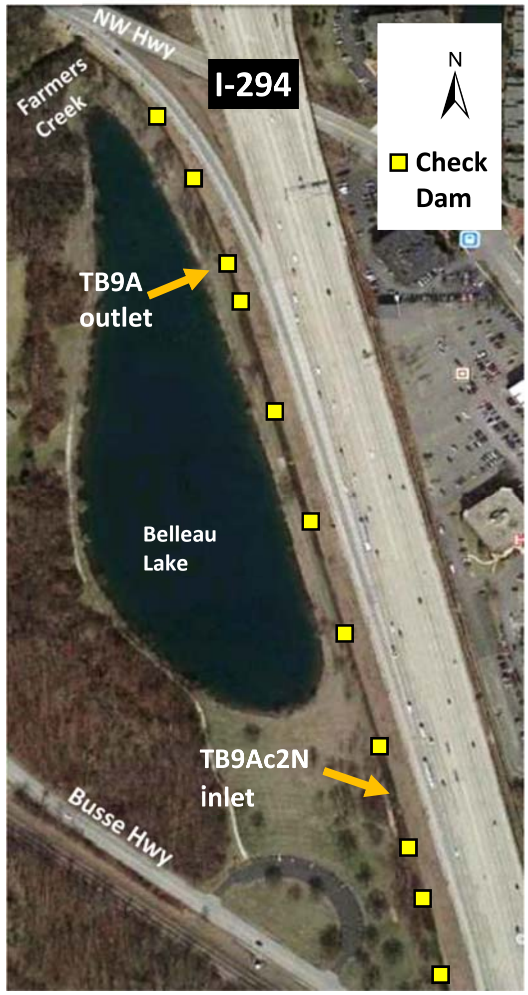


Figure 4. TB9A monitoring site locations (Aerial photo: Google Earth)

The post-construction site at TB15B was widened with one check dam installed at the downstream end of the monitored dry bioswale area (Figure 5b). A second check dam was installed further downstream from the dry bioswale area, and the groundwater pipe exited at this second check dam. Post-construction output was monitored at two locations, the underdrain output pipe (TB15Bgw) and the check dam at the surface-water exit in the dry bioswale (TB15Bsw). The surface-water monitoring site often did not have regular flow because most water infiltrated to the subsurface underdrain pipe, except during higher intensity precipitation events where the infiltration capacity was exceeded. The underdrain outlet pipe had near-constant flow that exited into a wet bioswale area downstream from the pipe, and the outlet area was occasionally ponded during high intensity precipitation events. One input culvert, TB15Bc1N (culvert 1 North), was monitored in Years 4 and 5 in an attempt to verify similarities between dry bioswale inputs and wet bioswale inputs at TB7B and TB9A.

5a. Pre-construction outlet TB15B

5b. Post-construction bioswale TB15B

5c. Bioswale site TB15B

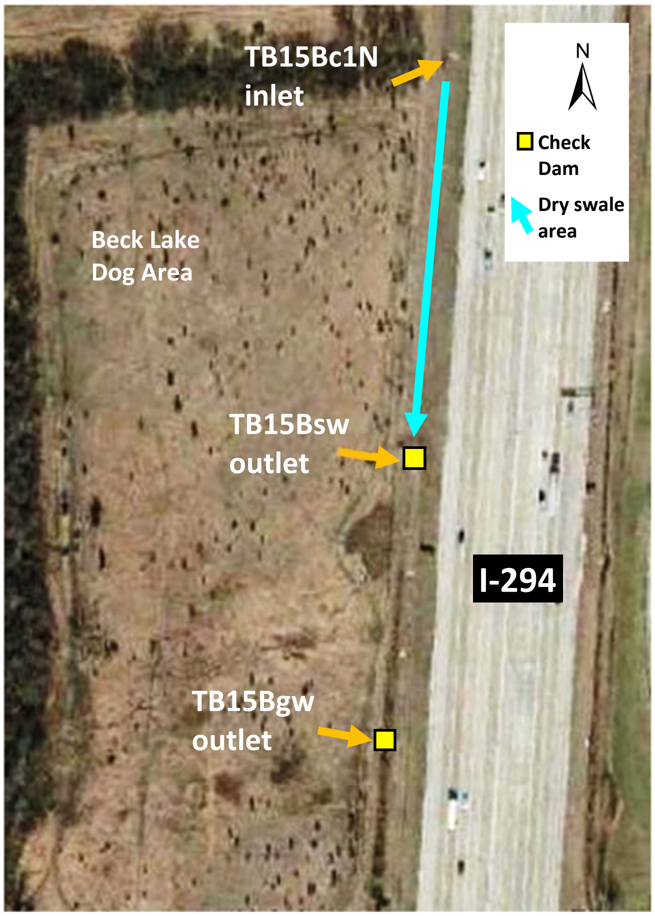


Figure 5. TB15B monitoring site locations (Aerial photo: Google Earth)

TB19

TB19 was located along a 1300-ft curved stretch of roadway at the bottom of a short (5-ft high) embankment (Figure 6). Inputs were diffuse runoff from the roadway shoulder and four small French drains, with no major input culverts present. One output area was monitored where runoff exited the bioswale to a local creek.

The pre-construction site was an unvegetated earthen ditch which was deeply eroded (Figure 6a). One output location (TB19/TB19r) was monitored. The original installation at TB19 between 2/21/08-3/3/09 was removed for ditch improvements, and reinstalled as TB19r from 9/9/09-6/1/10.

The post-construction site was widened (Figure 6b), with one check dam installed near the end of the monitored dry bioswale area and an 8” underdrain installed in sand substrate and exiting at a second check dam downstream from the dry bioswale area. No input culverts were available to be monitored in the post-construction phase. Post-construction output was monitored at two locations, the underdrain output pipe (TB19gw) and the surface-water exit at the dry swale check dam location (TB19sw).

The surface-water monitoring site did not flow very often because most water infiltrated to the underdrain pipe, except during high intensity precipitation events. The underdrain outlet pipe exited into a wet bioswale that drained into a local creek. This underdrain pipe did not have ponded conditions at the outlet location.

6a. Pre-construction outlet TB19, view to south

6b. Post-construction bioswale at TB19sw, view to north

6c. Bioswale site TB19

Figure 6. TB19 monitoring site locations (Aerial photo: Google Earth)

Field Measurements

At each site, discharge and water levels were measured to serve as the basis for the development of rating curves. Rating curves were created by plotting discharge versus water level and were used to obtain an average discharge rate for each water level. Discharge rates were calculated using the area-velocity method, multiplying the cross-section area of outlet openings in square feet by the velocity in ft/s to get a discharge in cubic feet per second. Validated water levels were then used to calculate total annual discharge volumes using rating curve values.

Manual and automated level and velocity measurements were used to plot the rating curves. Manual measurements were collected with a float method to obtain velocity measurements and a ruler to measure water levels. Discharge was then calculated with these parameters. Automated velocity and water level measurements were collected by Isco 750 Low-Profile Area-Velocity Flow Modules (AV modules) controlled by Isco 6712 or Isco Avalanche autosamplers during the pre-construction year and post-construction Years 1-3. The Isco 750 Area-Velocity modules were replaced with Isco 730 Bubbler Flow Modules during Years 4 and 5 to reduce level sensor drift and increase level measurement accuracy. Bubbler modules did not have an integrated velocity sensor, and automated velocity measurements were not collected when the bubbler modules were in place. To improve measurement of low-level flows, small weirs were installed in the flow channels during Years 1 and 2 post-construction monitoring. Flow channel weirs were constructed with hydraulic cement at the concrete culvert and check dam locations, and with PVC inserts in the 8-inch underdrain outlets in the dry bioswales. Flow channel weirs were removed after Year 2 to normalize stage/discharge relations.

Autosampler instrumentation was deployed with various power sources during the project. Isco 6712 unrefrigerated units powered with 12-volt lead-acid batteries were used during the pre-construction monitoring phase. During the post-construction phase, refrigerated Isco Avalanche autosamplers were used and powered with PCMS (Portable Changeable Message Sign) units containing an array of 12-volt lead-acid batteries recharged with large solar panels.

Parameter limits for autosampler instrumentation can be used to evaluate error in discharge calculations. Isco 750 Area-Velocity and 730 Bubbler flow modules had a level measurement range of 0.03 ft-10 ft, an accuracy of +/- 0.01 ft, and resolution of 0.001 ft. The 750 AV modules used stainless steel pressure transducers to measure water levels, and had a tendency to exhibit instrument drift over time. These were replaced with 730 bubbler modules that used compressed air to measure hydrostatic pressure, and had an automatic drift correction to 0.002 ft at 15-minute intervals. All level sensors were calibrated manually during bi-weekly site visits. Level and velocity data were recorded at the pre-construction sites Sanders and TB19 at 2-minute intervals, recorded as an average of multiple sensor readings collected by the instrument during every interval. During the later pre-construction phase and Years 1 and 2, 5-minute averaged intervals were used. This was changed to 15-minute averaged intervals from the middle of Year 2 through Year 5 at all sites for power and data management issues.

Velocity data were collected with the Isco 750 AV modules using a Doppler velocity sensor recording data in time-averaged intervals. Velocity measurement accuracy was +/- 0.1 ft/s between -5 ft/s and 5 ft/s, and resolution was 0.024 ft/s. Accurate sensor measurements were obtained at a minimum water depth of 0.083 ft and minimum velocity of 0.1 ft/s, and also when internal sensor and signal checks indicated there were no errors in the Doppler signal returns. Instrument installations for all sites are shown in Figure 7.

7a. TB7Bin 1.5-ft culvert

7b. TB7Bout 2-ft culvert

7c. TB7Bout check dam

7d. TB9Ac2N 1.5-ft culvert

7e. TB9A check dam

7f. TB15Bsw check dam

7g. TB15Bgw 8-in. underdrain pipe

7h. TB19sw check dam

7i. TB19gw 8-in. underdrain pipe

Figure 7. Instrument installations

Field Data Validation Procedures

Prior to development of the rating curves, data were screened to 1) remove data that were not representative of active flow conditions and 2) categorize active flow conditions to develop rating curves for specific flow configurations (i.e. small incised channels, pre-construction ditches, check dams, overtopping or backwater conditions). Preliminary evaluation and outlier screening of field data were performed using multiple sources of supporting data to determine the validity of monitoring instrument measurements. Level and velocity data were adjusted or removed from the data sets according to site conditions indicated by field observations and other instruments present. Level data in each measurement interval were evaluated by screening for instrument limitations, instrument drift, frozen surface water conditions, ponding, and similar issues.

Level data recorded at levels below instrument measurement limits had less certainty of being representative of active flow conditions because the instrument error was almost as large as the actual measurement, and these data were removed according to given field conditions. The pre-construction unlined ditch level measurements exhibited large diurnal signatures with level increases greater than 0.03 ft caused by daytime warming of the instruments and varying placements of the sensor on ditch surfaces. The level sensor lower limit was 0.03 ft, and the diurnal signature and differences in sensor height placement created low-level variability higher than the sensor limits. To minimize volume over-calculations from these sources, level data below 0.05 ft were removed from all records.

Velocity data were recorded using Doppler signal returns, and these signals were adversely affected by turbulent flow, clear water with a lack of reflectors, and low water depths. Data below sensor limits, including velocities less than 0.1 ft/s, depths below 0.083 ft, and data collected in frozen conditions, were removed and not used for rating curve construction. Level data were adjusted for observed instrument drift by comparing manual field measurements with instrument readings. Correctable instrument drift was considered as a gradual drift of baseline data in the level record. In such instances, level data were compared to biweekly manual measurements at site visits and data segments corrected to manual calibrations.

Frozen field conditions were identified with field observations of channel conditions, temperature data loggers in surface-water channels, local air temperature records, and level transducer data. Level and velocity data were removed when flow channels were frozen or slushy as identified with field observations of iced conditions, or when surface-water temperatures correlated with freezing air temperatures, and pressure transducer level data exhibited increased pressure or spikes during freezing weather. Intervals of melting during freezing weather were left in when they could be identified as having good level data.

Ponding over the monitoring instruments was evidenced by a slow rate of water level decline seen after event peaks in the sensor data, especially at TB7Bin, TB9A, TB15Bgw, and TB15Bc1N. Ponded conditions were also confirmed by manual level and velocity measurements during site visits, and slower velocities than previously recorded with the Isco sensor at a given water depth. When velocity was not being measured in Years 4 and 5, both field observations and the baseline of event peaks were used to evaluate ponded conditions. The ponded depths did not fit the rating curve velocity profiles used to calculate discharge totals, and were either adjusted or removed from the data set when identified as a consistently ponded condition. Level data were also removed when the instruments were noted as malfunctioning, either showing sensors moved out of place in the channel, excessive uncorrectable drift, or other conditions producing unusable data.

Varying flow regimes created by unsteady flow conditions were identified with analysis of stage-discharge relationships (ASTM 2008, Braca 2008). Varying flow regimes were seen in different areas of the stage-discharge plots, including backwater, ponding effects, and higher velocity anomalies. Most monitoring instruments were located at the end of culvert pipes, where unsteady flow can be produced by subcritical flow, pressure flow, tailwater effects, and other flow conditions (Schall et al. 2012, Franz and Melching 1997, Chow et al. 1988). Flow regimes were verified with site visit observations and manual discharge measurements. If necessary, non-conforming flow regimes such as backwater and over channel flow were removed before rating curves were generated and discharges for these conditions were calculated with an alternative method.

RATING CURVE DEVELOPMENT AND DISCHARGE CALCULATIONS

Annual discharge volume totals were calculated for inputs and outputs at each monitoring location using rating curve values. Discharge totals calculated for each 2-, 5-, or 15-minute sensor measurement interval were summed for bi-weekly water-quality sampling intervals and for annual totals.

Discharge volumes were calculated at all sites using stage-discharge rating curves to estimate a discharge for each depth measured in a sensor measurement interval, and the rate was multiplied by the interval time to calculate a total discharge volume for the interval. Rating curves provided a discharge for each level, and helped address unsteady flow conditions and multiple flow regimes that existed at the sites because measurements of all flow conditions contributed to the overall rating curve proportional to their occurrence. Rating curves were also used to calculate discharge because high-quality velocity data were intermittent or not available for all years at all sites, due to site conditions and instrument requirements.

Rating curves were constructed by graphing level and discharge data pairs for each flow channel configuration. Channel configurations changed between pre-construction and post-construction monitoring as installation took place and instruments were relocated, and also with the installation of temporary weirs in some flow channels during pre-construction and post-construction Years 1 and 2. Validated level and discharge data pairs were used to construct the rating curves through regression analyses to provide an average discharge value for all levels measured with the Isco pressure transducers. Regression analysis uses the entire population of valid data pairs for curve generation, thus averaging the varying flow regimes present at each site.

Discharge calculations were made with separate rating curves for each channel configuration at each monitoring location. Channel configurations included pre-construction unlined ditches, hardened cross-sections in concrete culverts, unobstructed flow channels, and channels with temporary weirs. Discharges were calculated with alternative methods for non-conforming flows including unlined ditches, overbank flows exceeding measurement channel heights, and pipe-full flow.

During the pre-construction phase, flow channels at TB9A, TB15B, TB19, and Sanders consisted of unlined earthen ditches. Base flow in these open ditches occurred in small incised channels in the wider ditch profiles at TB15B, TB19, and Sanders, and an additional rating curve was used to calculate discharge for low-level flows in these smaller channels. The open ditch at TB9A had a wide diffuse flow with no incised channel observed, and no alternative rating curve was used. TB7B had main channel flow in concrete culverts both before and after bioswale construction, so a single rating curve was used for each channel configuration at this site.

Overbank flows occurred in pre-construction open ditches as well as some concrete check dam channels after bioswale construction. Pre-construction discharge for higher flow depths in the large ditch profiles at TB15B, TB19r, and Sanders was estimated with a Manning equation calculation. Over-channel flow in check dam locations was calculated with the check dam rating curves, due to the anticipated higher accuracy of empirical velocity measurements. An underestimation likely occurs here because the cross-sectional area over the check dam would be increased, however the underestimation is not likely to be large because over-channel flow at check dams was uncommon and typically not much higher than bank full. TB9A is the only site where levels were occasionally ponded much higher than the check dam channel during large rain events due to back flooding from Farmers Creek and the Des Plaines River, and the area-velocity method was used at this site to calculate over-channel flow when velocity data were available. When no velocity data were recorded in Years 4 and 5, the main channel check dam equation was used.

Pipe-full flows occurred occasionally during larger events in the 8-inch diameter underdrain outlet pipes at TB15Bgw and TB19gw. There were no pipe-full flows recorded for the input and output culvert pipes at TB7B or TB9Ac2N. Pipe-full discharges were calculated with the area-velocity method, which was also used in the Isco software for pipe-full conditions, and therefore discharge should be calculated accurately through Year 3 when velocity data were collected. When no velocity data were available in Years 4 and 5, the main rating curve equation was used.

RUNOFF COEFFICIENT ASSESSMENT OF DISCHARGE TOTALS

Annual discharge totals at each site were compared to annual roadway runoff totals as a runoff coefficient, using the volume of bioswale discharge compared to the volume of precipitation contributed by the area of roadway drained by each input culvert (Smith and Granato 2009; International Stormwater BMP Database 2009). Runoff coefficients are reported here as a standardized yield, or the output volume from each bioswale divided by the precipitation volume that fell on the area of roadway that contributed runoff. Precipitation totals were obtained from the Midwestern Regional Climate Center (MRCC) for the Chicago O'Hare Airport Weather Service Office (WSO) (Midwestern Regional Climate Center 2015). The O'Hare precipitation data were used because the station is close to the project at approximately 4 miles southwest of the southernmost bioswale site, and it has the most continuous data set with well-maintained instruments that are heated through the winter. On-site rain gauges were present at some sites but did not collect continuous data throughout the study.

Standardized yields were calculated by dividing annual bioswale discharge totals by annual roadway precipitation volume totals to assess the calculated bioswale outputs at each monitoring location. A standardized yield of 1.00 means that 100% of calculated roadway precipitation volume passed through the measuring point. A standardized yield of less than one indicates the volume of runoff passing through a measuring point is less than the contribution from the roadway area drained, and a standardized yield greater than one indicates that more flow passed through the monitoring point than was contributed by the roadway. These results were assessed with precipitation statistics and known site conditions to validate calculated discharge volume estimates based on rating curves.

Post-construction bioswale performance at each site was calculated by summing the total discharge in all post-construction monitoring years and dividing by the total roadway generated volume. There was wide variability of annual precipitation amounts and output volumes during the study, and a post-construction total may be the best measure to evaluate bioswale performance and to smooth out inter-annual variations and other sources of error such as equipment malfunctions. Discharge reductions calculated between pre-construction and post-construction totals may not be as representative as desired because pre-construction monitoring was during one or two years with higher precipitation totals, and not as long as post construction monitoring. Pre-construction discharge totals may be slightly higher because both pre-construction monitoring years had higher than average precipitation with potentially higher contributions from overland runoff, and post-construction years had varying high and low annual precipitation amounts.

Additional precipitation analyses were used to verify bioswale totals that exceeded annual roadway contribution volumes, mainly at TB7Bout. Average depth, intensity, and antecedent times for precipitation events were calculated for each year and compared to calculated discharge totals. A six-hour inter-event time for precipitation events was used, and trace amounts of precipitation were included in the totals as they were indicated to have an effect on bioswale discharge characteristics.

RUNOFF FLOW RATES AND HYDROGRAPH EXTENSION ANALYSES

Bioswales are expected to improve roadway runoff by slowing runoff flow rates through the treatment structure, increasing settling of suspended solids, infiltration and dilution, extending contact time with vegetation and soils, and reducing flood flows (National Cooperative Highway Research Program 2006). Studies have shown that analyses of storm hydrographs and hydrograph extensions can indicate slower runoff flow rates with increases in storm volume mid-point arrival times (Granato 2012). Runoff travel times were evaluated in this study by analysis of volume mid-point, or centroid, travel times and event peak travel times between input and output locations. The analyses were done at bioswale TB7B, as this was the bioswale with the most directly measured comparison between input and output monitoring stations. Bioswale TB7B was a fairly isolated system with the same input and output measuring locations before and after bioswale construction.

Hydrograph extension is determined by an increase in the time it takes for the volume centroid of an event hydrograph to pass through a monitoring point. Hydrograph extension comparisons were made for a selection of events at TB7B with isolated peaks. Arrival times of event centroids were calculated and compared between the input and output monitoring locations. Event centroid times were determined by calculating the total volume of the hydrograph event peak, then identifying the time when half of the volume passed through the monitoring point. The selected event volume travel times between input and output were averaged to compare times before and after check dam installation.

The hydrograph centroid analysis was performed on selected isolated events to be representative of an average effect of check dams on event travel times for moderately-sized events. Larger multi-peak events were included in a peak flow time analysis between input and output using all events with relatively distinct peaks during the pre-construction phase and in Year 5 of post-construction monitoring. This provided an overall comparison of average event travel times between the pre-construction ditch to the last year of post-construction monitoring.

Travel times of event peaks were evaluated with the differences in times of peak flow level of a single discharge event between TB7Bin and TB7Bout. Peak flow level was determined for each event using the time of the highest level of a hydrograph peak in the input and output data records for the same precipitation event. An event peak travel time was then calculated from the difference between the input and output peak level times. Pre-construction and post-construction average travel times were calculated from the individual events.

DATA AND ANALYSIS

DISCHARGE MEASUREMENTS AND RATING CURVES USED FOR DISCHARGE CALCULATIONS

Overview of Discharge Measurements and Rating Curves

Rating curves used for discharge calculations for each channel configuration were selected from the regression lines that were a best fit to the data points which included all validated level-discharge pairs. A discharge volume was then calculated for each level measured using the corresponding rating curve value. Isco AV sensor instrument readings were validated by plotting them together with manual discharge measurements to confirm that both data sets were representative of similar site flow conditions.

Rating curves were selected between Isco data curves or manual data curves for each site, based on curve fit to the available data. Typically, a polynomial equation regression line fit the data best in sites showing dammed or ponded conditions, and a power equation regression line was the best fit to data in open channels without obstructions.

A number of monitoring locations displayed anomalous Isco sensor readings during higher-velocity flows. The anomalies may have been from either sensor error or altered flow conditions within the channel configurations. The higher velocities were found to have a disproportionate effect on the rating curves. This effect was seen most often at TB15Bgw and TB19gw, where high velocity flows in the small 8-inch diameter pipes created anomalous level and velocity readings between 0.1 ft and 0.25 ft. Effects from higher-velocity anomalies were addressed at all sites by removing flow data with velocities greater than 3 ft/s from the rating curves.

Data and site-specific issues based on site conditions and flow-channel configurations are included in the following sections. Figures show level and velocity data along with stage-discharge relationships and selected rating curves. Summary charts are included that detail data collection and discharge calculation methods at each monitoring location.

TB7B Results

TB7Bin Level and Velocity Data

Level and velocity data collected at the input to the bioswale are shown in Figure 8. A summary of data collection methods is in Table 1. TB7Bin has the most continuous level and velocity data through all monitoring years, with instrumentation installed through all pre-construction and post-construction phases. Flow configurations addressed at the site were: a culvert with continuous ponding before bioswale construction, an open culvert with no ponding after construction, a culvert with a temporary weir, and an open culvert with weir removed.

Figure 8. TB7Bin level and velocity data

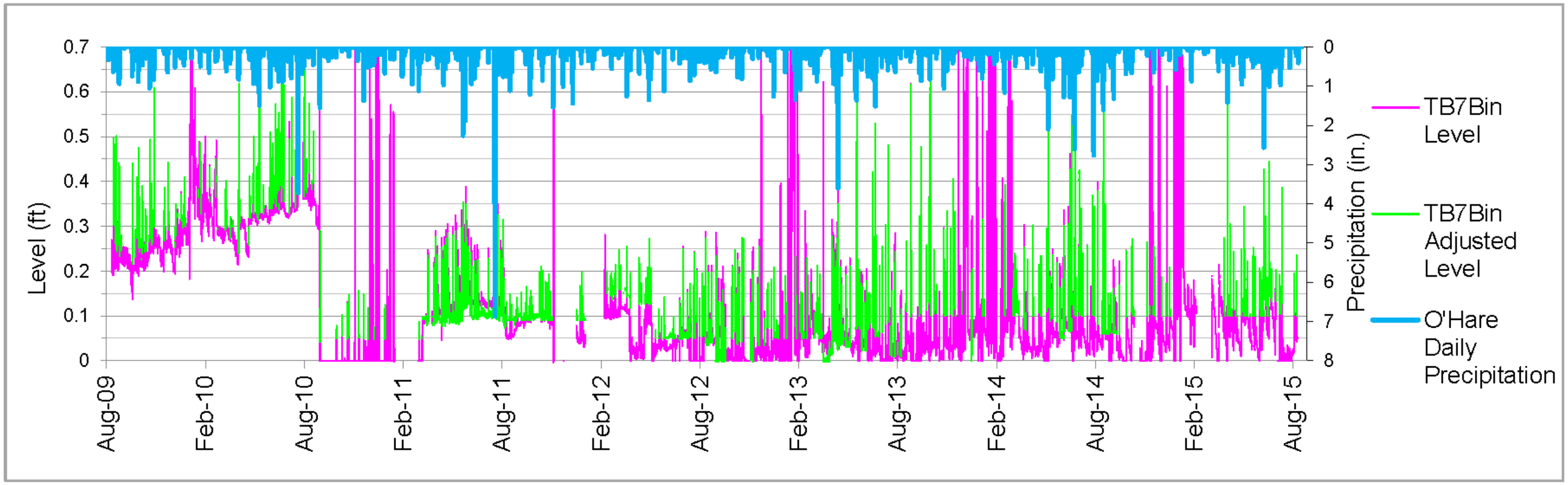


Figure 8a. Level adjustments and precipitation at TB7Bin

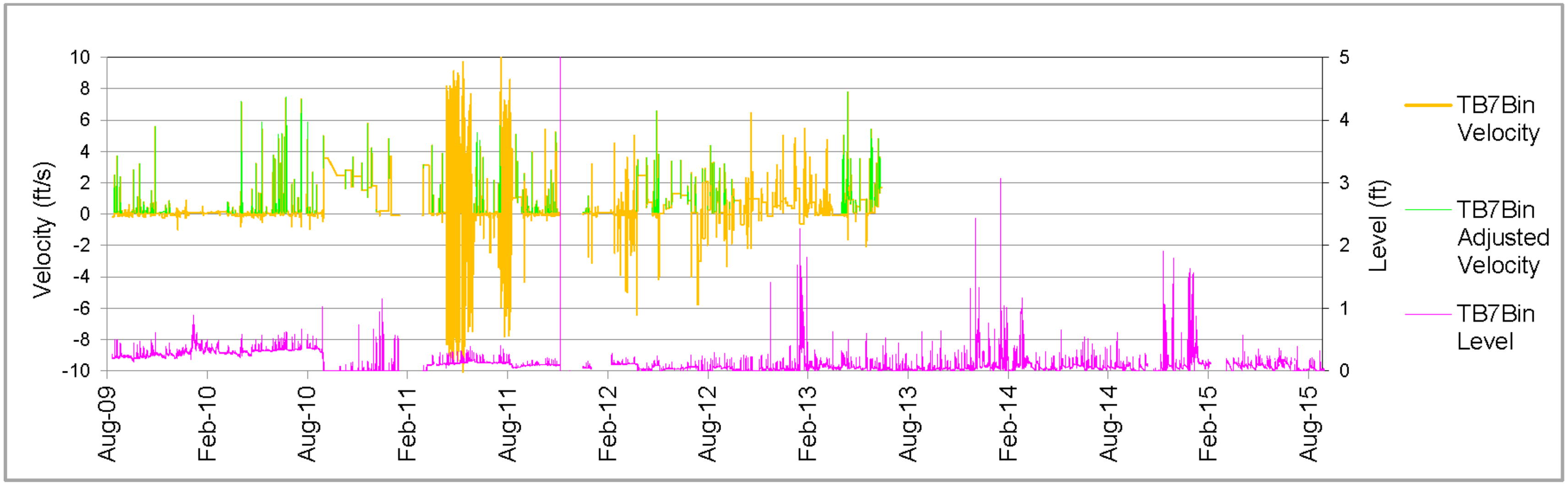


Figure 8b. Velocity measurements at TB7Bin

Table 1. TB7Bin level and velocity data collection methods

Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** TB7Bin 8/12/09 - 9/1/10	- 1.5' diameter open pipe - standing water between 0.2'-0.3'	- AV sensor - continually submerged because of ponding	- removed all levels without good sensor velocities because of ponding	- used only levels with good sensor velocities for volume calculations
Year 1 **Post-construction** TB7Bin 9/1/10 - 8/15/11	- 1.5' diameter open pipe - flow channel weir in 1.5' pipe (weir installed 3/11/11) - little to no ponding	- AV sensor	- removed levels below 0.05' AV sensor readings in open pipe or below weir height of 0.09'	- adjusted for sensor drift according to manual level calibrations (drift adjusted 0.012'-0.076')
Year 2 **Post-construction** TB7Bin 8/16/11 - 8/15/12	- 1.5' diameter pipe with weir (weir removed 5/8/12) - 1.5' diameter open pipe (after 5/8/12) - erosion control installation (11/30/11) - little to no ponding	- AV sensor	- removed levels below weir height or below 0.05' AV sensor readings in open channel	- adjusted for sensor drift according to manual level calibrations (drift adjusted 0.02'-0.098')
Year 3 **Post-construction** TB7Bin 8/16/12 - 8/15/13	- 1.5' diameter open pipe - little to no ponding	- AV sensor (removed 6/19/13) - bubbler flow module (installed 6/19/13)	- removed levels below 0.05' AV sensor readings	- adjusted for sensor drift according to manual level calibrations (drift adjusted 0.015'-0.052')
Year 4 **Post-construction** TB7Bin 8/16/13 - 8/15/14	- 1.5' diameter open pipe - increased ponding below 0.1' depth	- bubbler flow module	- removed levels according to post-peak baseline because of ponding (< 0.1')	- adjusted for sensor drift according to manual level calibrations (drift adjusted 0.013'-0.047')
Year 5 **Post-construction** TB7Bin 8/16/14 - 8/15/15	- 1.5' diameter open pipe - increased ponding below 0.1' depth	- bubbler flow module - bubbler module replaced 8/20/14 & 6/23/15	- removed levels according to post-peak baseline because of ponding (< 0.06' & < 0.1')	- adjusted for sensor drift according to manual level calibrations (drift adjusted 0.023'-0.071')

During pre-construction monitoring, water levels were continuously ponded above 0.2 ft in the inlet pipe between August 2009-September 2010, due to inefficient drainage pathways to the ditch outlet. Discharge was calculated with rating curves using only data intervals with valid velocity readings, indicating active flow during these ponded conditions. Velocity readings below 0.1 ft/s were indicated by the sensor as invalid, and these data intervals were not used to calculate discharge. Valid velocity readings were available for all active flow conditions during the entire pre-construction monitoring phase because the water level was continually above the minimum 0.083' depth for good velocity sensor readings. In the post-construction phase, the ponded conditions over the instruments were reduced when the area was re-graded and widened, causing faster drainage out of the culvert inlet.

During post-construction monitoring, a temporary weir was installed inside the culvert in Years 1 and 2 (March 2011-May 2012) to improve the capture of low-level flows. Level adjustments were made to remove all data below the level of the weir. Intermittent level drift occurred in the AV sensor pressure transducer in Years 1-3, and was corrected with instrument calibrations during site visits and level adjustments of individual data segments using manual field measurements. The AV sensor pressure transducer was replaced by a bubbler flow sensor in Years 3-5 to reduce instrument drift errors.

Increased ponding over the measurement instruments inside the culvert was observed in Years 4 and 5, with a gradual development of a plunge pool and mounding of eroded material and debris dams around the pool. Because no velocity data were available due to installed bubblers not having integrated velocity sensors, records below the baseflow of event peaks at 0.06 ft and 0.1 ft were removed from data in Years 4 and 5.

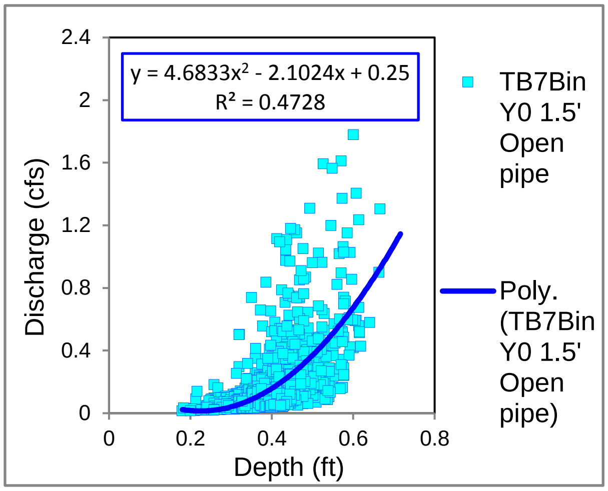
Velocity data were screened for erroneous sensor readings and velocity measurements were removed accordingly, including data between April-August 2011, which had highly erratic readings.

TB7Bin Rating Curves Used for Discharge Calculations

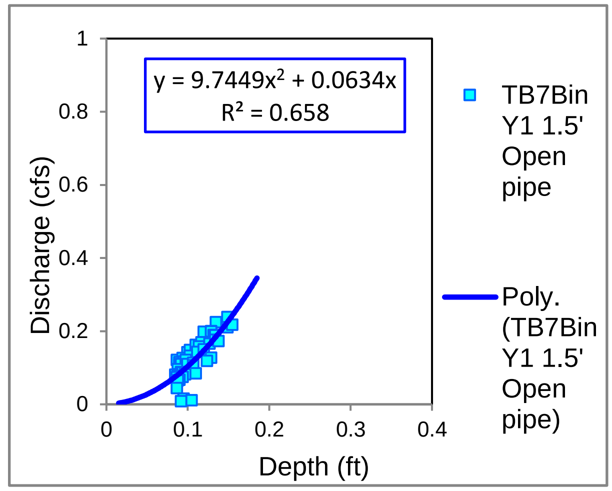
Rating curves for all flow configurations at TB7Bin are shown in Figure 9. Discharge calculation details are listed in Table 2. This site exhibited the widest range of flow variability because of high-energy discharge from the elevated roadway combined with occasional ponded conditions at the end of the pipe outlet. All measurements took place in a 1.5-ft diameter culvert pipe flowing from an elevated roadway.

Pre-construction flow conditions included continuous ponding of depths between 0.2 and 0.35 ft above the bottom of the pipe. The ponding partially inundated the end of the pipe, slowing the flow of runoff exiting the pipe. For rating curve construction in this flow channel configuration, discharge rates with velocities > 3 ft/s were removed because of probable higher velocity sensor anomalies, and a polynomial curve was fitted to the remaining data points (Figure 9a).

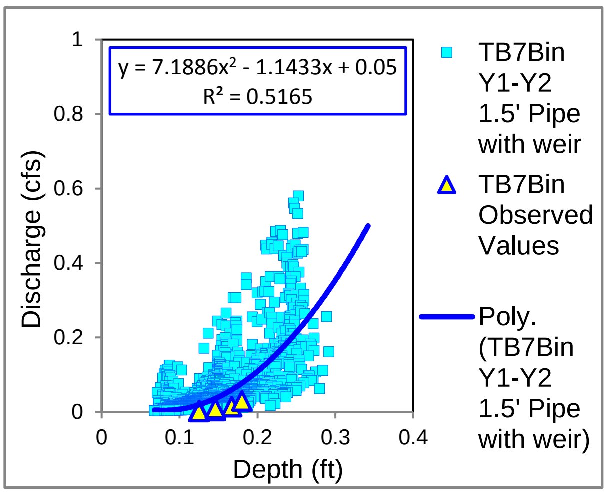
A separate rating curve was used for a brief interval, while the open pipe had flow without standing water, after bioswale construction and before a temporary weir was



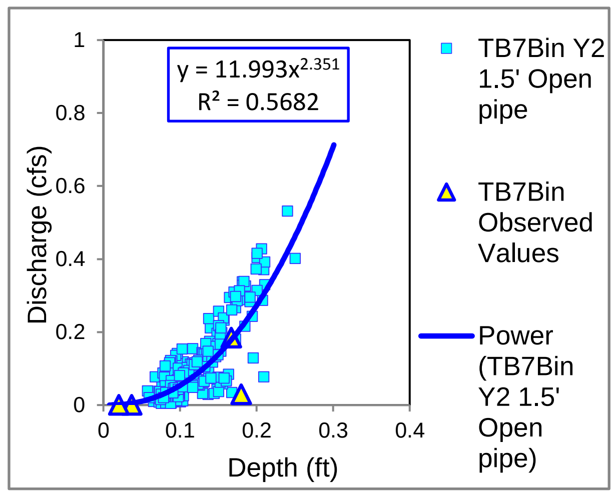
9a. Y0: 1.5’ Open pipe, standing water



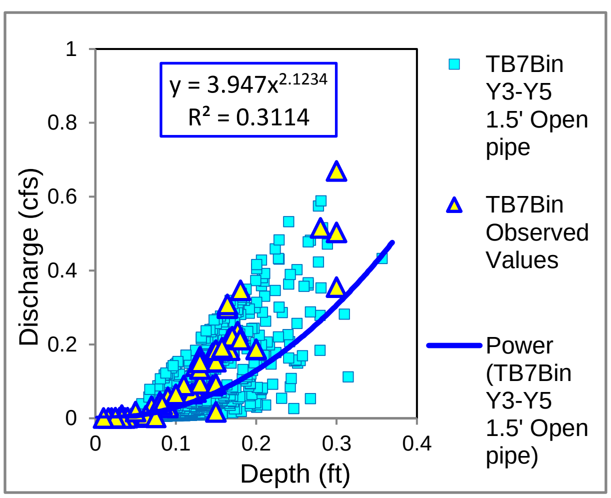
9b. Y1: 1.5’ Open pipe (9/1/10-3/11/11)



9c. Y1-Y2: 1.5’ Pipe with weir



9d. Y2: 1.5’ Open pipe (5/8/12-8/15/12)



9e. Y3-Y5: 1.5’ Open pipe (8/16/12-8/15/15)

Figure 9. TB7Bin rating curves

Table 2. TB7Bin discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** TB7Bin 8/12/09 - 9/1/10	**1.5' diameter open pipe,** **with standing water 0.2-0.3'** **8/12/09-9/1/10** Isco data rating curve Polynomial eqn. (data from 8/12/09-9/1/10) **(Figure 9a)**	**Pipe full flow - none**
Year 1 **Post-construction** TB7Bin 9/1/10 - 8/15/11	**1.5' diameter open pipe** **9/1/10-3/11/11** Isco data rating curve Polynomial eqn. (data from 9/1/10-3/11/11) **(Figure 9b)** **1.5' diameter pipe with weir** **3/11/11-8/15/11** Isco data rating curve Polynomial eqn. (data from 3/11/11-5/8/12) **(Figure 9c)**	**Pipe full flow - none** **Pipe full flow - none**
Year 2 **Post-construction** TB7Bin 8/16/11 – 8/15/12	**1.5' diameter pipe with weir** **3/11/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 3/11/11-5/8/12) **(Figure 9c)** **1.5' diameter open pipe** **5/8/12-8/15/12** Isco data rating curve Power eqn. (data from 5/8/12-8/15/12) **(Figure 9d)**	**Pipe full flow - none** **Pipe full flow - none**
Year 3 **Post-construction** TB7Bin 8/16/12 – 8/15/13	**1.5' diameter open pipe** **8/16/12-8/15/13** Isco data rating curve Power eqn. (data from 5/8/12-6/15/13) **(Figure 9e)**	**Pipe full flow - none**
Year 4 **Post-construction** TB7Bin 8/16/13 – 8/15/14	**1.5' diameter open pipe** **8/16/13-8/15/14** Isco data rating curve Power eqn. (data from 5/8/12-6/15/13) **(Figure 9e)**	**Pipe full flow - none**
Year 5 **Post-construction** TB7Bin 8/16/14 – 8/15/15	**1.5' diameter open pipe** **8/16/14-8/15/15** Isco data rating curve Power eqn. (data from 5/8/12-6/15/13) **(Figure 9e)**	**Pipe full flow - none**

installed (Figure 9b). The rating curve for the pipe with the weir in Years 1 and 2 is a polynomial curve with higher velocity data removed (Figure 9c). Another rating curve was used for the interval after the weir was removed and before the beginning of Year 3 monitoring (Figure 9d). This rating curve was used until ponded conditions recurred again in Years 3 through 5 (Figure 9e). Increased ponding and variable flow conditions are evident in this open-pipe rating curve seen in higher depth values with lower discharge rates. This lower velocity and discharge flow regime is under-represented by the manual measurement data, and therefore an Isco data curve was selected and the manual measurement curve was not used. There are also looped ratings evident exhibiting hysteresis for a number of discharge events, including events with velocities over 3 ft/s, resulting from ponded or unsteady flow conditions at the pipe outlet. The rating curve for this interval used a power regression line as most representative of all flows.

TB7Bout Level and Velocity Data

Level and velocity data collected at the TB7B output monitoring station (TB7Bout) are shown in Figure 10. A summary of data collection methods is shown in Table 3. There was no excessive ponding over the instruments and no instrument level drift evident. TB7Bout has a fairly continuous level and velocity record with instruments present at all times, except not installed in the first half of post-construction Year 1 monitoring (August 2010-February 2011).

Isco sensors in Year 3 had power failure issues from 9/17/12-5/15/13, and were not working continuously for much of the monitoring year, resulting in an unrepresentative and incomplete level record and lower volume totals for Year 3.

Smaller discharge events recorded at TB7Bin did not always reach the outlet pipe, so the level record at TB7Bout has fewer events than at TB7Bin. A temporary weir was installed in the TB7Bout culvert from September 2009 through May 2012 to capture low-level flows, and levels below the weir height were removed for discharge calculations.

Velocity data were screened for erroneous sensor readings and suspect data was removed, including selected data from April to August 2011 that displayed erratic readings.

TB7Bout Rating Curves Used for Discharge Calculations

Rating curves for all flow configurations at TB7Bout are shown in Figure 11. Discharge calculation details are listed in Table 4. Measurements at TB7Bout took place in a 2-ft diameter culvert at the downstream end of the bioswale during pre-construction and post-construction Years 1-3. Late in Year 3 and through Years 4 and 5 the instruments were relocated slightly upstream and installed in the downstream check dam due to concerns about loss of flow near the culvert pipe opening. Flow was not subject to ponding or highly unsteady conditions in either configuration.

Figure 10. TB7Bout level and velocity data

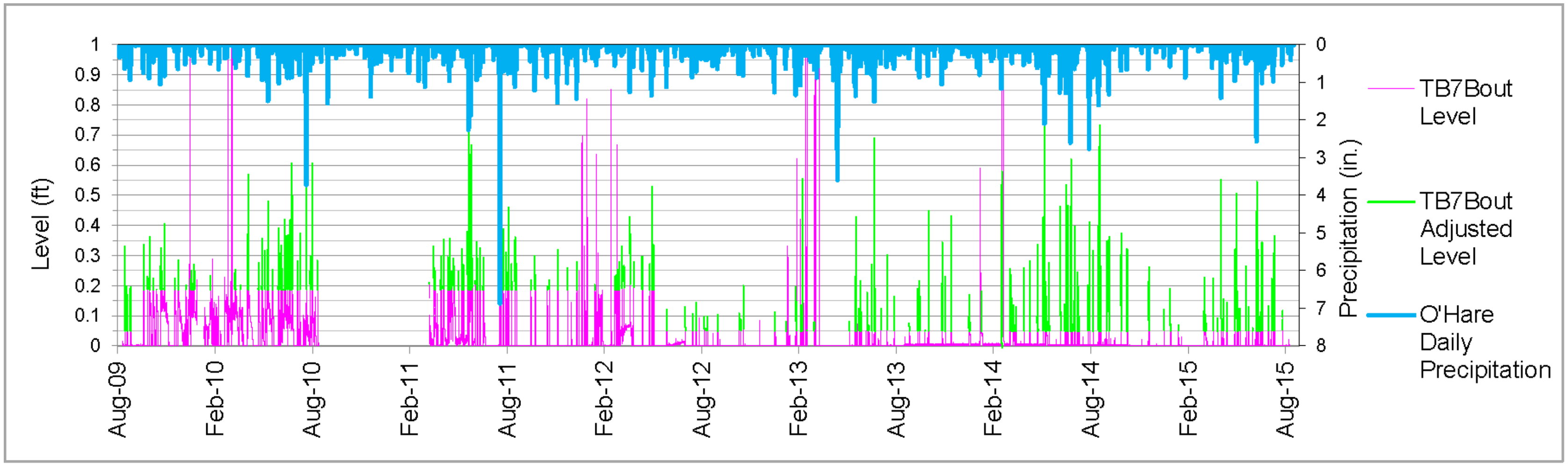


Figure 10a. Level adjustments and precipitation at TB7Bout

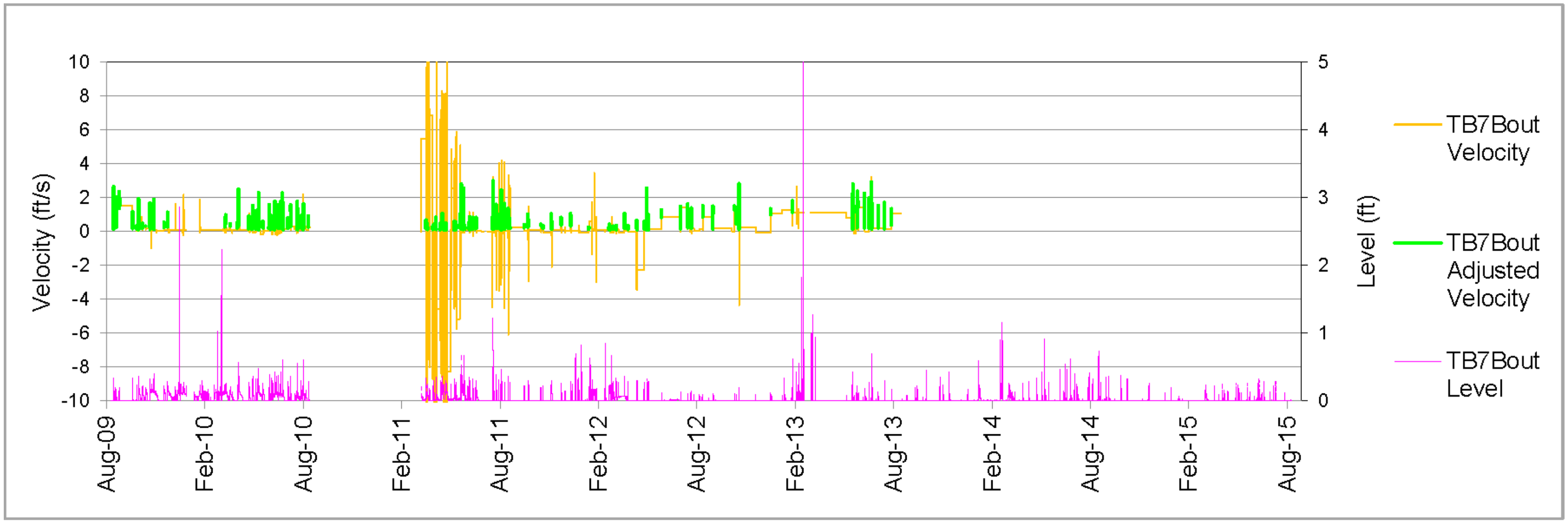
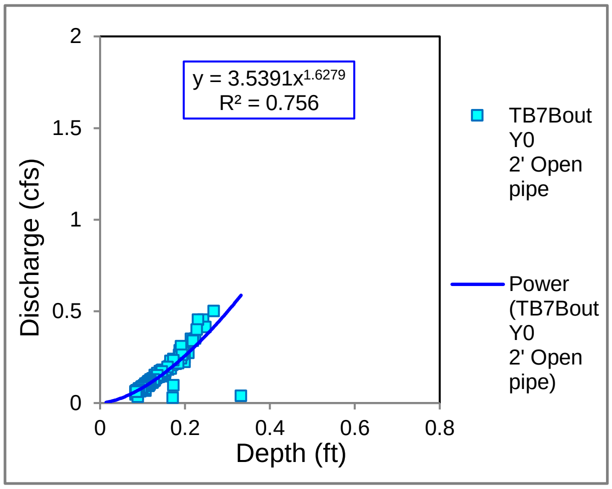


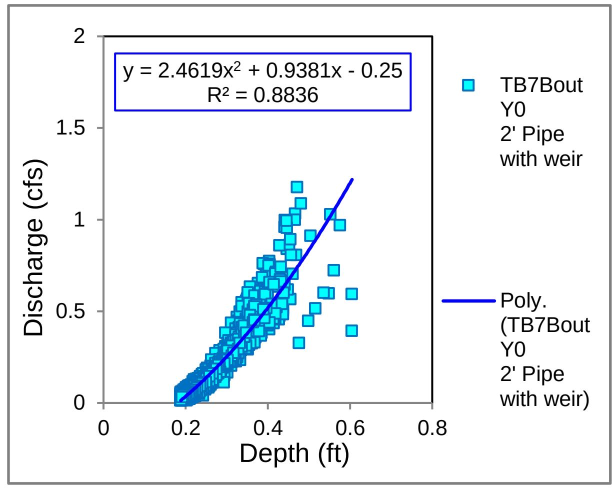
Figure 10b. Velocity measurements at TB7Bout

Table 3. TB7Bout level and velocity data collection methods

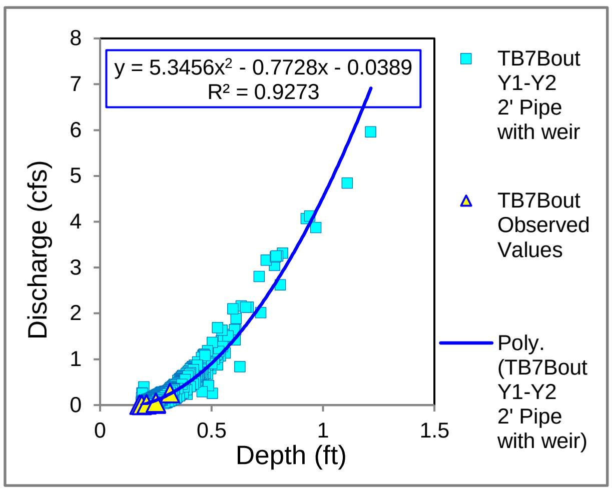
Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** TB7Bout 8/11/09 - 8/15/10	- 2' diameter open pipe - 2' diameter pipe with weir (weir installed 9/9/09)	- AV sensor	- removed sensor level data below 0.05' in 2' open pipe - removed sensor level data below weir height (0.187') in 2’ diameter pipe with weir	- no level drift in AV sensor data
Year 1 **Post-construction** TB7Bout 3/11/11 - 8/15/11	- 2' diameter pipe with weir - no ponding over instruments	- AV sensor	- removed sensor level data below weir height (0.187')	- no level drift in AV sensor data
Year 2 **Post-construction** TB7Bout 8/16/11 - 8/15/12	- 2' diameter pipe with weir (weir removed 5/8/12) - 2' diameter open pipe (after 5/8/12)	- AV sensor	- removed sensor level data below weir height (0.187') - removed sensor level data below 0.05' in 2’ diameter open pipe	- no level drift in AV sensor data
Year 3 **Post-construction** TB7Bout 8/16/12 - 8/15/13	- 2' diameter open pipe (8/16/12-6/13/13) - concrete check dam sensor relocation (after 6/13/13) - rectangular concrete check dam channel - 0.59' height at sensor	- AV sensor - Instrument power issues	- removed sensor level data below 0.05' in 2’ diameter open pipe	- no level drift in AV sensor data
Year 4 **Post-construction** TB7Bout 8/16/13 - 8/15/14	- open concrete check dam	- AV sensor (removed 8/19/13) - bubbler flow module (installed 8/19/13)	- removed sensor level data below 0.05' in 2’ diameter open pipe	- no level drift in AV sensor data - no level drift in bubbler sensor data
Year 5 **Post-construction** TB7Bout 8/16/14 - 8/15/15	- open concrete check dam	- bubbler flow module	- removed sensor level data below 0.05' in 2’ diameter open pipe	- no level drift in bubbler sensor data



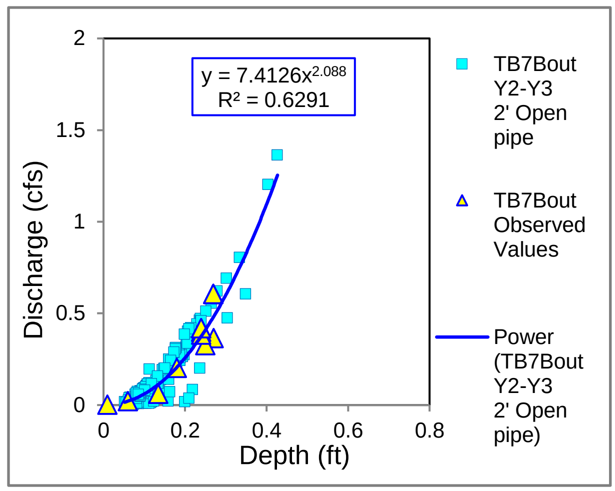
11a. Y0: 2’ Open pipe



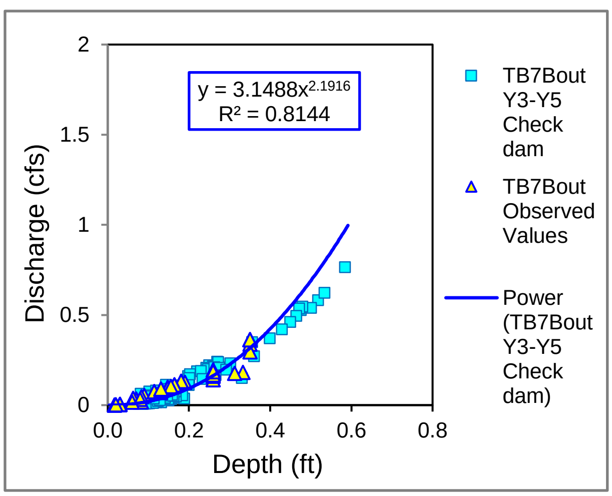
11b. Y0: 2’ Pipe with weir



11c. Y1-Y2: 2’ Pipe with weir



11d. Y2-Y3: 2’ Open pipe



11e. Y3-Y5: Open check dam

Figure 11. TB7Bout rating curves

Table 4. TB7Bout discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** TB7Bout 8/16/09 - 8/16/10	**2' diameter open pipe** **8/16/09-9/9/09** Isco data rating curve Power eqn. (data from 8/16/09-9/9/09) **(Figure 11a)** **2' diameter pipe with weir** **9/9/09-8/16/10** Isco data rating curve Polynomial eqn. (data from 9/9/09-8/16/10) **(Figure 11b)**	**Pipe full flow – none** **Pipe full flow - none**
Year 1 **Post-construction** TB7Bout 3/11/11 - 8/15/11	**2' diameter pipe with weir** **3/11/11-8/15/11** Isco data rating curve Polynomial eqn. (data from 3/11/11-5/8/12) **(Figure 11c)**	**Pipe full flow - none**
Year 2 **Post-construction** TB7Bout 8/16/11 – 8/15/12	**2' diameter pipe with weir** **8/16/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 3/11/11-5/8/12) **(Figure 11c)** **2' diameter open pipe** **5/8/12-8/15/12** Isco data rating curve Power eqn. (data from 5/8/12-6/13/13) **(Figure 11d)**	**Pipe full flow - none** **Pipe full flow - none**
Year 3 **Post-construction** TB7Bout 8/16/12 – 8/15/13	**2' diameter open pipe** **8/16/12-6/13/13** Isco data rating curve Power eqn. (data from 5/8/12-6/13/13) **(Figure 11d)** **Open concrete check dam - 6/13/13-8/15/13** Isco data rating curve Power eqn. (data from 6/13/13-8/19/13) **(Figure 11e)**	**Pipe full flow – none** **Over channel flow – 9%** Isco power rating curve 6/26/13
Year 4 **Post-construction** TB7Bout 8/16/13 – 8/15/14	**Open concrete check dam - 8/16/13-8/15/14** Isco data rating curve Power eqn. (data from 6/13/13-8/19/13) **(Figure 11e)**	**Over channel flow – 15%** Isco power rating curve 2/20/14, 5/12/14, 6/30/14
Year 5 **Post-construction** TB7Bout 8/16/14 – 8/15/15	**Open concrete check dam - 8/16/14-8/15/15** Isco data rating curve Power eqn. (data from 6/13/13-8/19/13) **(Figure 11e)**	**Over channel flow – 5%** Isco power rating curve 8/22/14-8/23/14

Pre-construction flow conditions include a short span of open culvert flow in August 2009 (Figure 11a), and a weir configuration starting in September 2009 (Figure 11b). A weir was installed very early in the pre-construction phase to improve capture of low level flows. During the Year 1 post-construction monitoring (Figure 11c) after installation of the check dams, higher-velocity flows than the pre-construction year were measured at the TB7Bout culvert location. It is possible that installation of the bioswale check dam just upstream of the culvert monitoring location created a channelization of flow directly through the check dam channel to the culvert pipe outlet, causing an increase of flow velocities in the culvert pipe that was not present during pre-construction monitoring. Higher culvert velocities in Year 1 were seen with three large precipitation events on 5/25/11, 5/29/11, and 7/23/11. Similar-sized events occurred in the pre-construction phase that did not have similarly high velocities. The flow channel weir was removed late in Year 2 (Figure 11d), and monitoring instruments were moved into the last check dam location in Years 4 and 5 (Figure 11e), where flow velocities were lower than those of the original culvert pipe location. Polynomial regression equations using Isco data were used as the best fit for when the weir was installed and power equations were used for open flow conditions without a weir.

TB9A Results

TB9Ac2N Input Level and Velocity Data

Level and velocity data collected at the TB9A bioswale input monitoring station TB9Ac2N are shown in Figure 12. A summary of data collection methods is presented in Table 5. TB9Ac2N was monitored during Years 4 and 5 as one of five input culverts to the bioswale to assess whether it was comparable to the other direct input culvert from the elevated roadway at TB7Bin. Flow conditions at the TB9Ac2N site exceeded instrument design capabilities during monitoring, making the data record incomplete and not representative for the purposes of calculating discharge volumes. In addition, uncorrectable instrument level drift was observed in the data record and removed from March through June 2014, in August 2014, and in March 2015, resulting from bubbler line malfunction. Data are presented here to document activities and provide approximate comparisons.

Field observations of high-velocity flows greater than the range of the monitoring instrument were made at the inlet pipe, resulting from high-energy runoff from the elevated roadway during storm events. This high-velocity flow resulted in poor quality velocity data during larger precipitation events. This restricted the range of good quality readings and created a simplified rating curve that did not represent data for the full range of flows. For these reasons, conclusions regarding TB9Ac2N are not presented in this report.

TB9Ac2N Rating Curve Used for Discharge Calculations

The rating curve for the channel configuration at TB9Ac2N is shown in Figure 13. Site discharge calculation details are listed in Table 6. The bioswale inlet at TB9Ac2N was

Figure 12. TB9Ac2N level and velocity data

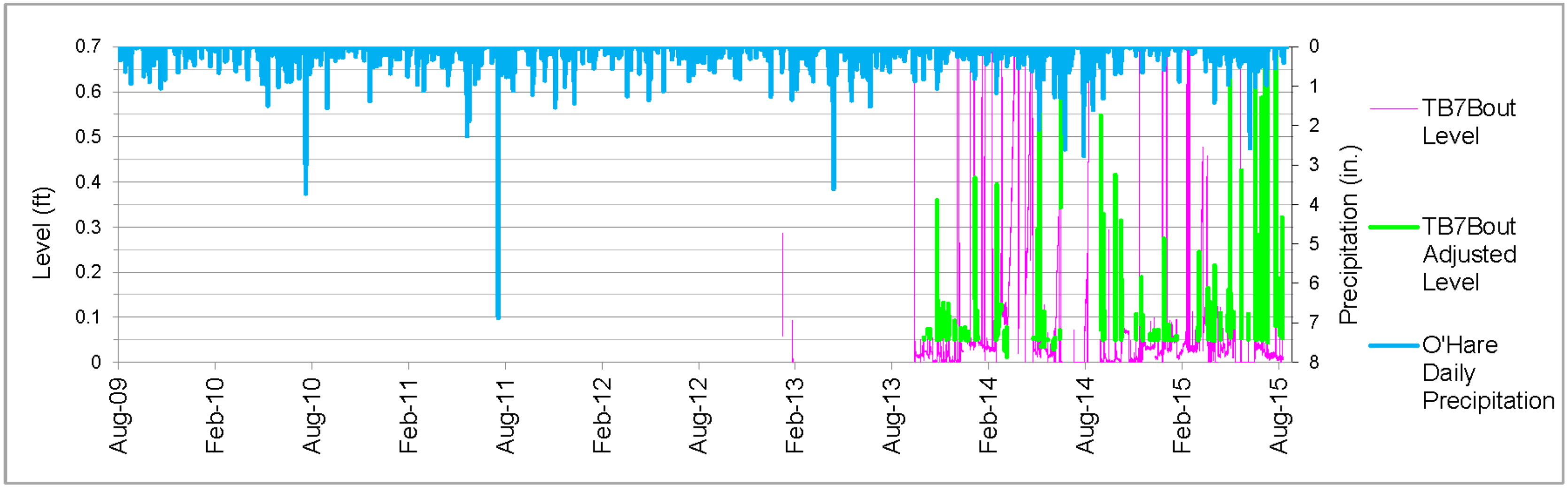


Figure 12a. Level adjustments and precipitation at TB9Ac2N

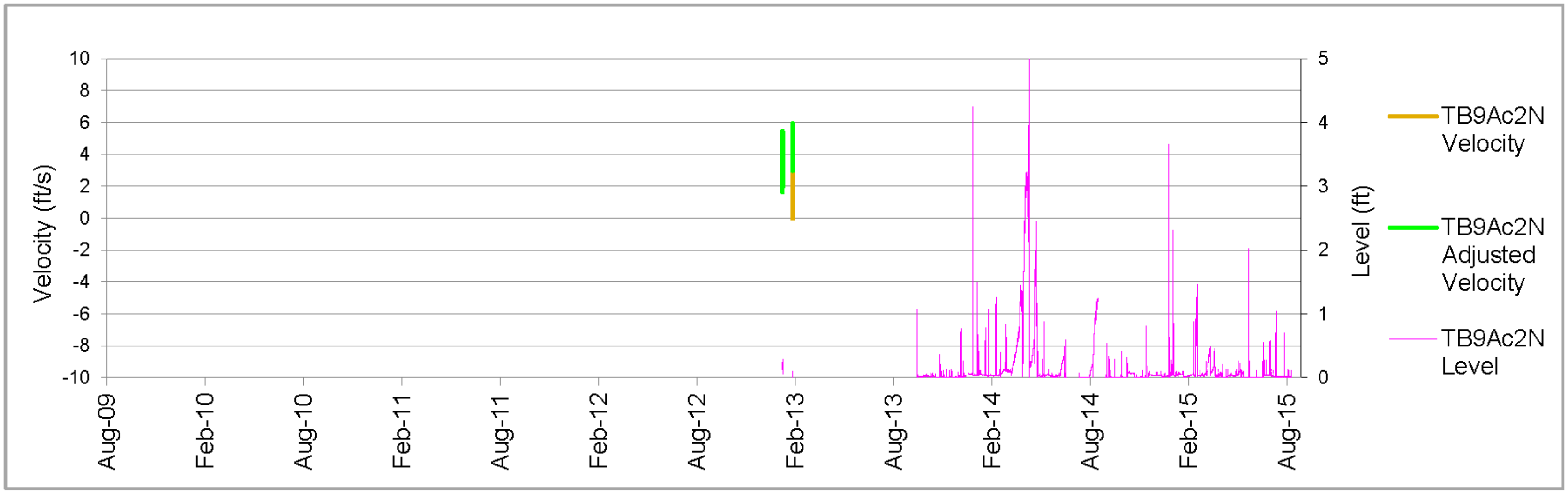
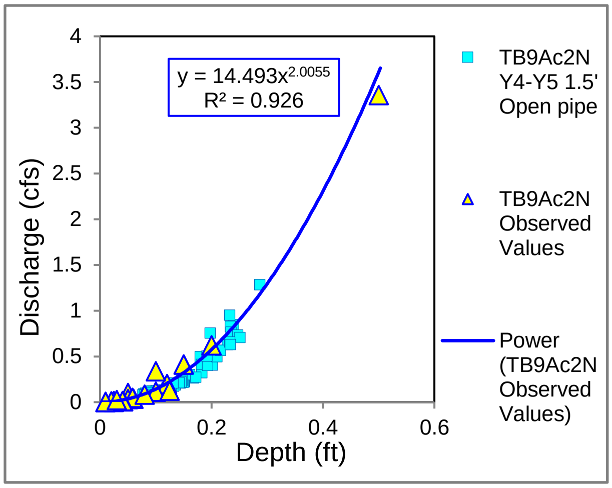


Figure 12b. Velocity measurements at TB9Ac2N

Table 5. TB9Ac2N level and velocity data collection methods

Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not monitored			
Year 1 **Post-construction** 8/16/10 - 8/15/11	Not monitored			
Year 2 **Post-construction** 8/16/11 - 8/15/12	Not monitored			
Year 3 **Post-construction** TB9Ac2N (1/10/13-1/30/13)	- Monitored for stage-discharge relationships - 1.5' diameter open pipe	- AV sensor (1/10/13-1/30/13)		
Year 4 **Post-construction** TB9Ac2N 9/17/13 - 8/15/14	- 1.5' diameter open pipe	- bubbler flow module	- removed sensor level data below 0.05' - removed instrument malfunction data / level drift: 3/12/14 05:51 - 4/30/14 13:00 6/11/14 06:30 - 6/18/14 10:30 6/24/14 11:00 - 8/15/14 23:59	- uncorrectable level drift in bubbler sensor data
Year 5 **Post-construction** TB9Ac2N 8/16/14 - 8/15/15	- 1.5' diameter open pipe	- bubbler flow module - bubbler module replaced 6/9/15	- removed sensor level data below 0.05' - removed instrument malfunction data: 8/16/14-9/3/14 3/17/15-3/26/15 5/27/15-6/23/15	- adjusted for sensor drift according to manual level calibrations - adjusted for sensor drift according to baseline levels - 4/28/15-5/17/15



13. Y4-Y5: 1.5’ Open pipe

Figure 13. TB9Ac2N rating curve

Table 6. TB9Ac2N discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not Monitored	Not Monitored
Year 1 **Post-construction** 8/16/10 - 8/15/11	Not Monitored	Not Monitored
Year 2 **Post-construction** 8/16/11 - 8/15/12	Not Monitored	Not Monitored
Year 3 **Post-construction** 1/10/13-1/30/13	Not Monitored	Not Monitored
Year 4 **Post-construction** TB9Ac2N 9/17/13 - 8/15/14	**2' diameter open pipe** **8/16/13-8/15/14** Manual observations data rating curve Power eqn. (data from 10/1/13-3/10/14) **(Figure 13)**	**Pipe full flow - none**
Year 5 **Post-construction** TB9Ac2N 8/16/14 - 8/15/15	**2' diameter open pipe** **8/16/14-8/15/15** Manual observations data rating curve Power eqn. (data from 10/1/13-3/10/14) **(Figure 13)**	**Pipe full flow - none**

monitored in Years 4 and 5 in a 1.5-ft diameter culvert. The culvert did not have a weir installed. This site exhibited highly varied flows because of runoff draining directly from the elevated roadway, similar to the setup at TB7Bin. The highly varied flows caused difficulties in Isco AV sensor instrument level and velocity readings, so the selected rating curve was constructed with manual observation data for volume calculations, and was less representative of all flow conditions at the site.

TB9A Output Level and Velocity Data

Level and velocity data collected at the TB9A bioswale output monitoring station TB9A are shown in Figure 14. A summary of data collection methods is in Table 7. TB9A has a continuous data record during the pre-construction phase and also from late in Year 1 to Year 5 (6/8/2011-8/15/2015). Flow configurations were adjusted for a temporary weir in Years 1 and 2 and sensor drift during the last month of the pre-construction phase.

The level and velocity sensors generally worked well at this site, with adjustment for level sensor drift in July 2010 being the only correction needed. A weir was installed in Year 1, and discharge was adjusted to remove calculated flows below weir height. TB9A had occasional ponding during large events, and velocity data were used in pre-construction and post-construction Years 1-3 for discharge calculations to identify intervals of active flow in ponded conditions. Rating curves were used in Years 4 and 5 for over-channel flow as velocity data were not collected. Any underestimation of over-channel flow in Years 4 and 5 likely was not a large amount, as there were very few large precipitation events, and over-channel levels during these events were brief and averaged only 0.32 ft above the check dam channel height.

TB9A Rating Curves Used for Discharge Calculations

Rating curves for all flow configurations at TB9A are shown in Figure 15. Site discharge calculation details are listed in Table 8. Pre-construction measurements took place in a vegetated ditch at the downstream end of the bioswale installation. After bioswale construction, instruments were installed in the check dam closest to the pre-construction monitoring location. This site was subject to infrequent high-level backwater conditions after large rain events, most notably when there was flooding along Farmers Creek, where the bioswale discharged. Some degree of low-level backup was also evident after smaller events.

Pre-construction flow conditions show the vegetated ditch measurements with high levels of backwater, and highly varied velocity and discharge rates for depths above 1.55 ft. To calculate discharge volumes for depths below 1.55 ft, levels above 1.55 ft and velocities greater than 3 ft/s were removed from the data to make the rating curve (Figure 15a). Discharge volumes for depths above 1.55 ft were calculated with Isco AV sensor data.

Post-construction monitoring with the temporary weir installed in Years 1-2 is shown in Figure 15b. Velocities above 3 ft/s were removed to make the rating curve due to high variability. After the flow channel weir was removed, stage-discharge relations

Figure 14. TB9A level and velocity data

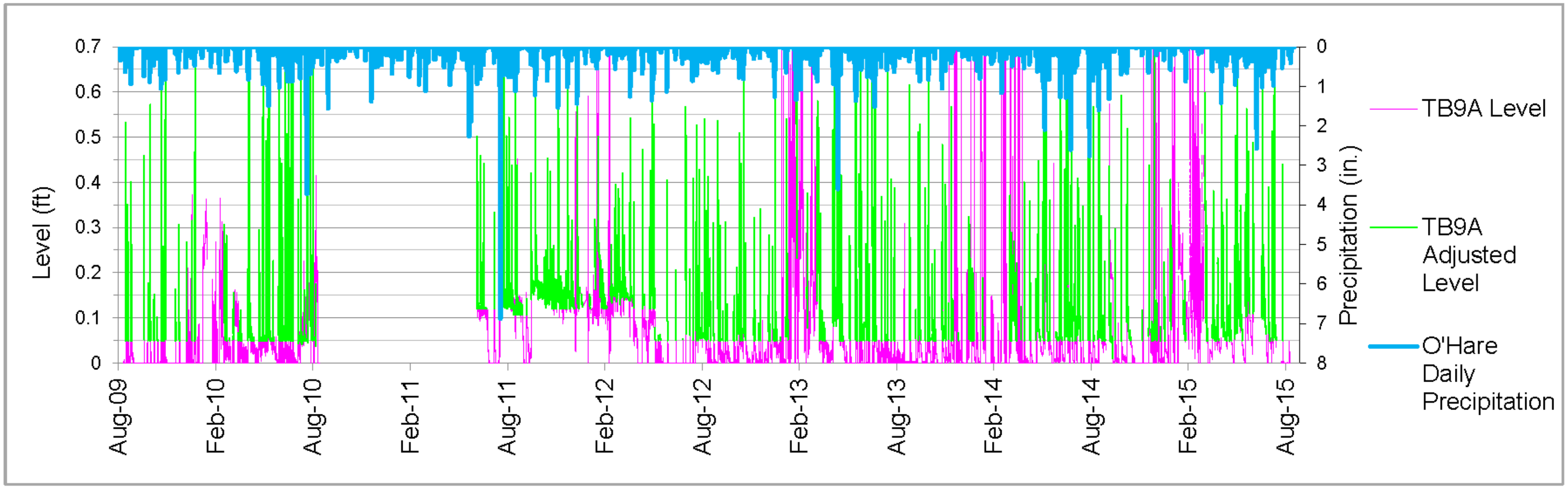


Figure 14a. Level adjustments and precipitation at TB9A

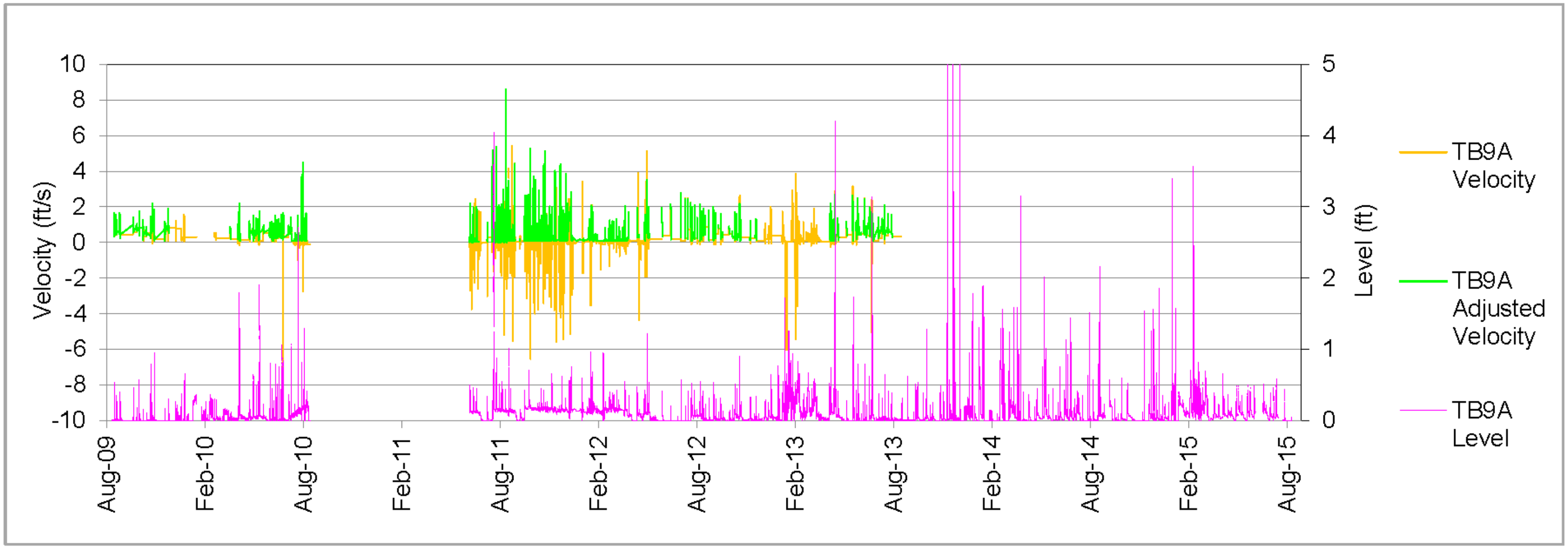
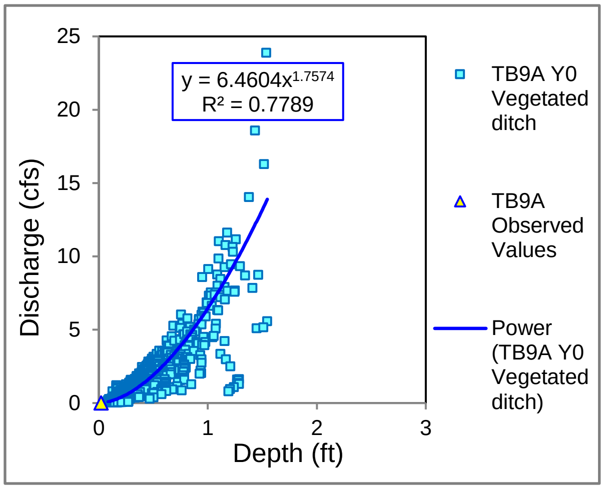


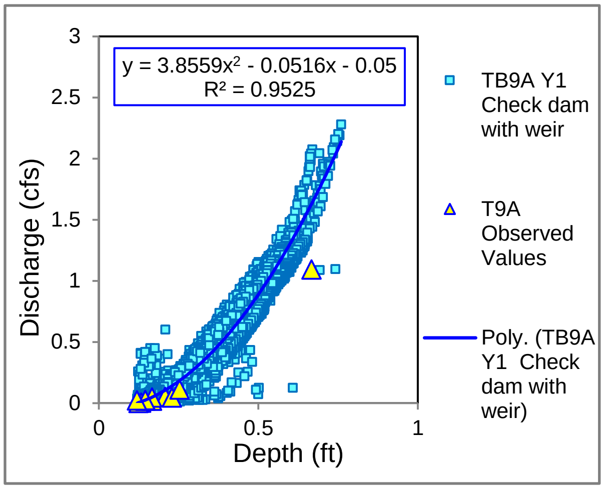
Figure 14b. Velocity measurements at TB9A

Table 7. TB9A level and velocity data collection methods

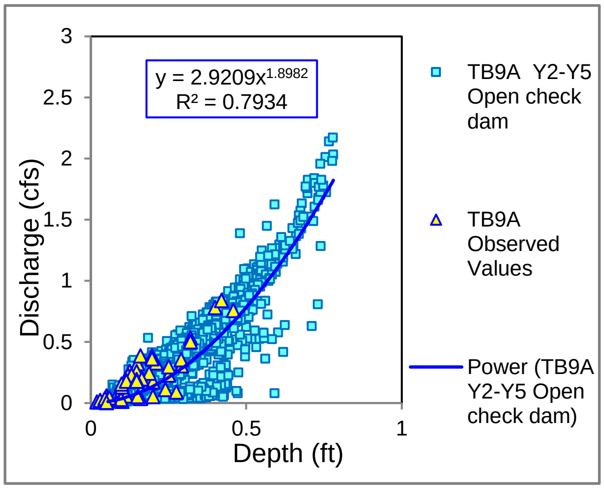
Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** TB9A 8/12/09 - 8/15/10	- vegetated ditch - large channel measurements: 2 ft. bottom width 15.5 ft. top width 2 ft. max height	- AV sensor	- removed sensor level data below 0.05'	- adjusted for sensor drift according to baseline levels - 7/6/10-8/13/10 (0.292') - backwater (levels > 1.55') 4/3/10-4/6/10, 5/13/10, 7/24/10
Year 1 **Post-construction** TB9A 6/8/11 - 8/15/11	- concrete check dam sensor location with weir - check dam rectangular channel 0.78' height at sensor	- AV sensor	- removed sensor level data below weir height (0.121') in concrete check dam channel with weir	- no level drift in AV sensor data
Year 2 **Post-construction** TB9A 8/16/11 - 8/15/12	- concrete check dam sensor location with weir (weir removed 5/8/12) - open concrete check dam (after 5/8/12)	- AV sensor	- removed sensor level data below weir height (0.121') - removed sensor level data below 0.05' sensor levels in open check dam channel	- no level drift in AV sensor data
Year 3 **Post-construction** TB9A 8/16/12 - 8/15/13	- open concrete check dam	- AV sensor	- removed sensor level data below 0.05'	- no level drift in AV sensor data - backwater (selected AV sensor velocities used) 4/16/13-4/18/13, 6/26/13
Year 4 **Post-construction** TB9A 8/16/13 - 8/15/14	- open concrete check dam	- AV sensor (removed 8/21/13) - bubbler flow module (installed 8/21/13)	- removed sensor level data below 0.05'	- no level drift in AV sensor data - two large slush events removed: 1/10/14-1/14/14, 2/19/14-2/24/14 - no level drift in bubbler sensor data
Year 5 **Post-construction** TB9A 8/16/14 - 8/15/15	- open concrete check dam	- bubbler flow module	- removed sensor level data below 0.05'	- no level drift in bubbler sensor data - two large slush events removed: 1/17/15-1/27/15, 3/7/15-3/9/15



15a. Y0: Open vegetated ditch



15b. Y1-Y2: Check dam with weir



15c. Y2-Y5: Open check dam

Figure 15. TB9A rating curves

Table 8. TB9A discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** TB9A 8/12/09 - 8/15/10	**Vegetated ditch - 8/16/09-9/9/09** Isco data rating curve Power eqn. (data from 8/16/09-8/15/10) **(Figure 15a)**	**Backwater flow** **(Levels > 1.55') – 11%** Isco AV sensor 4/5/10, 5/13/10, 7/23-7/24/10 **Flow above Y1 channel height 0.78' – 46%**
Year 1 **Post-construction** TB9A 6/8/11 - 8/15/11	**Concrete check dam with weir** **6/8/11-8/15/11** Isco data rating curve Polynomial eqn. (data from 6/8/11-5/8/12) **(Figure 15b)**	**Over channel flow – 57%** Isco AV equation 7/23/11, 7/29/11
Year 2 **Post-construction** TB9A 8/16/11 - 8/15/12	**Concrete check dam with weir** **8/16/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 6/8/11-5/8/12) **(Figure 15b)** **Open concrete check dam channel** **5/8/12-8/15/12** Isco data rating curve Power eqn. (data from 5/8/12-8/15/13) **(Figure 15c)**	**Over channel flow – 4%** Isco AV equation 8/20/11, 5/3/12
Year 3 **Post-construction** TB9A 8/16/12 - 8/15/13	**Open concrete check dam channel** **8/16/12-8/15/13** Isco data rating curve Power eqn. (data from 5/8/12-8/15/13) **(Figure 15c)**	**Over channel flow – 35%** Isco AV equation 10/23/12, 1/29/13, 4/18-4/19/13, 5/20/13, 5/22/13, 5/30/13, 6/12/13, 6/26/13
Year 4 **Post-construction** TB9A 8/16/13 - 8/15/14	**Open concrete check dam channel** **8/16/13-8/15/14** Isco data rating curve Power eqn. (data from 5/8/12-8/15/13) **(Figure 15c)**	**Over channel flow – 33%** Isco power rating curve 10/5/13, 5/12-5/15/14, 6/21/14, 6/24/14, 6/30/14, 7/1/14, 8/4/14
Year 5 **Post-construction** TB9A 8/16/14 - 8/15/15	**Open concrete check dam channel** **8/16/14-8/15/15** Isco data rating curve Power eqn. (data from 5/8/12-8/15/13) **(Figure 15c)**	**Over channel flow – 20%** Isco power rating curve 8/22-8/23/14, 12/3/14, 4/9/15, 5/8/15, 6/25/15, 7/18/15

remained very similar, indicating occasional backwater after the weir was removed (Figure 15c). There were no velocities above 3 ft/s in the open check dam discharge measurements. Backwater or ponding was not fully represented with manual measurements, and Isco data were used for the rating curve. Discharge volumes above the check dam rectangular channel height of 0.78 ft were calculated separately with Isco area-velocity data and rating curve equations.

TB15B Results

TB15Bc1N Input Level and Velocity Data

Level and velocity data collected at the TB15B bioswale input monitoring station TB15Bc1N are shown in Figure 16. A summary of data collection methods is in Table 9. TB15Bc1N was monitored during Years 4 and 5 as one of three input culverts to the bioswale to assess whether it was comparable to TB7Bin. This location had frequent flow backed up with silt and debris below a 0.1 ft depth and did not drain freely into the bioswale drainage area. The frequently backed-up flow condition was adjusted for by removal of stagnant levels below 0.1 ft from volume calculations and removing selected velocities above 1 ft/s from the rating curve. There was also uncorrectable level sensor drift between March and June 2015. These altered flow conditions made the site unsuitable for direct discharge and volume calculations. Data are presented for approximate comparisons.

TB15Bc1N Rating Curves Used for Discharge Calculations

The rating curve for flow conditions at TB15Bc1N is shown in Figure 17. Site discharge calculation details are listed in Table 10. The bioswale inlet for TB15B was monitored in Years 4 and 5 in a concrete channel just outside of a 2-ft diameter round culvert pipe. The culvert did not have a weir installed. This site exhibited variable flow regimes because of ponding and debris dams that formed at the culvert exit. Flow damming effects were seen as wide variations in data with velocities above 1 ft/s. This higher velocity data was removed to construct the rating curve using Isco data.

TB15B Output Level and Velocity Data

Level and velocity data collected at the pre-construction vegetated ditch output location at TB15B and the post-construction underdrain output pipe at TB15Bgw are shown in Figure 18. Level and velocity data for the post-construction TB15Bsw dry bioswale surface water output is shown in Figure 19. A summary of data collection methods is in Tables 11 and 12.

The TB15B pre-construction monitoring instrument was set in an open ditch, and data showed a large diurnal signature in the transducer data between March 2009 and July 2009. This diurnal signature was minimized in later level data by minimizing daily heating of the instrument and cable and raising the flowsensor height.

Figure 16. TB15Bc1N level and velocity data

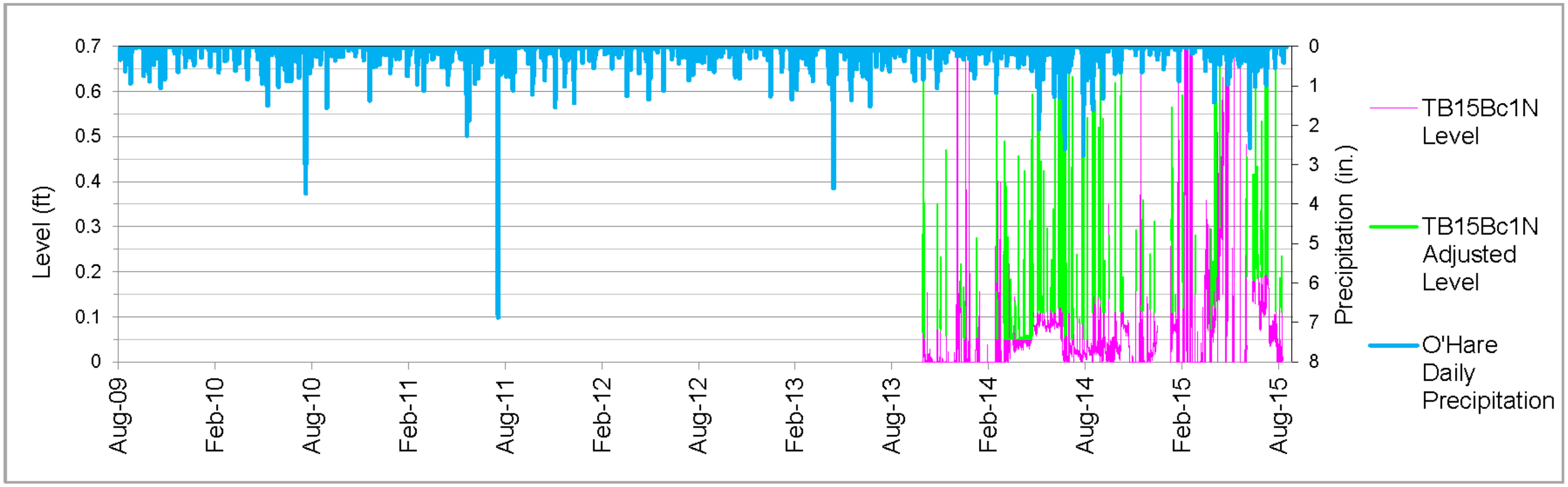


Figure 16a. Level adjustments and precipitation at TB15Bc1N

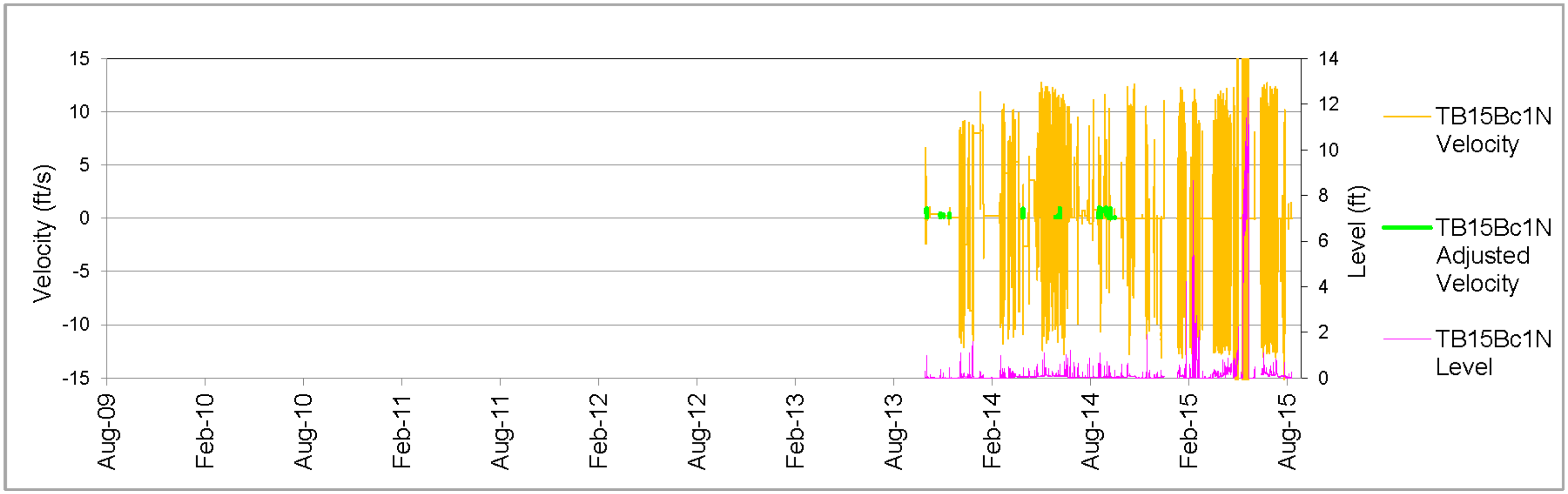
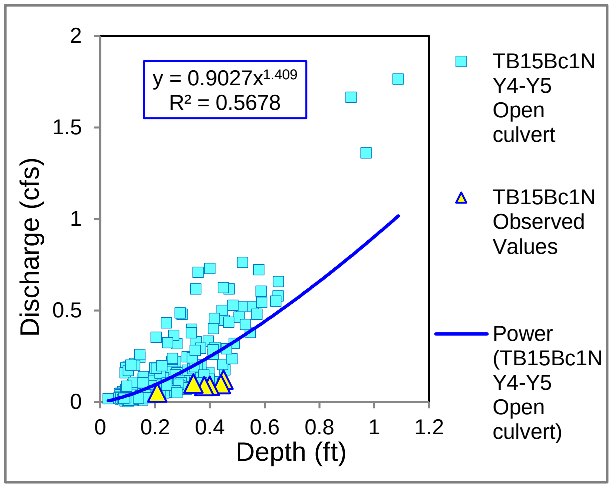


Figure 16b. Velocity measurements at TB15Bc1N

Table 9. TB15Bc1N level and velocity data collection methods

Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** 8/16/09-8/15/10	Not monitored			
Year 1 **Post-construction** 8/16/10-8/15/11	Not monitored			
Year 2 **Post-construction** 8/16/11-8/15/12	Not monitored			
Year 3 **Post-construction** 8/16/12-8/15/13	Not monitored			
Year 4 **Post-construction** TB15Bc1N 10/01/13 - 8/15/14	- 2' diameter open culvert pipe, monitored in rectangular concrete outlet channel	- AV sensor	- removed sensor level data below 0.05' - removed stagnant levels below 0.11 ft. after 5/1/14	- very little level drift in AV sensor data - high degree of ponding with silt and debris buildup
Year 5 **Post-construction** TB15Bc1N 8/16/14 - 8/15/15	- 2' diameter open pipe	- AV sensor	- removed stagnant levels below 0.11 ft. after 5/1/14	- very little level drift in AV sensor data - high degree of ponding with silt and debris buildup



17. Y4-Y5: 2' Open culvert

Figure 17. TB15Bc1N rating curve

Table 10. TB15Bc1N discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** 8/16/09-8/15/10	Not Monitored	Not Monitored
Year 1 **Post-construction** 8/16/10-8/15/11	Not Monitored	Not Monitored
Year 2 **Post-construction** 8/16/11-8/15/12	Not Monitored	Not Monitored
Year 3 **Post-construction** 8/16/12-8/15/13	Not Monitored	Not Monitored
Year 4 **Post-construction** TB15Bc1N 10/01/13 - 8/15/14	**2' diameter open pipe** **10/1/13-8/15/14** Isco data rating curve Power eqn. (data from 10/1/13-9/21/14) **(Figure 17)**	**Over channel flow - none**
Year 5 **Post-construction** TB15Bc1N 8/16/14 - 8/15/15	**2' diameter open pipe** **8/16/14-8/15/15** Isco data rating curve Power eqn. (data from 10/1/13-9/21/14) **(Figure 17)**	**Over channel flow - none**

Figure 18. TB15B level and velocity data

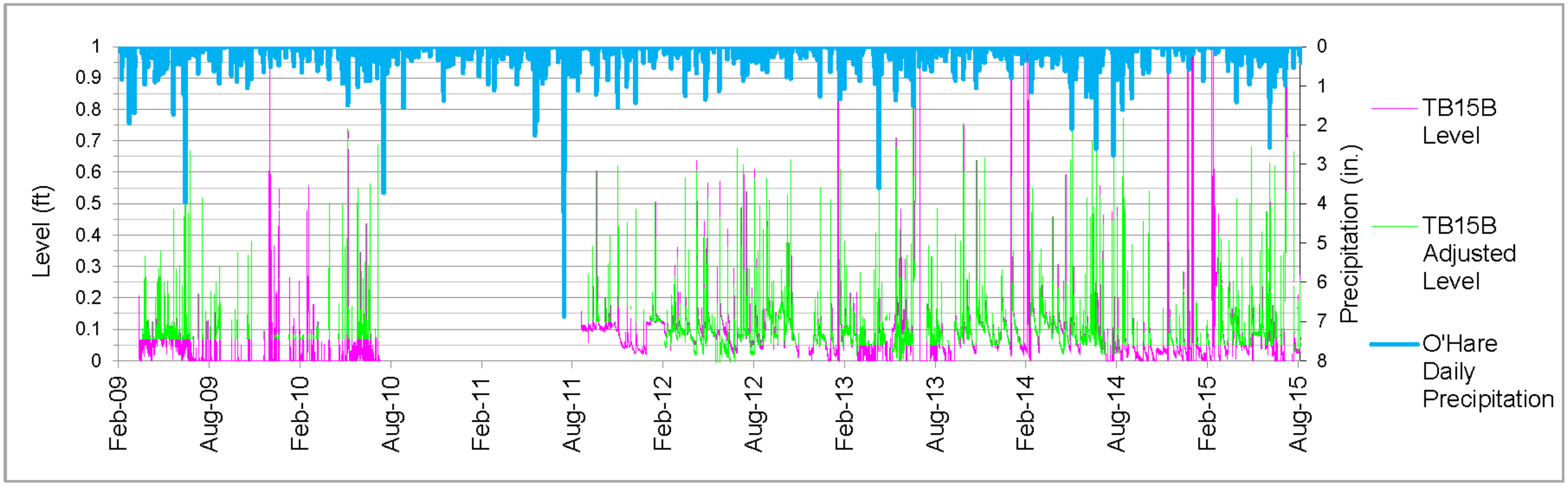


Figure 18a. Level adjustments and precipitation at TB15B

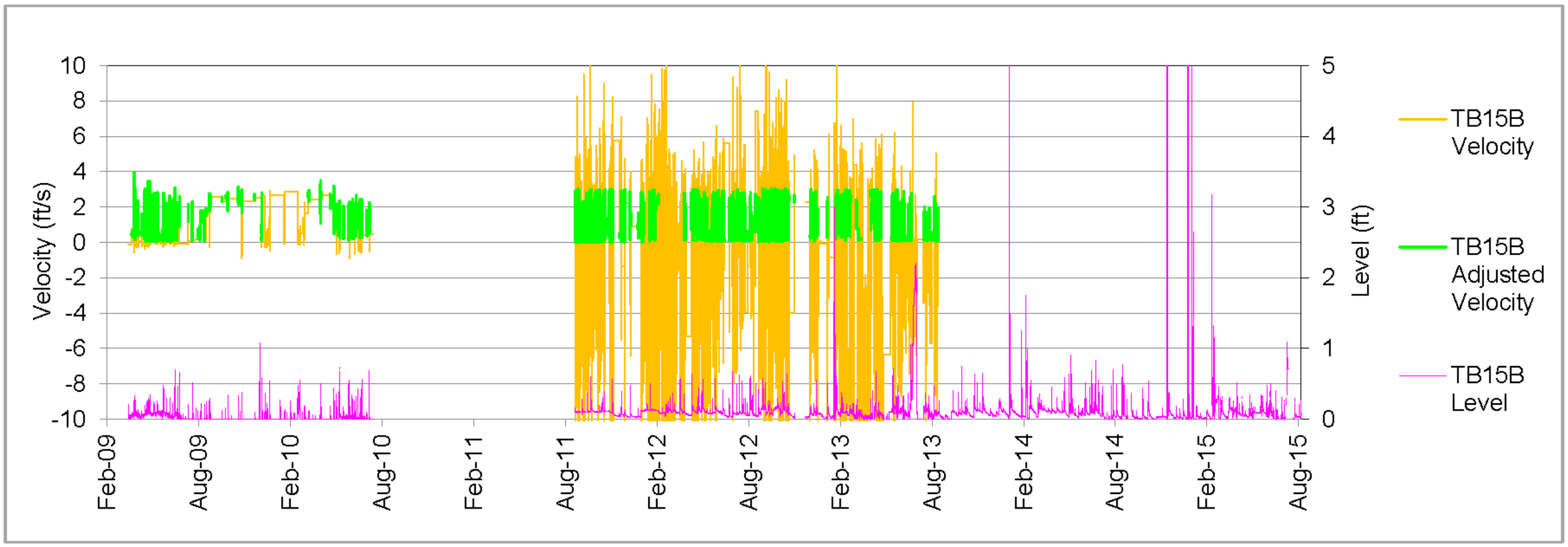


Figure 18b. Velocity measurements at TB15B

Figure 19. TB15Bsw level and velocity data

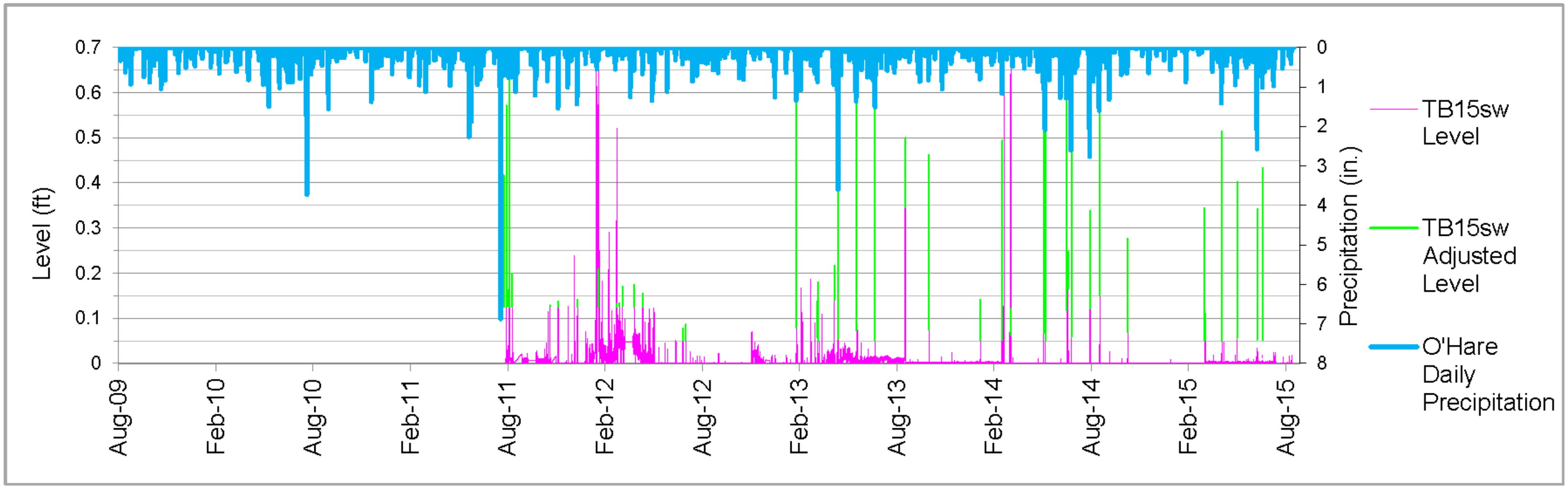


Figure 19a. Level adjustments and precipitation at TB15Bsw

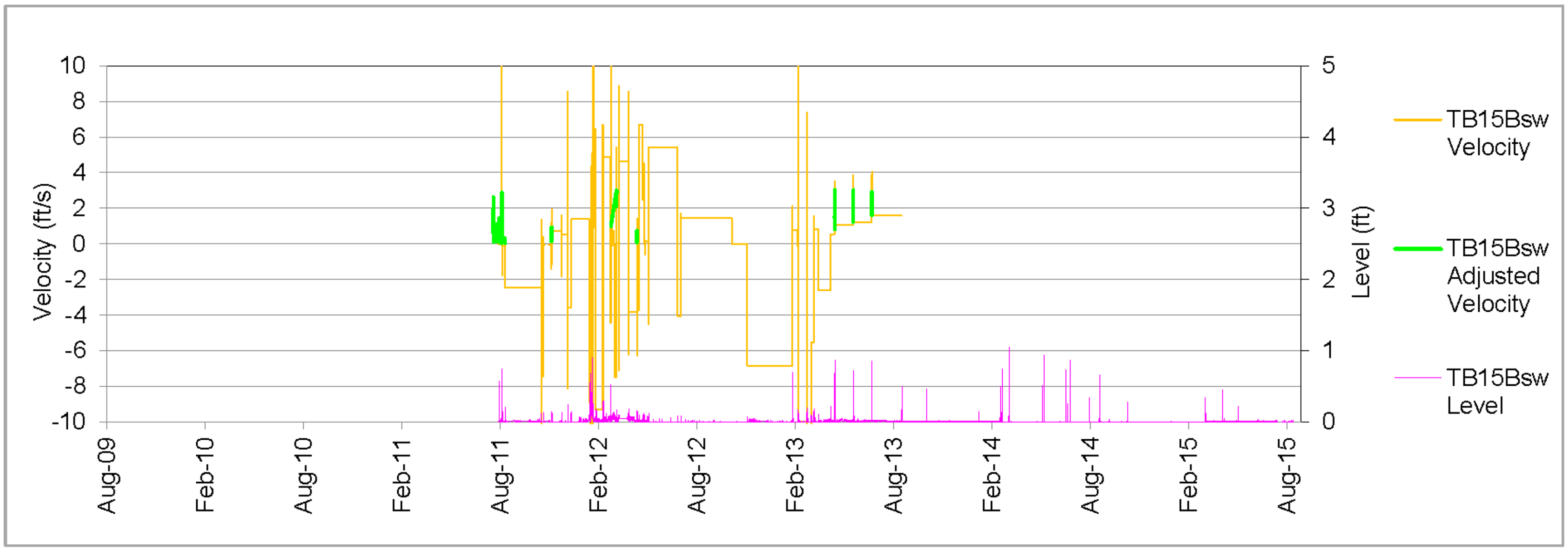


Figure 19b. Velocity measurements at TB15Bsw

Table 11. TB15B level and velocity data collection methods

Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** TB15B 3/17/09 - 7/19/10	- vegetated ditch - large channel measurements: 4 ft. bottom width 19.1 ft. top width 1.5 ft. max height	- AV sensor	- removed sensor level data below 0.05'	- adjusted for small incised channel below 1 inch depth - Manning equation estimations used for depths above 1 inch
Year 1 **Post-construction** TB15Bgw 8/16/10 - 8/15/11	Not monitored			
Year 2 **Post-construction** TB15Bgw 8/26/11 - 8/15/12	- 8-inch diameter dry swale PVC underdrain outlet pipe with weir (weir removed 2/10/12) - 8-inch diameter open pipe (after 2/10/12)	- AV sensor	- removed sensor level data below weir height (0.125') - removed sensor level data below 0.05' in open channel	- some level drift in AV sensor data corrected to manual observations
Year 3 **Post-construction** TB15Bgw 8/16/12 - 8/15/13	- 8-inch diameter open pipe	- AV sensor	- removed sensor level data below 0.05' - level drift removed in AV sensor data 6/29-7/10/13	- very little level drift in AV sensor data
Year 4 **Post-construction** TB15Bgw 8/16/13 - 8/15/14	- 8-inch diameter open pipe	- AV sensor (removed 8/21/13) - bubbler flow module (installed 8/21/13)	- removed sensor level data below 0.05'	- very little level drift in AV sensor data - very little level drift in bubbler sensor data
Year 5 **Post-construction** TB15Bgw 8/16/14 - 8/15/15	- 8-inch diameter open pipe	- bubbler flow module	- removed sensor level data below 0.05'	- very little level drift in bubbler sensor data

Table 12. TB15Bsw level and velocity data collection methods

Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not monitored			
Year 1 **Post-construction** TB15Bsw 6/9/11 - 8/15/11	- concrete check dam sensor location with weir - concrete check dam rectangular channel 0.83' height at sensor	- AV sensor	- removed sensor level data below weir height (0.125') in concrete channel with weir	- no level drift in AV sensor data
Year 2 **Post-construction** TB15Bsw 8/16/11 - 8/15/12	- concrete check dam sensor location with weir (weir removed 5/7/12) - open concrete check dam (after 5/7/12)	- AV sensor	- removed sensor level data below weir height (0.125') - removed sensor level data below 0.05' in open check dam channel	- no level drift in AV sensor data
Year 3 **Post-construction** TB15Bsw 8/16/12 - 8/15/13	- open concrete check dam	- AV sensor	- removed sensor level data below 0.05'	- no level drift in AV sensor data
Year 4 **Post-construction** TB15Bsw 8/16/13 - 8/15/14	- open concrete check dam	- AV sensor (removed 8/21/13) - bubbler flow module (installed 8/21/13)	- removed sensor level data below 0.05'	- no level drift in AV sensor data - no level drift in bubbler sensor data
Year 5 **Post-construction** TB15Bsw 8/16/14 - 8/15/15	- open concrete check dam	- bubbler flow module	- removed sensor level data below 0.05'	- no level drift in bubbler sensor data

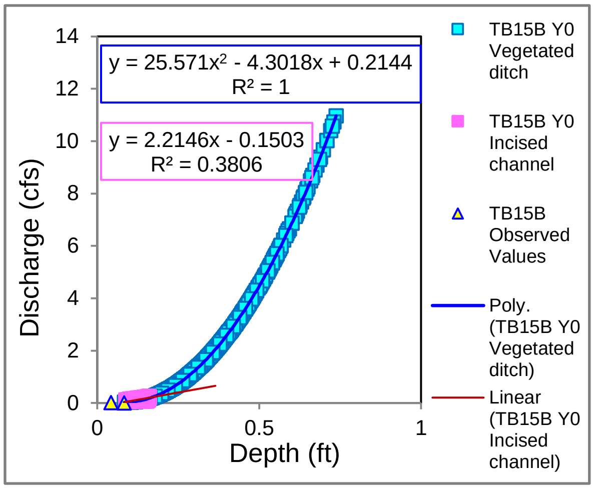
The post-construction surface water outlet at TB15Bsw was monitored at the end of Year 1 through Year 5 (6/9/11-8/15/15). Post-construction discharge at the TB15Bgw dry bioswale underdrain pipe was monitored in Years 2-5. A temporary weir was installed for Years 1 and 2 at the TB15Bsw and TB15Bgw sites, and discharge was adjusted to remove calculated flows below weir height.

Post-construction velocity data in the TB15Bgw 8-inch underdrain pipe were erratic, possibly due to the small diameter pipe and resultant acoustic effects on the Doppler signal. The length and slope of the pipe may also have altered critical depths and flow regimes, especially when combined with occasional ponding in the wet bioswale immediately outside the pipe outlet after larger precipitation events. Adjustments were not made for this ponding condition as it was not regularly observed in the field or in the data record.

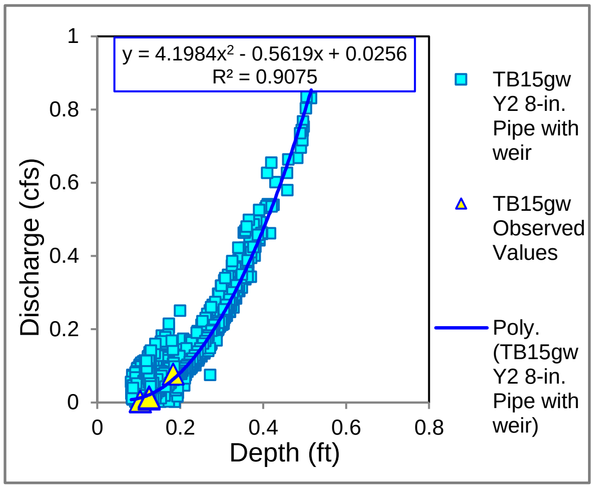
TB15B Rating Curves Used for Discharge Calculations

Rating curves for all flow configurations at TB15B are shown in Figures 20-21. Discharge calculation details are listed in Tables 13 and 14. Pre-construction measurements took place in a vegetated ditch at the downstream end of the bioswale installation at TB15B (Figure 20a). Flow conditions in the vegetated ditch occurred as base flow in a small, 1-inch deep incised channel, and storm flow occupied the larger channel cross-section. The AV sensor was installed in the small base-flow channel, which was significantly narrower than the larger channel. The small channel velocities are not directly applicable to flows in the larger channel, especially at lower flow levels. Lower levels in the larger channel cross-section would have more contact with vegetation and ditch material, and therefore slower velocities than the incised channel flow. To provide more applicable discharge calculation parameters, a Manning equation was used for all depths greater than 0.08 ft in the larger ditch channel. A channel slope of 0.05 was measured on site and a Manning channel roughness number of 0.09 was estimated using appropriate tables for vegetated highway channels (Oregon Department of Transportation 2014).

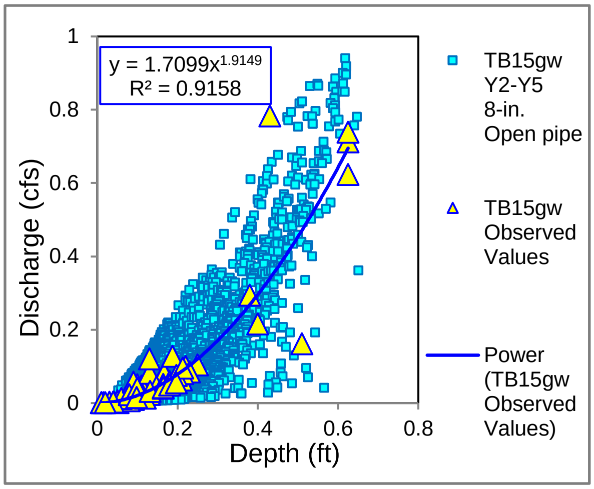
Post-construction monitoring took place at TB15Bgw in the 8-inch underdrain outlet pipe of the dry bioswale, and at TB15Bsw in the surface-water check dam monitoring location close to the original pre-construction ditch monitoring location. The TB15Bgw underdrain pipe flow configurations have a large number of higher discharge readings at lower levels occurring with velocities greater than 3 ft/s, which do not fit the lower velocity data profile. These readings often occurred on the trailing limb of event hydrographs and may be due to erroneous Doppler readings or altered flow regimes in the smaller diameter pipe, when water levels were receding or ponded after peak discharges of an event. Data above 3 ft/s were removed, and a rating curve from Isco sensor data was constructed for the pipe with the weir (Figure 20b). There were more manual measurements available in Years 2-5 for the open pipe without the weir, and a rating curve from the manual measurements was selected for this flow configuration (Figure 20c). This rating curve may over-represent discharge during lower velocity flows because occasional ponding occurs in the wet bioswale at the end of the pipe, and this may affect discharge totals.



20a. Y0: Open vegetated ditch

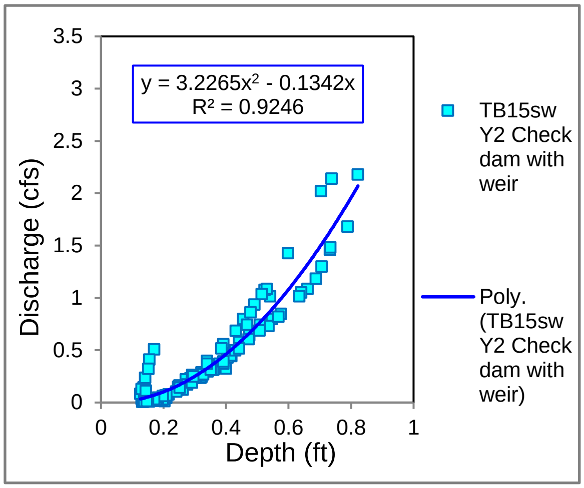


20b. Y2: 8" Pipe with weir

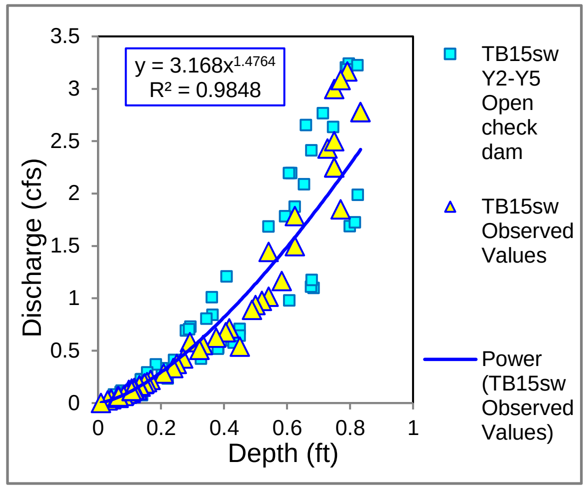


20c. Y2-Y5: 8" Open pipe

Figure 20. TB15B rating curves



21a. Y1-Y2: Check dam with weir



21b. Y2-Y5: Open check dam

Figure 21. TB15Bsw rating curves

Table 13. TB15B discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** TB15B 3/17/09 - 7/19/10	**Vegetated ditch - 3/17/09-7/19/10** **Small incised channel** (1” depth, 8” width) Isco data rating curve Power eqn. (data from 3/17/09-7/19/10) **(Figure 20a)** **Large ditch channel** (above 1” depth) Manning equation rating curve (slope 0.050, n 0.09) **(Figure 20a)**	**Over channel flow - none**
Year 1 **Post-construction** TB15Bgw 8/16/10 - 8/15/11	Not Monitored	
Year 2 **Post-construction** TB15Bgw 8/26/11 - 8/15/12	**8-in. diameter underdrain pipe with weir – 8/26/11-2/10/12** Isco data rating curve Polynomial eqn. (data from 8/26/11-2/10/12) **(Figure 20b)** **8-in. diameter underdrain open pipe 2/10/12-8/15/12** Manual observations data rating curve Power eqn. (data from 2/14/12-7/29/15) **(Figure 20c)**	**Pipe full flow - none** **Pipe full flow – 0.5%** Isco Area-Velocity sensor 7/5/12
Year 3 **Post-construction** TB15Bgw 8/16/12 - 8/15/13	**8-in. diameter underdrain open pipe – 8/16/12-8/15/13** Manual observations data rating curve Power eqn. (data from 2/14/12-7/29/15) **(Figure 20c)**	**Pipe full flow – 5%** Isco Area-Velocity sensor 4/18/13, 5/22/13, 6/26/13
Year 4 **Post-construction** TB15Bgw 8/16/13 - 8/15/14	**8-in. diameter underdrain open pipe – 8/16/13-8/15/14** Manual observations data rating curve Power eqn. (data from 2/14/12-7/29/15) **(Figure 20c)**	**Pipe full flow – 1%** Observations power rating curve 10/5/13, 5/12/14, 6/21/14, 6/30/14, 8/4/14
Year 5 **Post-construction** TB15Bgw 8/16/14 - 8/15/15	**8-in. diameter underdrain open pipe – 8/16/14-8/15/15** Manual observations data rating curve Power eqn. (data from 2/14/12-7/29/15) **(Figure 20c)**	**Pipe full flow – 3%** Observations power rating curve 8/23/14, 7/16/15, 8/2/15

Table 14. TB15sw discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not Monitored	
Year 1 **Post-construction** TB15Bsw 6/9/11 - 8/15/11	**Concrete check dam with weir** **6/9/11-8/15/11** Isco data rating curve Polynomial eqn. (data from 6/11/11-5/8/12) **(Figure 21a)**	**Over channel flow – 63%** Isco polynomial rating curve 7/22-7/23/11, 7/28/11, 7/29/11, 8/2/11, 8/8/11, 8/13/11
Year 2 **Post-construction** TB15Bsw 8/16/11 - 8/15/12	**Concrete check dam with weir** **8/15/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 6/11/11-5/8/12) **(Figure 21a)** **Open concrete check dam** **5/8/12-8/15/12** Manual observations data rating curve Power eqn. (data from 1/29/13-7/29/15) **(Figure 21b)**	**Over channel flow** - none **Over channel flow – 2%** Observations power rating curve 7/5/12
Year 3 **Post-construction** TB15Bsw 8/16/12 - 8/15/13	**Open concrete check dam** **8/16/12-8/15/13** Manual observations data rating curve Power eqn. (data from 1/29/13-7/29/15) **(Figure 21b)**	**Over channel flow – 13%** Observations power rating curve 4/18/13, 6/26/13
Year 4 **Post-construction** TB15Bsw 8/16/13 - 8/15/14	**Open concrete check dam** **8/16/13-8/15/14** Manual observations data rating curve Power eqn. (data from 1/29/13-7/29/15) **(Figure 21b)**	**Over channel flow – 10%** Observations power rating curve 3/8/14, 5/12/14, 6/30/14
Year 5 **Post-construction** TB15Bsw 8/16/14 - 8/15/15	**Open concrete check dam** **8/16/14-8/15/15** Manual observations data rating curve Power eqn. (data from 1/29/13-7/29/15) **(Figure 21b)**	**Over channel flow** - none

The post-construction surface-water site at TB15Bsw had discharge only during larger precipitation events due to infiltration of smaller events to the subsurface underdrain. Discharge with the temporary weir and with the weir removed are similar, having hysteretic rating curves likely due to changes in water surface gradients during flow pulses. A rating curve constructed using the Isco AV sensor data was selected for the weir configuration (Figure 21a), and a rating curve using manual measurements was selected for the open check dam configuration (Figure 21b).

TB19 Results

TB19 Output Level and Velocity Data

Level and velocity data collected at the pre-construction bioswale output monitoring stations TB19 and TB19r and the post-construction TB19gw underdrain pipe are shown in Figure 22. The post-construction TB19sw surface-water output level and velocity data are shown in Figure 23. A summary of data collection methods is in Tables 15 and 16.

Pre-construction monitoring instruments for TB19 and TB19r were set in a ditch at the downstream end of the future bioswale installation. The channel was an unlined earthen ditch with exposed instruments, which created a large diurnal signature in the level data. The level sensor was set at various heights in an attempt to mitigate the diurnal signature while capturing low-level flows. The erratic nature of low-level readings was more pronounced in the later TB19r installation, with a diurnal signature well above 0.1 ft, and the level record was not easily delineated for adjustment.

Post-construction instruments were installed in Years 2-5. The post-construction monitoring locations were an underdrain outlet at TB19gw and the surface-water check dam outlet at TB19sw, which was close to the pre-construction monitoring location. Flow channel configurations at these sites included temporary weirs during the Year 2 monitoring, and discharge was adjusted to remove calculated flows below weir height.

Velocity data were screened for erroneous sensor readings and data removed. Velocity data in the 8-inch underdrain pipe at TB19gw were erratic, possibly due to the small diameter pipe and resultant acoustic effects on the Doppler signal similar to the TB15B outlet pipe. The length and slope of the pipe may also have affected changes in critical depths and stage-discharge relationships. There was no ponding observed at the outlet of the pipe.

TB19 Rating Curves Used for Discharge Calculations

Rating curves for TB19, TB19r, TB19gw, and TB19sw are shown in Figures 24-25. Site discharge calculation details are listed in Tables 17 and 18. Pre-construction rating curves for TB19 represent measurements in the excavated earthen ditch (Figure 24a). The AV sensor was installed in the ditch where base flow channel dimensions were

Figure 22. TB19 level and velocity data

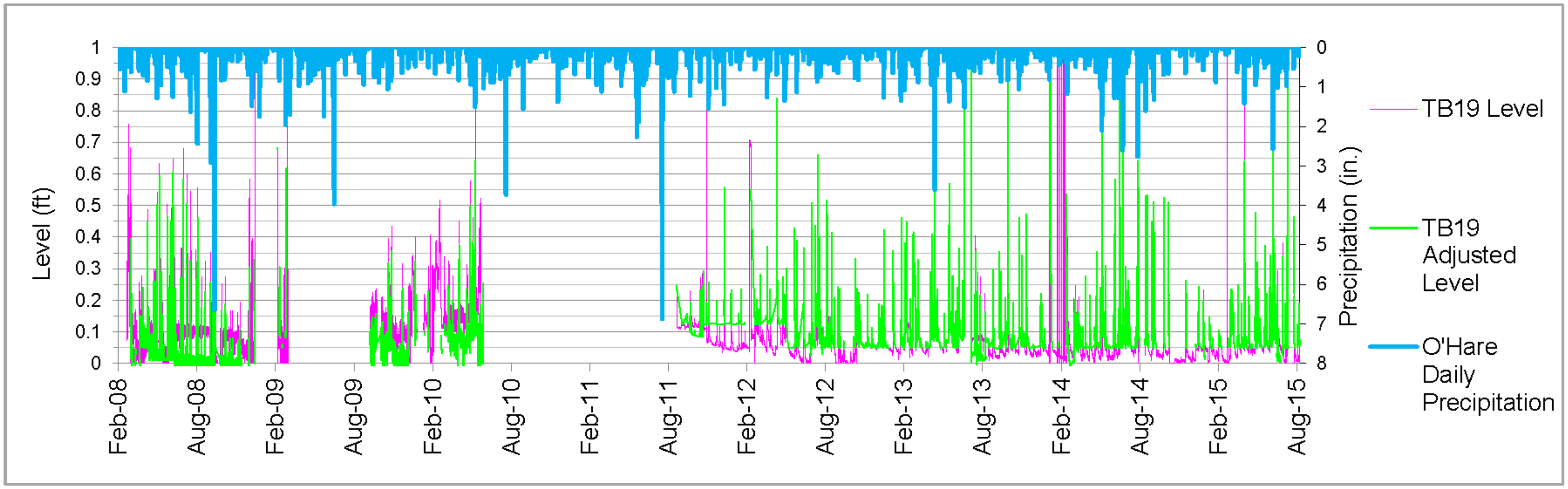


Figure 22a. Level adjustments and precipitation at TB19

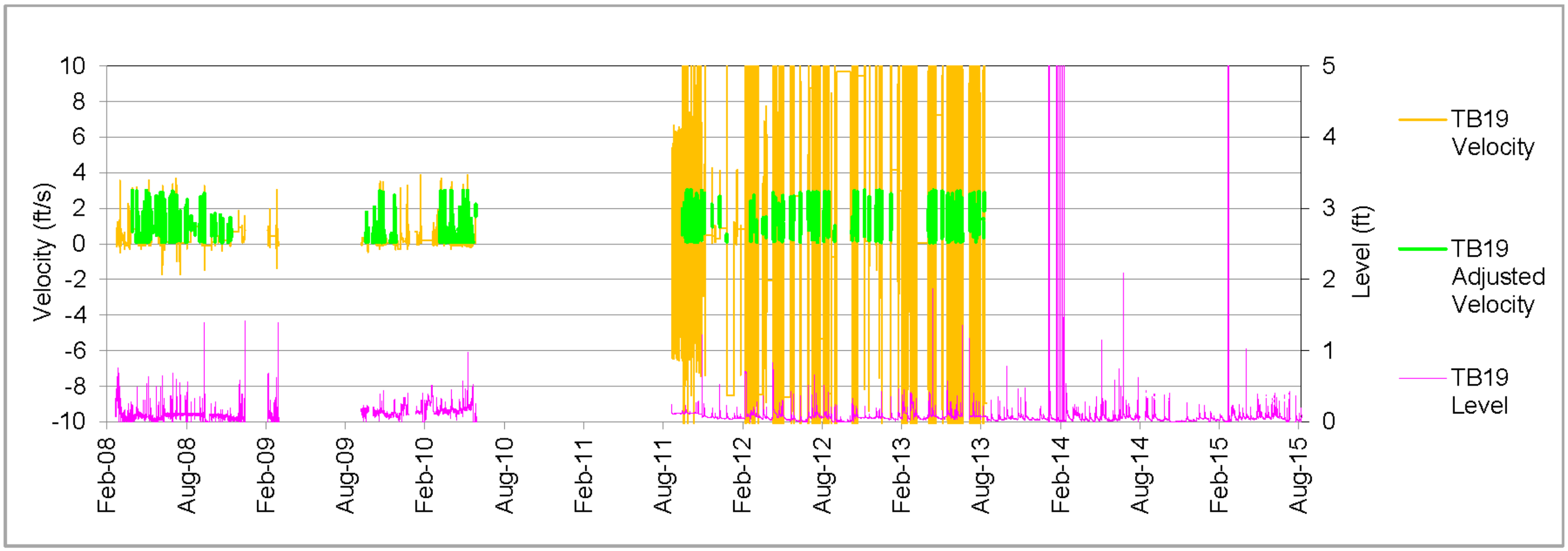


Figure 22b. Velocity measurements at TB19

Figure 23. TB19sw level and velocity data

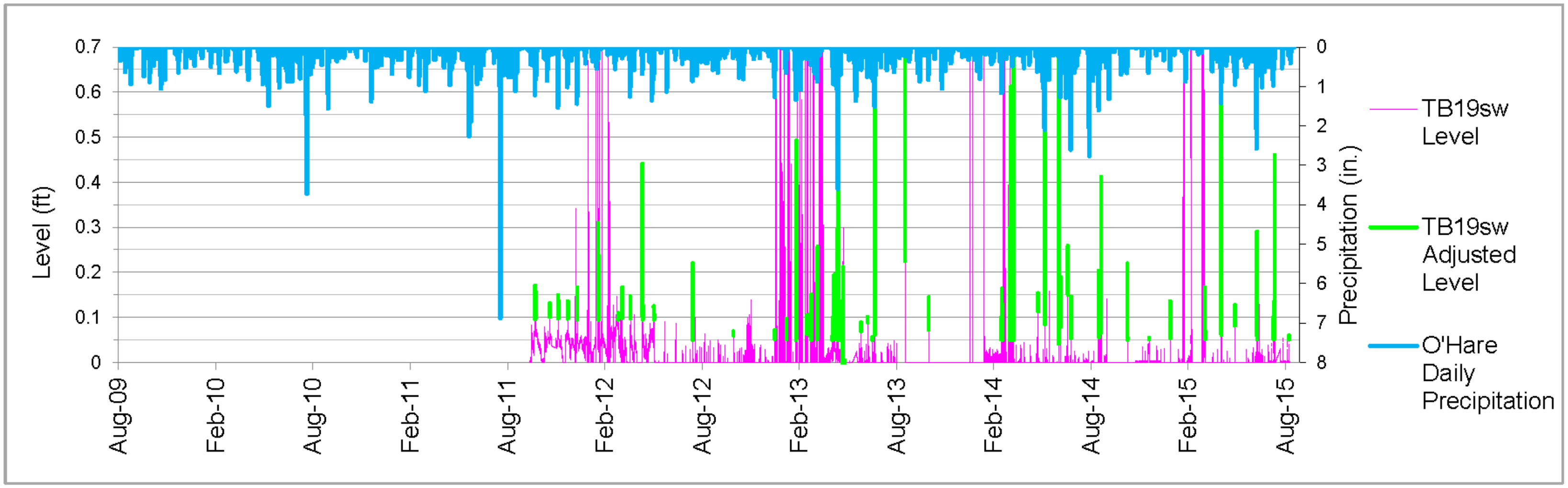


Figure 23a. Level adjustments and precipitation at TB19sw

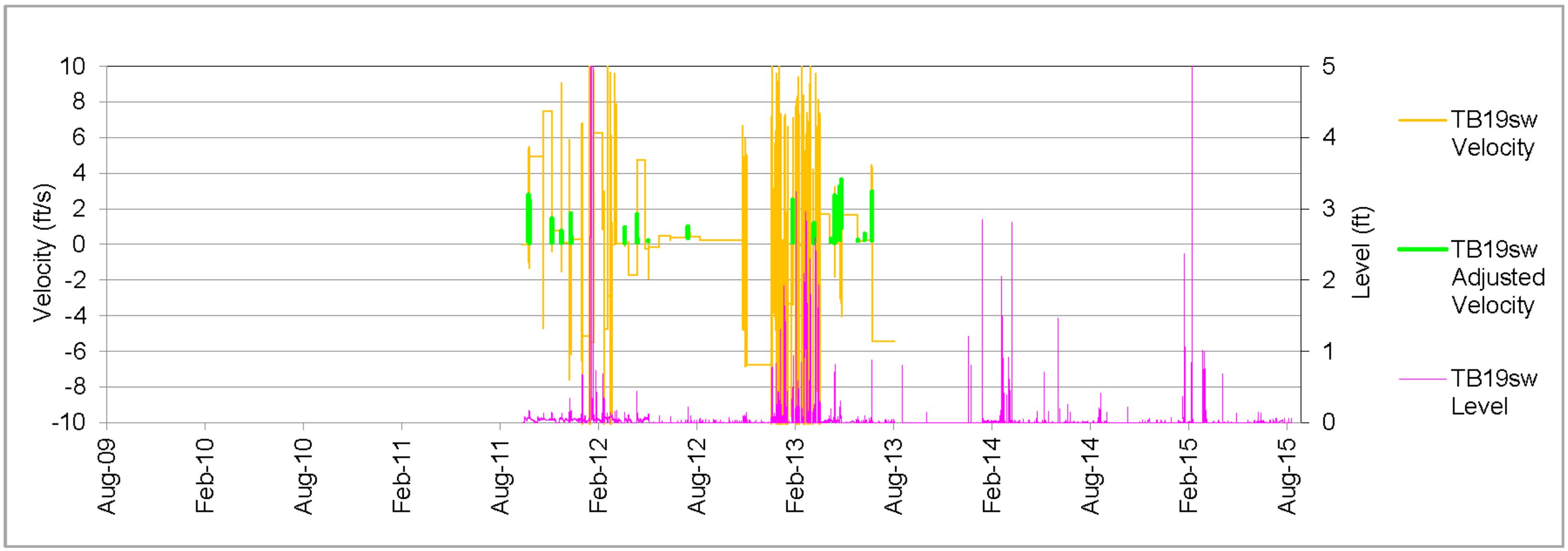


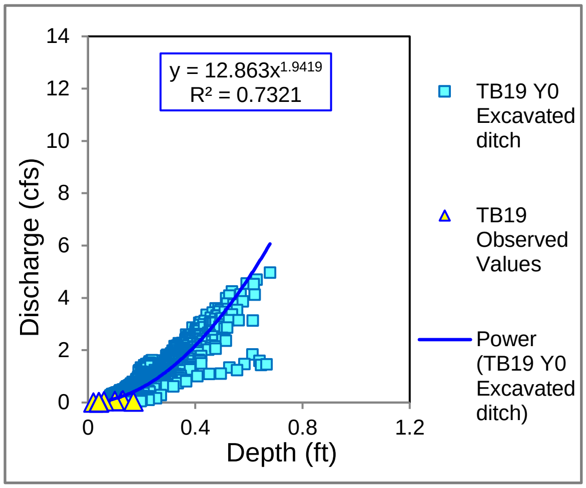
Figure 23b. Velocity measurements at TB19sw

Table 15. TB19 level and velocity data collection methods

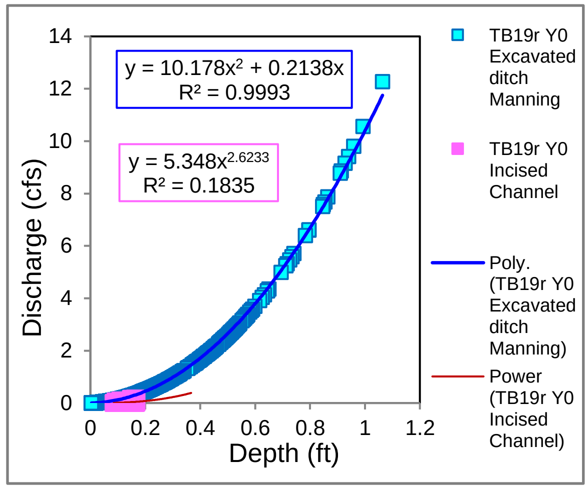
Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Pre-construction TB19 2/21/08 - 3/3/09	- unlined earthen ditch - channel measurements: 2 ft. bottom width 7.5 ft. top width 2.3 ft. max height	- AV sensor	- removed sensor level data below 0.05'	- adjusted for small incised channel below 2-inch depth - drift 0.04'-0.09' adjusted to baseline measurements
Year 0 **Pre-construction** TB19r 9/9/09 - 6/1/10	- unlined earthen ditch - channel measurements: 3 ft. bottom width 12 ft. top width 1.04 ft. max height	- AV sensor - sensor set low on ditch surface – levels adjusted to manual measurements	- removed sensor level data below 0.05'	- adjusted for small incised channel below 2-inch depth - Manning equation estimations used for depths above 2 inches
Year 1 **Post-construction** 8/16/10 - 8/15/11	Not monitored			
Year 2 **Post-construction** TB19gw 8/26/11 - 8/15/12	- 8-inch diameter dry swale PVC underdrain outlet pipe with weir (weir removed 5/7/12) - 8-inch diameter open pipe (after 5/7/12)	- AV sensor	- removed sensor level data below weir height (0.125') - removed sensor level data below 0.05' in open channel	- some level drift in AV sensor data corrected to manual observations
Year 3 **Post-construction** TB19gw 8/16/12 - 8/15/13	- 8-inch diameter open pipe	- AV sensor	- removed sensor level data below 0.05'	- some level drift in AV sensor data corrected to manual observations
Year 4 **Post-construction** TB19gw 8/16/13 - 8/15/14	- 8-inch diameter open pipe	- AV sensor (removed 8/21/13) - bubbler flow module (installed 8/21/13)	- removed sensor level data below 0.05'	- very little level drift in AV sensor data - very little level drift in bubbler sensor data
Year 5 **Post-construction** TB19gw 8/16/14 - 8/15/15	- 8-inch diameter open pipe	- bubbler flow module - power issues 8/6/2014-9/3/2014	- removed sensor level data below 0.05'	- very little level drift in bubbler sensor data

Table 16. TB19sw level and velocity data collection methods

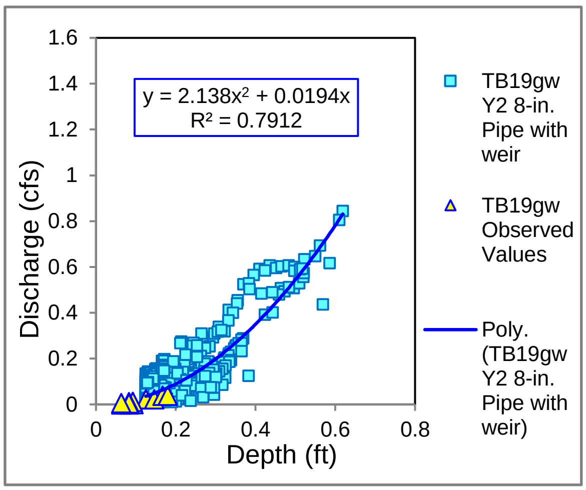
Monitoring Year	Site Setup / Flow Conditions	Equipment Installation	QA/QC Data Removal	QA/QC Data Adjustments
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not monitored			
Year 1 **Post-construction** TB19sw 8/16/10 - 8/15/11	Not monitored			
Year 2 **Post-construction** TB19sw 8/16/11 - 8/15/12	- concrete check dam sensor location with weir (weir removed 5/7/12) - concrete check dam rectangular channel 0.62' height at sensor - open concrete check dam (after 5/7/12)	- AV sensor	- removed sensor level data below weir height (0.095') - removed sensor level data below 0.05' in open channel check dam	- no level drift in AV sensor data
Year 3 **Post-construction** TB19sw 8/16/12 - 8/15/13	- open concrete check dam	- AV sensor	- removed sensor level data below 0.05'	- no level drift in AV sensor data
Year 4 **Post-construction** TB19sw 8/16/13 - 8/15/14	- open concrete check dam	- AV sensor (removed 8/21/13) - bubbler flow module (installed 8/21/13) - bubbler issues 7/23/14-10/14/14	- removed sensor level data below 0.05'	- no level drift in AV sensor data - very little level drift in bubbler sensor data
Year 5 **Post-construction** TB19sw 8/16/14 - 8/15/15	- open concrete check dam	- bubbler flow module - bubbler module replaced 8/20/14 & 10/14/14	- removed sensor level data below 0.05'	- very little level drift in bubbler sensor data



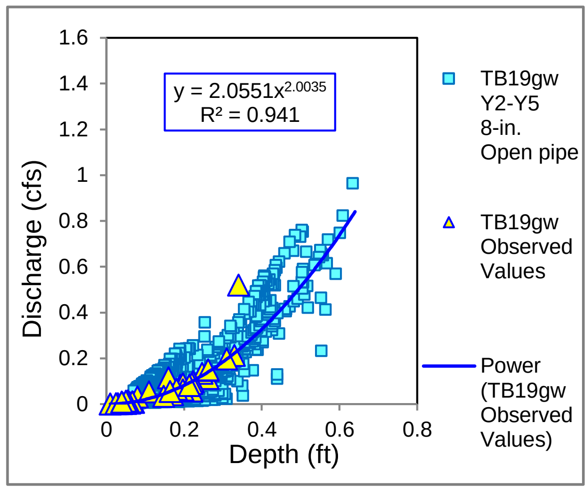
24a. TB19 Excavated ditch



24b. Y0: TB19r Excavated ditch

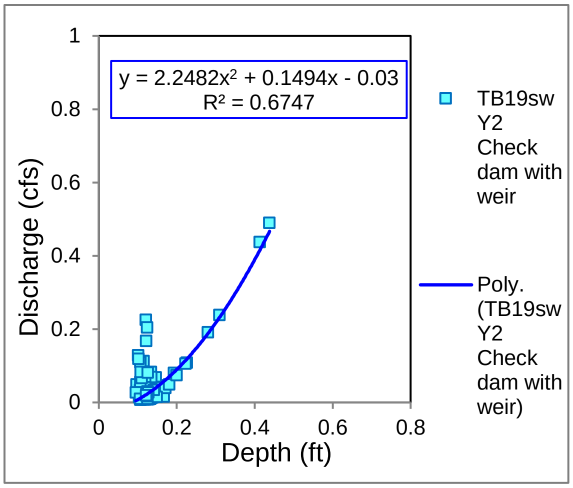


24c. Y2: 8” pipe with weir

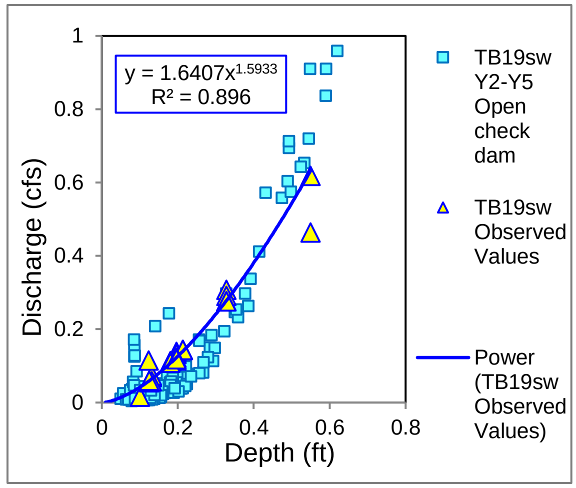


24d. Y2-Y5: 8” Open pipe

Figure 24. TB19 rating curves



25a. Y2: Check dam with weir



25b. Y2-Y5: Open check dam

Figure 25. TB19sw rating curves

Table 17. TB19 discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Pre-construction TB19 2/21/08 - 3/3/09	**Excavated ditch - 2/21/08-3/3/09** Isco data rating curve Power eqn. (data from 2/21/08-3/3/09) **(Figure 24a)**	**Backwater flow** **(Levels > 0.679 ft.) – 15%** Isco Area Velocity Sensor 7/2/08, 9/13/08, 2/7/09
Year 0 **Pre-construction** TB19r 9/9/09 - 6/1/10	**Excavated ditch - 9/9/09-6/1/10** **Small Incised Channel** Isco data rating curve Power eqn. (data from 9/9/09-6/1/10) **(Figure 24b)** **Large ditch channel** (above 2” depth) Manning equation rating curve (slope 0.0046, n 0.05) **(Figure 24b)**	**Backwater flow –** none
Year 1 **Post-construction** 8/16/10 - 8/15/11	Not Monitored	
Year 2 **Post-construction** TB19gw 8/26/11 - 8/15/12	**8-in. diameter underdrain pipe with weir** **8/26/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 8/26/11-5/8/12) **(Figure 24c)** **8-in. diameter underdrain open pipe** **5/8/12-8/15/12** Manual observations data rating curve Power eqn. (data from 7/24/12-7/30/15) **(Figure 24d)**	**Pipe full flow – 2%** Isco area velocity sensor 4/15/12, 7/18/12
Year 3 **Post-construction** TB19gw 8/16/12 - 8/15/13	**8-in. diameter underdrain open pipe** **8/16/12-8/15/13** Manual observations data rating curve Power eqn. (data from 7/24/12-7/30/15) **(Figure 24d)**	**Pipe full flow – 4%** Isco area velocity sensor 4/18/13, 6/26/13, 7/11/13
Year 4 **Post-construction** TB19gw 8/16/13 - 8/15/14	**8-in. diameter underdrain open pipe** **8/16/13-8/15/14** Manual observations data rating curve Power eqn. (data from 7/24/12-7/30/15) **(Figure 24d)**	**Pipe full flow – 11%** Isco pipe full equation 10/5/13, 1/11/14, 1/12/14, 5/12/14, 5/13/14, 6/21/14, 6/30/14, 7/1/14
Year 5 **Post-construction** TB19gw 8/16/14 - 8/15/15	**8-in. diameter underdrain open pipe** **8/16/14-8/15/15** Manual observations data rating curve Power eqn. (data from 7/24/12-7/30/15) **(Figure 24d)**	**Pipe full flow – 2%** Isco pipe full equation 6/15/15, 7/18/15

Table 18. TB19sw discharge calculation methods

Monitoring Year	Main Channel Flow	Over Channel / Pipe Full Flow
Year 0 **Pre-construction** 8/16/09 - 8/15/10	Not Monitored	
Year 1 **Post-construction** TB19sw 8/16/10 - 8/15/11	Not Monitored	
Year 2 **Post-construction** TB19sw 8/16/11 - 8/15/12	**Concrete check dam with weir** **9/15/11-5/8/12** Isco data rating curve Polynomial eqn. (data from 9/26/11-5/8/12) **(Figure 25a)** **Open concrete check dam** **5/8/12-8/15/12** Manual observations data rating curve Power eqn. (data from 1/29/13-8/9/15) **(Figure 25b)**	**Over channel flow** - none
Year 3 **Post-construction** TB19sw 8/16/12 - 8/15/13	**Open concrete check dam** **8/16/12-8/15/13** Manual observations data rating curve Power eqn. (data from 1/29/13-8/9/15) **(Figure 25b)**	**Over channel flow – 64%** Observations power rating curve 4/18/13, 6/26/13
Year 4 **Post-construction** TB19sw 8/16/13 - 8/15/14	**Open concrete check dam** **8/16/13-8/15/14** Manual observations data rating curve Power eqn. (data from 1/29/13-8/9/15) **(Figure 25b)**	**Over channel flow – 35%** Observations power rating curve 8/23/13, 3/13/14, 3/14/14, 5/12/14, 6/7/14, 6/8/14
Year 5 **Post-construction** TB19sw 8/16/14 - 8/15/15	**Open concrete check dam** **8/16/14-8/15/15** Manual observations data rating curve Power eqn. (data from 1/29/13-8/9/15) **(Figure 25b)**	**Over channel flow – 33%** Observations power rating curve 4/9/15

similar to the bottom 2-ft width of the larger channel. This enabled the use of the velocity sensor data for both base flow and large channel flow at this site. There was a large amount of unsteady or backwater flow recorded above 0.68 ft that was removed from the Isco data along with velocities greater than 3 ft/s to construct the rating curve. The unsteady or backwater flow was alleviated after the ditch grading and subsequent reinstallation of instruments as TB19r.

Pre-construction rating curves for TB19r represent measurements in the regraded and widened unlined earthen ditch (Figure 24b). The sensors were installed in a small incised channel in the ditch created by base flow. The ditch was widened by construction, and velocities in the smaller incised channel were not applicable to velocities in the larger channel cross section, similar to the TB15B pre-construction channel. The smaller channel had free flow at low depths, where the lower depths in the larger ditch cross-section were slowed by contact with eroded ditch materials. A Manning formula equation was used to calculate discharge volumes in the larger channel for all depths greater than 2 inches. A channel slope of 0.0046 was measured on site and a Manning roughness number of 0.050 was estimated using appropriate tables for excavated highway channels.

Post-construction monitoring took place at TB19gw in the 8-inch underdrain outlet pipe of the dry bioswale and in the surface-water check dam location at TB19sw. The TB19gw flow configurations with and without a weir have a large number of higher-discharge readings at low levels with velocities greater than 3 ft/s that do not fit the main flow path. These readings often occurred on the trailing limb of event hydrographs, and may be due to erroneous Doppler readings, or altered flow regimes when flow levels were receding and transitioning between pipe-full and open pipe flow, or with varying energy gradients in storm flows. There were more high velocities with lower levels recorded here than at TB15Bgw, possibly because of the lack of ponding in the ditch outside the pipe invert. Data above 3 ft/s were removed, and Isco sensor data were used to construct a rating curve for the pipe with the weir (Figure 24c). There were more manual measurements available in Years 2-5 for the pipe with the weir removed, and a rating curve from manual measurements was selected for this flow configuration (Figure 24d).

The post-construction surface-water site at TB19sw had discharge only during larger events due to infiltration of smaller events to the subsurface underdrain pipe. Discharge with the temporary weir and with the weir removed are similar. An Isco data rating curve was selected for the check dam weir configuration (Figure 25a), and a manual measurement rating curve was used for the open check dam configuration (Figure 25b).

Sanders Results

Sanders Output Level and Velocity Data

Level and velocity data collected at the pre-construction Sanders monitoring station are shown in Figure 26. Monitoring at the Sanders station was primarily for method

Figure 26. Sanders level and velocity data

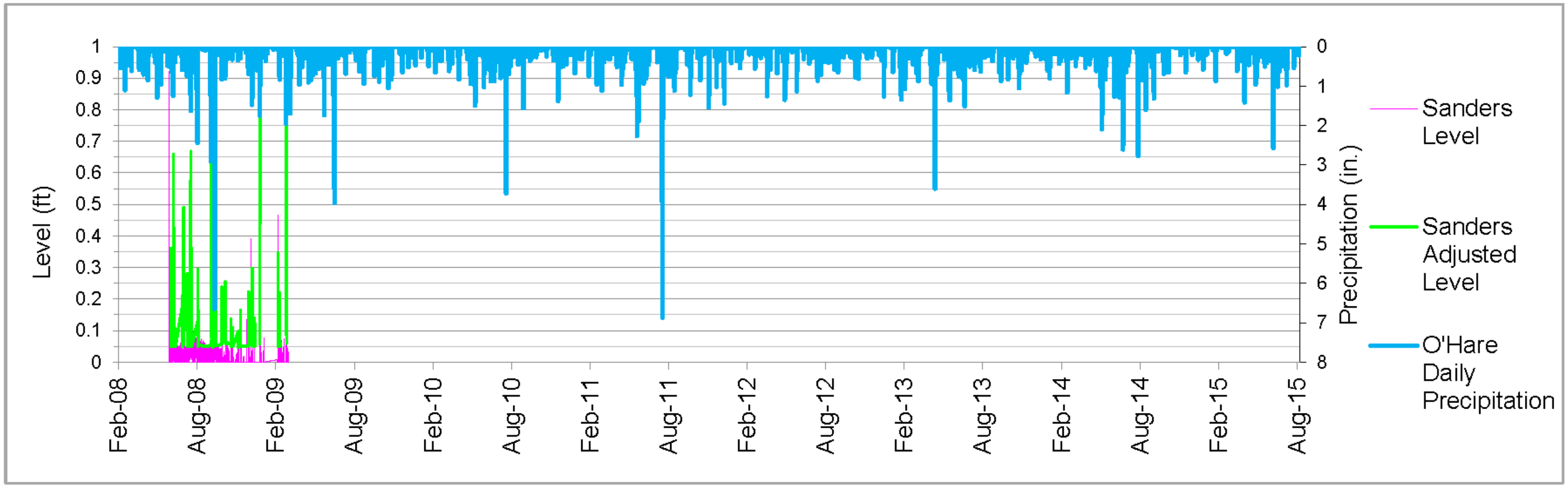


Figure 26a. Level adjustments and precipitation at Sanders

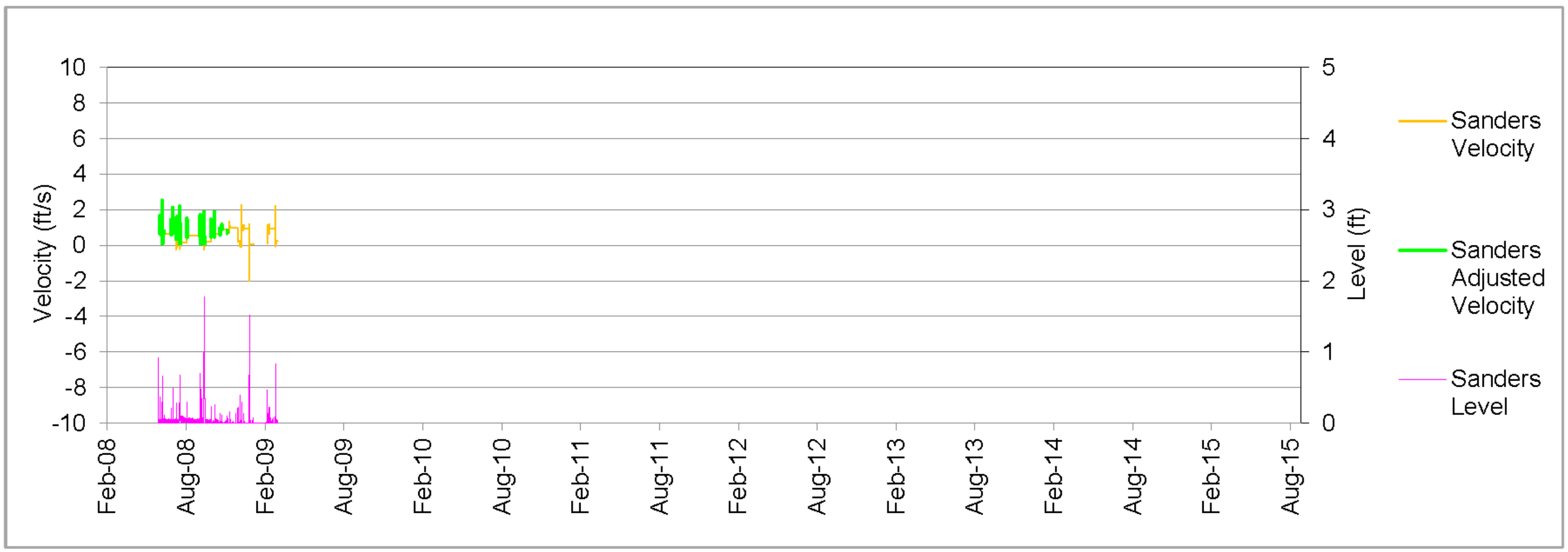


Figure 26b. Velocity measurements at Sanders

development purposes and no conclusions will be presented. One output location at the site was monitored for discharge volumes and water quality from 5/29/08 to 3/3/09, and the monitoring was discontinued as no bioswale was constructed at this site. Monitoring instruments at Sanders were installed in a vegetated ditch similar to the TB15B pre-construction monitoring site. The Sanders site had similar issues with a small channel incised in the larger cross-section, with small channel velocities not applicable to larger channel measurements. Velocity data were screened for erroneous sensor readings and data removed. No velocities above 3 ft/s were recorded.

Sanders Rating Curve used for Discharge Calculations

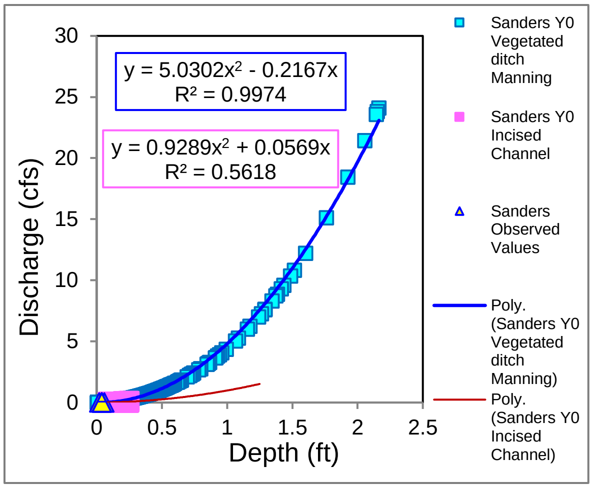
The rating curve for the vegetated ditch flow configuration at Sanders is shown in Figure 27. Instruments were installed in a smaller incised channel within a larger channel cross-section similar to the TB15B pre-construction site. Velocities measured in the small channel are not applicable to large channel flow, and so a similar Manning equation solution was used here for large channel calculations above a 2-inch depth. A channel slope of 0.003 was obtained from construction plans and a channel roughness value of 0.125 was estimated from appropriate tables for highway channels.

There was a large backwater component evident in the stage-discharge data, without a clear delineation by depth between normal and backwater flow. The unsteady flow conditions were mitigated with use of the Manning equation rating curve, but this estimation created a large uncertainty in the discharge calculation results and does not account for the large amount of backwater variability in the data.

ANNUAL DISCHARGE VOLUME CALCULATIONS AND RUNOFF COEFFICIENT ASSESSMENT

Calculated bioswale discharge volumes are compared as a proportion of roadway volume contributing to the bioswale, which is calculated from the amount of precipitation falling on the roadway area drained for each site. A standardized yield of 1.00 shows that 100% of roadway generated volume passed through the monitoring location. Discharge totals as a percentage of roadway volume are comparable within the sites from year to year. Comparisons between pre-construction and post-construction discharges indicate total bioswale performance.

Average annual precipitation for the Chicago O’Hare airport location is 36.89 inches per year (MRCC 2015). During the six monitoring years of the study, three years had above average precipitation (pre-construction 8/16/08-8/16/09 – 51.21”, pre-construction 8/16/09-8/16/10 – 43.05” and post-construction Year 1 – 44.91”), two years had slightly above average precipitation (Year 3 – 40.84” and Year 4 – 39.00”), and two had below average precipitation (Year 2 – 31.09” and Year 5 – 33.22”). Monitoring instruments for each site were deployed for different portions of each year, and annual precipitation totals for each deployment vary with each installation. Calculated discharge output results generally correspond to annual roadway volume totals calculated with local



27. Open vegetated ditch

Figure 27. Sanders rating curve

precipitation totals, with some variations between sites. Results for each bioswale are presented in the following sections.

TB7B Discharge Calculations and Precipitation Totals

Discharge totals and corresponding roadway runoff calculations for TB7B are shown in Table 19. The pre-construction output discharge was 25% less than input volumes, and the Year 1-5 total post-construction output discharge was 31% less than input volumes, when compared as the percent change ((input value - output value)/input value) between input and output. This suggests a greater decrease in output volumes when compared to input volumes after bioswale installation. Annual post-construction input totals at TB7Bin range between 91% and 112% of precipitation volumes that fell on contributing roadway areas. The input at TB7Bin is a direct input from a roadway section, and these calculated input totals agree with typical runoff coefficients for completely paved areas, where approximately 90% of precipitation is expected to convert to runoff (Oregon Department of Transportation 2014). Years 4 and 5 show increased runoff percentages of 100% and 112%, probably overestimates due to observed ponding over the instruments.

Bioswale output totals at TB7Bout vary with the amount of annual precipitation. Totals are around 70% of roadway precipitation totals for three years (pre-construction - 73%, Year 4 - 70%, and Year 5 - 70%). Year 1 had an output of 132%, much greater than roadway contributing volume, which may be explained by higher event intensities and lower antecedent times (Table 20), resulting in less infiltration and more runoff contribution from surrounding areas in Year 1 than the same time frame of March through August in the pre-construction year. The average intensity for precipitation events greater than one inch was higher in Year 1 (0.24 inches/hour) than in the pre-construction year (0.14 inches/hour), even though both years had above average precipitation. Year 1 also had a greater frequency of events over 1 inch, with average antecedent times at 19.6 days between events greater than 1 inch, compared to 35.6 days during pre-construction monitoring. These factors, combined with four additional inches of precipitation in Year 1, created fewer opportunities for infiltration and more bioswale input from surrounding upstream areas, and resulted in a bioswale output volume larger than the contributing roadway volume. Year 2 was the driest year, having the lowest intensities and highest antecedent times for precipitation events, and had the lowest percentage output of 52%. Year 3 also had a very low percent output at 28% of roadway volume, but the station had instrument power issues and sensor energizing malfunctions throughout the year, which resulted in a very low discharge total. If the Year 3 output total was a more typical 70% of roadway volume, this would suggest the average total post-construction discharge is closer to 77% of roadway volume, indicating an average decrease in total output slightly smaller than reported above.

Table 19. TB7B discharge volume results

TB7B Precipitation and Volume Totals

	O'Hare WSO Precipitation (in.)	Calculated Roadway Runoff (ft^3)	Calculated Bioswale Discharge (ft^3)
TB7Bin	(during deployment)		
Pre-construction	43.78	203,420	197,172
Year 1	44.91	208,671	194,432
Year 2	31.09	144,457	139,013
Year 3	40.84	189,760	172,263
Year 4	39.00	181,210	181,307
Year 5	33.22	154,354	172,649
Year 1-5 total	189.06	878,452	859,664
TB7Bout			
Pre-construction	43.05	200,028	145,405
Year 1	30.40	141,251	186,241
Year 2	31.09	144,457	74,696
Year 3	40.84	189,760	52,932
Year 4	39.00	181,210	126,661
Year 5	33.22	154,354	107,297
Year 1-5 total	174.55	811,032	547,827

TB7B Standardized Yields
(Bioswale discharge volume / Roadway runoff volume from contributing area)

	O'Hare WSO Precipitation Annual Totals (in.)	TB7Bin	TB7Bout
Pre-construction	43.05	0.97	0.73
Year 1	44.91	0.93	1.32
Year 2	31.09	0.96	0.52
Year 3	40.84	0.91	0.28*
Year 4	39.00	1.00	0.70
Year 5	33.22	1.12	0.70
Year 1-5	37.81**	0.98	0.68

High annual precipitation
Average annual precipitation
Low annual precipitation
*Likely affected by equipment malfunctions
**Mean annual precipitation

Table 20. Precipitation totals, intensity, and antecedent times

Average Precipitation Event Intensity (inches/hour)

	Annual Precipitation total (in.)	Events > 0.05" (in./hr)	Events > 0.50" (in./hr)	Events > 0.75" (in./hr)	Events > 1.00" (in./hr)
TB7Bout Pre-construction (March-August 2010)	24.30	0.07	0.12	0.14	0.14
TB7Bout Year 1 (March-August 2011)	28.48	0.09	0.11	0.15	0.24
Pre-construction	43.05	0.04	0.08	0.10	0.09
Year 1	44.91	0.06	0.09	0.13	0.18
Year 2	31.09	0.04	0.08	0.08	0.08
Year 3	40.84	0.07	0.12	0.10	0.09
Year 4	39.00	0.05	0.11	0.13	0.22
Year 5	33.22	0.04	0.07	0.09	0.11

Average Precipitation Event Antecedent Time (days between similar-sized events)

	Annual Precipitation total (in.)	Events > 0.05" (days)	Events > 0.50" (days)	Events > 0.75" (days)	Events > 1.00" (days)
TB7Bout Pre-construction (March-August 2010)	24.30	3.54	9.5	10.6	35.6
TB7Bout Year 1 (March-August 2011)	28.48	3.24	6.5	10.9	19.6
Pre-construction	43.05	3.51	10.9	16.5	45.6
Year 1	44.91	3.38	10.3	19.5	29.9
Year 2	31.09	4.50	16.9	29.0	32.0
Year 3	40.84	3.41	12.2	14.4	22.1
Year 4	39.00	3.43	11.4	19.6	39.2
Year 5	33.22	3.66	17.3	28.9	48.4

TB9A Discharge Calculations and Precipitation Totals

Discharge and precipitation totals for the TB9A bioswale are shown in Table 21. No comparisons were made using the input data at TB9Ac2N due to the short length of instrument deployment and monitoring difficulties. The total post-construction output at TB9A had a 17% change from pre-construction totals, with pre-construction at 133% of roadway volume and post-construction 111% of roadway volume, suggesting a decrease in output volume after bioswale installation. Bioswale output totals for all years range between 97% and 133% of roadway volumes. There is little decrease in bioswale output totals compared to roadway volumes at this site, in part due to site hydrology near Belleau Lake that may prevent infiltration and allow groundwater inputs to the bioswale area. Groundwater additions to discharge totals are likely, based on standardized yields greater than 100% of roadway volumes.

Bioswale output totals at TB9A correspond to annual rainfall totals. Pre-construction and Year 1 monitoring had higher output volumes of 133% and 125% of roadway precipitation. This high percentage during the two years with the highest precipitation may be due to additional contribution from surrounding areas, including backflows from Farmers Creek during large events, a higher degree of runoff from the steep roadway embankment, and low infiltration rates or groundwater discharge due to a higher water table from the adjacent lake and roadway embankment. Year 2 had the lowest precipitation total, and a standardized yield of 117%. Years 3 and 4 had average precipitation and Year 5 had lower precipitation, with yields of 122%, 97%, and 100% respectively. The lower yields in Years 4 and 5 are in part due to large melting/slush events in January-February 2014 and January 2015, where discharge volumes could not be calculated with regular rating curves, and discharges were not evaluated. Years 4 and 5 may also have lower totals because over-channel flow was calculated with the small channel rating curve instead of the area-velocity method. This may have underestimated totals because velocity data were not available in Years 4 and 5 to evaluate over-channel flow intervals, but underestimation is not expected to be significant because over-channel flows were infrequent and averaged 0.32 ft above channel height. If Years 4 and 5 output totals were a more typical 115% of roadway volume, this would suggest the total post-construction discharge is closer to 120% of roadway volume than 112%, suggesting that post-construction total discharge reductions may be slightly over-estimated.

TB15B Discharge Calculations and Precipitation Totals

Discharge and precipitation totals for bioswale TB15B are shown in Table 22. The input from TB15Bc1N is not used for direct input and output discharge comparisons because of the short deployment time and monitoring difficulties. The total post-construction discharge increased from pre-construction discharge by 6%, with pre-construction yield at 113% of roadway volume in the TB15B ditch and Year 1-5 total post-construction at 120% of roadway volume at TB15Bgw+sw. Post-construction output totals for individual years range between 98% and 144% of roadway volumes. Output totals in most post-construction years are greater than the contributing roadway volume, in part due to the

Table 21. TB9A discharge volume results

TB9A Precipitation and Volume Totals

	O'Hare WSO Precipitation (in.)	Calculated Roadway Runoff (ft^3)	Calculated Bioswale Discharge (ft^3)
TB9Ac2N	(during deployment)		
Pre-construction	not monitored		
Year 1	not monitored		
Year 2	not monitored		
Year 3	not monitored		
Year 4	25.52	784,640	216,689
Year 5	33.22	1,021,385	285,812
Year 1-5 total	58.74	1,806,025	502,501
TB9A			
Pre-construction	43.05	1,323,619	1,756,622
Year 1	17.07	524,836	655,352
Year 2	31.09	955,896	1,117,117
Year 3	40.84	1,255,670	1,535,549
Year 4	39.00	1,199,097	1,162,656
Year 5	33.22	1,021,385	1,015,308
Year 1-5 total	161.22	4,956,884	5,485,982

TB9A Standardized Yields
(Bioswale discharge volume / Roadway runoff volume from contributing area)

	O'Hare WSO Precipitation Annual Totals (in.)	TB9Ac2N	TB9A
Pre-construction	43.05		1.33
Year 1	44.91		1.25
Year 2	31.09		1.17
Year 3	40.84		1.22
Year 4	39.00	0.28	0.97*
Year 5	33.22	0.28	1.00*
Year 1-5	37.81**	0.28	1.11

High annual precipitation
Average annual precipitation
Low annual precipitation
*Winter melting events not captured
**Mean annual precipitation

Table 22. TB15B discharge volume results

TB15B Precipitation and Volume Totals

	O'Hare WSO Precipitation (in.)	Calculated Roadway Runoff (ft^3)	Calculated Bioswale Discharge (ft^3)
TB15B	(during deployment)		
Pre-construction	54.75	804,907	910,179
TB15Bc1N			
Pre-construction	not monitored		
Year 1	not monitored		
Year 2	not monitored		
Year 3	not monitored		
Year 4	35.76	525,726	237,765
Year 5	33.22	488,384	246,920
Year 2-5 total	68.98	1,014,110	484,685
TB15Bgw			
Pre-construction	not monitored		
Year 1	not monitored		
Year 2	29.33	431,195	507,445
Year 3	40.84	600,409	658,619
Year 4	39.00	573,359	781,919
Year 5	33.22	488,384	448,834
Year 2-5 total	142.39	2,093,347	2,396,817
TB15Bsw			
Pre-construction	not monitored		
Year 1	13.92	204,645	45,502
Year 2	31.09	457,070	5,063
Year 3	40.84	600,409	70,028
Year 4	39.00	573,359	45,080
Year 5	33.22	488,384	30,527
Year 2-5 total	144.15	2,119,221	150,698
TB15Bsw+gw			
Pre-construction	not monitored		
Year 2	31.09	457070	512,508
Year 3	40.84	600,409	728,647
Year 4	39.00	573,359	826,999
Year 5	33.22	488,384	479,361
Year 2-5 total	144.15	2,119,221	2,547,515

Table 22 (continued). TB15B discharge volume results

TB15B Standardized Yields

(Bioswale discharge volume / Roadway runoff volume from contributing area)

	O'Hare WSO Precipitation Annual Totals (in.)	TB15Bc1N	TB15B & TB15Bgw	TB15Bsw	TB15B sw+gw
Pre-construction - TB15B	43.05		1.13**		
Year 1	44.91			0.22	
Year 2 - TB15Bsw/gw	31.09		1.18	0.01	1.12
Year 3	40.84		1.10	0.12	1.21
Year 4	39.00	0.45	1.36	0.08	1.44
Year 5	33.22	0.51	0.92*	0.06	0.98
Year 2-5	36.04***	0.48	1.14	0.07	1.20

High annual precipitation

Average annual precipitation

Low annual precipitation

* Sensor placement issues

** Manning estimation

***Mean annual precipitation

dry bioswale underdrain pipe being located below the water table and allowing for near-constant groundwater inputs to the underdrain.

Bioswale output totals for the outlets at the pre-construction TB15B location and post-construction combined TB15Bgw and TB15Bsw locations range between 92% and 144% of roadway precipitation totals. The pre-construction year, Years 2, and 3 have standardized yields of 113%, 112%, and 121% respectively. This range seems to represent a typical output, as these totals occurred in years with both below and above average precipitation. The Manning equation total for the pre-construction vegetated ditch of 113% above roadway volume has more uncertainty than rating curve totals in post-construction years, because the Manning slope and channel roughness estimations have a wide range of applicable values. Year 4 has a yield of 144% of roadway precipitation, which may be an overestimate due to increased ponding at the outlet that is observable in the Isco level record below 0.1 ft during Year 4. The manual measurement rating curve did not compensate for the increased ponding as there were no manual measurements taken at times of ponding after precipitation events. The increased ponding did not appear in the Year 5 Isco data record, and no compensation was made for the higher calculated totals in Year 4. Year 5 volume totals were 92% of roadway totals. This lower total is possibly due to low annual precipitation in Year 5, or an observed but undocumented upward shift in the level sensor noted in the underdrain pipe. These conditions would also account for an absence of increased ponding in the Isco level record. No compensation was implemented for possible unmeasured volumes.

Surface-water output totals at the TB15Bsw dry bioswale location closely follow annual precipitation totals. Because most runoff infiltrated and exited via the underdrain, surface water output yields are a small percentage of total output, ranging from 1% of roadway volume in Year 2 with the lowest annual precipitation, to 22% of roadway volume in Year 1 with the highest annual precipitation. Yields for the two years with average precipitation are 12% in Year 3 and 8% in Year 4. Year 5 has a lower annual precipitation total and 6% standardized yield. The higher percentage of surface flow in higher precipitation years is affected by increased overland flow from surrounding bioswale areas as the infiltration capacity of the dry bioswale is exceeded. Infiltration rates may decrease with elevated groundwater levels at this site.

There is an overall increase in post-construction discharge volumes compared to pre-construction discharge at the site, possibly due to the underdrain receiving groundwater inputs, or increased roadway area draining to the bioswale after more traffic lanes were added to the highway during construction.

TB19 Discharge Calculations and Precipitation Totals

Discharge and precipitation totals for bioswale TB19 are shown in Table 23. TB19 did not have an input monitoring location, and runoff entered the bioswale by overland flow from the roadway. Post-construction discharge at TB19 increased 8-11% from pre-construction, with pre-construction discharges 104% and 101% of roadway volume for

Table 23. TB19 discharge volume results

TB19 Precipitation and Volume Totals

	O'Hare WSO Precipitation (in.)	Calculated Roadway Runoff (ft^3)	Calculated Bioswale Discharge (ft^3)
TB19 (2/21/08-3/3/09) (during deployment)			
Pre-construction	50.81	539,983	559,961
TB19r (9/9/09-6/1/10)			
Pre-construction	23.18	246,345	249,624
Tb19gw			
Year 1	not monitored		
Year 2	29.33	311,705	290,339
Year 3	40.84	434,027	511,701
Year 4	39.00	414,473	425,235
Year 5	33.22	353,046	311,862
Year 2-5 total	142.39	1,513,250	1,539,137
TB19sw			
Pre-construction	not monitored		
Year 1	not monitored		
Year 2	29.17	310,004	7,734
Year 3	40.84	434,027	65,164
Year 4	39.00	414,473	77,871
Year 5	33.22	353,046	13,781
Year 2-5 total	142.23	1,511,550	164,550
TB19sw+gw			
Pre-construction	not monitored		
Year 1	not monitored		
Year 2	29.33	311,705	298,073
Year 3	40.84	434,027	576,865
Year 4	39.00	414,473	503,106
Year 5	33.22	353,046	325,643
Year 2-5 total	142.39	1,513,250	1,703,687

Table 23 (continued). TB19 discharge volume results

TB19 Standardized Yields

(Bioswale discharge volume / Roadway runoff volume from contributing area)

	O'Hare WSO Precipitation Annual Totals (in.)	TB19, TB19r, & TB19gw	TB19sw	TB19 sw+gw
Pre-construction - TB19	50.81	1.04		
Pre-construction - TB19r	43.05	1.01**		
Year 1	44.91			
Year 2 - TB19sw/gw	31.09	0.93	0.02	0.96
Year 3	40.84	1.18	0.15	1.33
Year 4	39.00	1.03	0.19	1.21
Year 5	33.22	0.88	0.04	0.92
Year 2-5	36.04***	1.02	0.11	1.13

High annual precipitation

Average annual precipitation

Low annual precipitation

**Manning estimation

***Mean annual precipitation

TB19 and TB19r and total post-construction discharge 113% of roadway volume at TB19gw+sw. Bioswale output totals for all years range between 92% and 133% of roadway volumes. Discharges may be higher than contributing roadway volumes because of groundwater inputs to the underdrain or an increase in contributing lane-miles from concurrent highway construction.

Output discharge totals generally follow the trend of annual precipitation totals, where both pre-construction years and Years 3 and 4 have average to above average precipitation and discharge yields are a higher percentage of roadway volumes, 104%, 101%, 133%, and 121% respectively. Years 2 and 5 have below average precipitation and discharge yields are a lower percentage of roadway volumes at 96% and 92%. The TB19gw monitoring location did not have issues with ponding over the instruments, and discharge totals above 100% of roadway volume are likely due to increased overland flow from surrounding contributing areas or groundwater flow into the bioswale underdrain.

Surface-water output totals at TB19sw closely follow annual precipitation totals. Yields range from 2 to 19% of roadway volumes, with the low precipitation Years 2 and 5 yielding 2% and 4%, and average precipitation Years 3 and 4 yielding 15% and 19%. The higher percentage of surface water discharge volumes in higher precipitation years is affected by increased overland flow as infiltration capacity of the dry bioswale is exceeded.

EVENT PEAK TRAVEL TIMES AND HYDROGRAPH EXTENSION ANALYSES

Runoff travel times through the bioswales were evaluated with hydrograph extension analyses and peak arrival time differences between the inlet and outlet at TB7Bin and TB7Bout. Bioswale TB7B was used for these analyses as the only continually monitored bioswale in an isolated basin with a single input pipe and a single outlet location, both of which were similarly instrumented.

A selection of events with distinct hydrograph peaks was evaluated for hydrograph extensions before and after the bioswale and check dams were installed. The results in Table 24 show that event volume centroids had an average arrival time difference between input and output locations of 0.56 hours before construction and 2.42 hours after construction.

Average travel times of event peak levels for these selected events was 0.271 hours in the pre-construction year before bioswale check dam installation, and 2.17 hours after check dams were installed. Average travel times for all event peaks with fairly distinct peaks was 0.44 hours in August through October of the pre-construction year, and 0.88 hours in Year 5 of post-construction monitoring. These peak travel times for all events reflected inclusion of events with compound peaks and various levels of antecedent soil moisture and water levels, which affected infiltration and flow velocities through the bioswale. Event travel times of larger multi-peak events can be faster than isolated single peak events, but the average travel time for all events remained slower in the

Table 24. Event hydrograph analyses

Event #	Peak discharge time difference TB7Bin to TB7Bout (hours)	Volume centroid time difference TB7Bin to TB7Bout (hours)
Pre-construction		
1	0.25	0.33
2	0.17	0.42
3	0.50	0.75
4	0.17	0.75
Average	0.27	0.56
Post-construction		
5	2.25	2.25
6	2.25	2.75
7	2.00	2.25
Average	2.17	2.42

TB7Bin

Event #	Start time	End time	Volume (ft^3)	Time to peak discharge (hours)	Time to volume centroid (hours)
Pre-construction					
1	8/19/2009 16:30	8/19/2009 18:20	1579	0.83	0.92
2	8/21/2009 16:30	8/21/2009 21:25	2253	0.17	0.25
3	9/27/2009 20:40	9/27/2009 22:10	395	0.08	0.17
4	11/24/2009 17:10	11/24/2009 23:05	3504	1.00	2.33
Post-construction					
5	4/3/2014 06:00	4/3/2014 10:15	2144	1.25	1.75
6	5/16/2014 08:30	5/16/2014 15:45	1139	1.00	2.00
7	4/13/2015 04:00	4/13/2015 08:45	1803	1.00	1.25

TB7Bout

Event #	Start time	End time	Volume (ft^3)	Time to peak discharge (hours)	Time to volume centroid (hours)
Pre-construction					
1	8/19/2009 17:20	8/19/2009 19:00	897	0.25	0.42
2	8/21/2009 16:30	8/21/2009 18:25	706	0.33	0.67
3	9/27/2009 21:10	9/27/2009 22:15	188	0.08	0.42
4	11/24/2009 17:50	11/25/2009 00:35	4094	0.50	2.42
Post-construction					
5	4/3/2014 08:30	4/3/2014 17:45	1961	1.00	1.50
6	5/16/2014 10:45	5/16/2014 17:00	378	1.00	2.50
7	4/13/2015 06:15	4/13/2015 11:00	714	0.75	1.25

post-construction phase with the check dams installed than in the pre-construction open-channel drainage ditches. Slowing of runoff travel times through this bioswale are likely due to functions of the installed bioswale and check dams, and would indicate an increase in runoff retention time, an anticipated function of the bioswales.

DISCUSSION OF ERROR

Discharges calculated in this report used rating curve analyses and comparisons to precipitation volumes from contributing roadway runoff areas, and may contain a number of potential sources of error. Errors relate to methods and instrumentation, and estimates of these errors are difficult to quantify due to multiple sources of unknown magnitude, and these sources indicate limitations in the methodology presented. While calculations of error are generally not made, the following are some sources of error considered for discharge measurements and runoff coefficient analyses in this report.

Possible error sources in methodologies include estimations from various data acquisition and comparison procedures. Discharges were compared to roadway runoff volumes and were calculated with roadway drainage areas provided in Tollway construction plans. The plans may not be representative of the complete area drained but are the best source of available data. Areas surrounding the bioswales that were not included in roadway catchment areas on construction plans may also have contributed to discharge totals, and this source was not measured or estimated. Precipitation amounts used as comparison for bioswale discharge volumes were calculated with data from the Chicago O’Hare WSO, which was about 4 miles from the closest bioswale site, and may not represent the same amount of precipitation that directly fell on the sites during specific storm events. Below freezing temperatures and other unfavorable site conditions such as instrument failure caused occasional gaps in data, and these were partially accounted for with maintenance at biweekly site visits, but no estimates of runoff were made when malfunctioning equipment was a factor. Further, rating curves are an average of all flow conditions and were selected as the best method of calculating flows under various unsteady flow regimes, but they may not fully represent all actual conditions present at a site. This may create an over- or under-estimation of calculated volumes depending on the degree to which the rating curve represents actual field conditions. These errors in methods were minimized by multiple field site maintenance visits, extensive data review, and long-duration monitoring of conditions for rating curve development.

Possible error sources from instrumentation can be from non-optimal sensor functioning under a variety of flow conditions. The velocity sensor that was used to calculate discharge rates for the rating curves may not function correctly in all field conditions, including in the small diameter underdrain pipes that may have an adverse Doppler signal reflection environment, and also when there was less turbid water and a lack of suitable reflectors for accurate Doppler velocity measurements. Errors with Doppler velocity sensors can be due to turbulent flow, clear flow, or transitions between pipe-full and open-channel flow that produce highly unsteady or unreadable signal reflections (International Stormwater BMP Database 2009, Granato et al. 2003). Higher-velocity flows may have caused errors in pressure transducer level readings by creating a vacuum under the sensor resulting in lower than actual level readings. Altered flow regimes may also have been created by higher-velocity flows when combined with flood waves in longer sloping culverts and small diameter pipes, or with large vertical drops from elevated roadways combined with ponded conditions at the pipe inlet. Changes in critical flow conditions have also been identified as having altered stage-discharge relationships (Franz and Melching 1997), and may occur more frequently in the smaller diameter pipes. These instrumentation errors were partially mitigated by optimizing instrument locations and appropriate equipment selections, but monitoring was limited by the engineered structures at individual site locations.

The procedure described in this report for comparing annual discharge results to contributing roadway runoff volumes provides a basis for uniformity in methods and analysis techniques, and resultant comparable data for the bioswale sites. Compilation of discharge totals in annual intervals created an averaged discharge over longer time scales and included greater measured variability, reducing error over the extended time frame. Efforts to identify improvements in calculation techniques were ongoing throughout the study, and will provide support for additional discharge calculations in follow-up studies on continued bioswale performance or in other similar projects.

SUMMARY

Discharge volumes were calculated with rating curve methods and used to evaluate input and output discharges in roadside drainageways before and after bioswale installations. Of the four bioswales monitored, one wet bioswale (TB7B) was located in a setting that allowed infiltration due to permeable native materials, resulting in an average 31% reduction in discharge volume between input and output locations after bioswale installation. The second wet bioswale at TB9A, located next to a lake, and two dry bioswales TB15B and TB19, where the underdrains were located close to the water table, had probable interception of higher groundwater tables resulting in less infiltration and additional output volumes, with a 6-17% increase in output volumes after the installation of bioswales.

Bioswale output discharges and retention times are also affected by precipitation amounts and intensity of events. Higher intensity precipitation events provided important additions to bioswale flow volumes from surrounding areas of runoff. In the wet bioswales, the additional runoff volumes were not retained long enough to allow for adequate subsurface infiltration during higher intensity events to reduce total output volumes. These factors, plus additional groundwater contributions and direct precipitation may have resulted in bioswale output discharge volumes greater than the volume of precipitation provided by the contributing roadway area.

The rating curve method was used for calculation of annual bioswale flow discharges, and results were verified based on comparisons to corresponding precipitation volumes from contributing roadway areas. Because the seven monitoring years included three years with above average precipitation, two years with average precipitation, and two years with below average precipitation, it was possible to evaluate input and output volumes in both wetter and drier years.

In the most isolated and continuously instrumented bioswale system at wet bioswale TB7B, input volumes remained a fairly steady percentage of roadway precipitation, between 91 and 112%, while output volumes varied between 52 and 132% according to the amount of precipitation in the year. Input discharge volumes at the TB7Bin culvert were from a completely paved area piped directly from the roadway, with results close to the commonly used Rational Method values of 90% of precipitation converted to runoff from paved areas. Output volumes at TB7Bout were lower than input volumes and ranged from 52 to 73% of roadway volumes during pre-construction and post-construction Years 2, 4, and 5. Year 1 had a calculated volume of 132% of roadway volume, which was likely high because Year 1 had the highest annual precipitation and highest intensity events of all monitoring years. The variation in results between wet and dry years provided validation that the bioswale was infiltrating runoff in drier years. Infiltration trends between pre- and post-construction monitoring were not identified because pre-construction monitoring took place during a single year with above average precipitation, and data for changes in infiltration amounts between wet and dry years in the pre-construction ditch were not available.

The wet bioswale at TB9A showed a fairly steady output volume during pre-construction and Years 1-3 ranging between 117 and 132% of roadway volumes. Years 4 and 5 had lower output percentages between 97 and 100%, affected by wintertime slush flows that were unmeasured plus the lack of an in-channel velocity sensor that made identifying and removing ponded or backflooded conditions difficult. Infiltration and higher output volumes compared to roadway precipitation volumes at this site may have been affected by groundwater contributions, flood backups during larger precipitation events, and the bioswale location between a lake and a steep road grade.

Infiltration at dry bioswales functioned as designed, indicated by the surface-water output stations TB15Bsw and TB19sw discharging only 1%-22% of roadway volumes, and the main underdrain outlet pipes TB15Bgw and TB19gw that discharged between 92% and 144% of roadway volumes. Groundwater inputs into the underdrain pipes at these sites likely increased output percentages above roadway contribution volumes.

Hydrograph analyses at TB7B indicated there was slowing of flow and an increase in runoff travel times after the bioswale and check dams were installed. The average pre-construction event peak travel time between TB7Bin and TB7Bout for all events was 0.44 hours, and the average in the last year of monitoring was 0.88 hours. Event volume mid-point travel times for seven selected single peak events showed a 0.56 hour average before construction and 2.42 hour average after construction. Increased peak travel times would indicate increased residence times in the bioswale, and therefore increased treatment through more infiltration and longer contact with bioswale plants and materials. Attenuation of flood peaks also occurs with additional storage times and slowing of runoff flow.

The effectiveness of slowing runoff flow and increasing residence times in the bioswales to enhance runoff treatment is further evaluated with calculations of bioswale mass loadings and constituent removal efficiencies in a separate report (Miner et al. 2016). Discharge volumes calculated in this study are used in the subsequent report for calculations of mass loadings and investigations of mass reductions in all four monitored bioswales. Bioswale design recommendations and site-specific choices are also provided in Miner et al. (2016).

FUTURE WORK

Monitoring of selected bioswales with Isco 730 bubblers, 750 AV modules, and manual discharge measurements will continue through 2019 in order to confirm and follow longer-term trends. No additional discharge data will be collected.

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