Monitoring edge-of-field surface-water runoff: a three-state pilot project to promote and evaluate a simple, inexpensive, and reliable gauge

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Funding provided by USDA-NRCS Conservation Innovation Grant

Executive Summary

This three-state project field-tested prototype gauging stations in a variety of landscapes while demonstrating and promoting this promising new system designed to obtain low-cost, good-quality edge-of-field monitoring data in production agricultural settings that can be used in tiered efforts to develop local knowledge and expertise in water quality management.

In response to a growing demand for edge-of-field runoff monitoring data from organizations with limited resources, the University of Wisconsin-Platteville Pioneer Farm Research team worked with UW-Platteville's Electrical Engineering department to develop a prototype runoff monitoring gauge designed to both reduce costs and address weaknesses with conventional monitoring equipment. A broad coalition of partners from Wisconsin, Minnesota, and Iowa installed and field-tested the prototype monitoring stations, engaged farmers, increased regional monitoring capacity, and provided public outreach.

By testing the equipment exclusively on private land and providing reimbursement for time, farmers were engaged in the process throughout the study period. Farmers attended training sessions, public field days, and worked with research staff one-on-one to select station locations, inquire about the project, and discuss results. In one case, the farmer was the local field technician and Soil and Water Conservation District member. This farmer spoke about his role at public field days and demonstrated the equipment.

After some initial modifications, the prototype equipment provided results comparable to a conventional station. Analysis of data generated from prototype sensors, conventional sensors, and photographic observations indicates that both the prototype and conventional ultrasonic sensors provide the same degree of accuracy. Testing performed at the St. Anthony Falls lab

shows that the prototype Modified HXL flume provides accurate estimates of discharge except during turbulent flow conditions where discharge may be underestimated. The flume heater successfully aided winter maintenance and saved hours of field time. Sediment and nutrient concentrations collected from the prototype sampler indicates no statistically significant difference from grab samples. Real-time submergence correction was flawed by an error in the datalogger code, but post-event corrections were possible. The conventional system is incapable of monitoring during submergence, so this feature gave the prototype a significant performance advantage. Weaknesses in the prototype gauge addressed through continued development include: remote access, flume weight and cost, data storage and transfer, and photo validation of data.

Background and Approach

Conservation practices are implemented within agricultural fields and knowledge of conservation impacts on water quality are incomplete without monitoring at the individual field scale. The Mississippi River Basin Initiative (MRBI) recognized the importance of monitoring water quality at multiple scales including the field scale by devising a tiered approach to assess conservation effectiveness. From a research standpoint however, edge-of-field runoff monitoring has been largely orphaned in favor of plot-scale and watershed scale monitoring. Watershed loads of sediment and nutrients do not provide accurate estimates of upland contributions from fields that have preventive practices implemented. On the other hand, plot-scale research quantifies movement of sediment and nutrients, but it is not always clear how the results are representative of actual field losses, especially where conservation practices such as grassed waterways are in use. To determine the export of sediment and/or nutrients at the field scale, accurate measurements of both discharge and concentration must be obtained at the edge of the field. A widely-used conventional method of monitoring edge-of-field runoff involves the use of a pre-fabricated fiberglass h-flume, datalogger, refrigerated sampler, stage sensor, and enclosure. This system provides a high degree of flexibility and very good accuracy; however, it also requires experienced, technically skilled staff to operate. The high capital and labor costs prevent conventional systems from being widely deployed, and may deter effective multi-scale efforts in MRBI watershed projects.

This three-state (Wisconsin, Minnesota, and Iowa) project tested, demonstrated, and promoted a promising new system to obtain low-cost, good-quality edge-of-field monitoring data in production agricultural settings within a three-state region that can be used in tiered efforts to develop local knowledge and expertise in water quality management. The University of Wisconsin-Platteville Pioneer Farm, in collaboration with UW-Platteville Engineering, developed an innovative, low-cost monitoring system that enabled widely-deployed, coordinated edge-of-field monitoring. By eliminating unnecessary features, the prototype monitoring system derives the majority of cost savings with minimal sacrifice in accuracy. Despite costing less than conventional systems, features have been added to reduce both the failure rate and maintenance costs while improving data quality. These features include a tail-water sensor, backup photographic stage data, backup sampler, a flume heater (for preparing flumes in winter), and easily replaceable components.

Figure 1. Public field day on August 21, 2014

All edge-of-field runoff monitoring systems estimate pollutant export, but no monitoring system is 100% accurate. Each component (e.g. flume, stage sensor, sampler) in the monitoring system introduces error, thus overall accuracy is dependent upon the cumulative error of all system components (Harmel 2006). Conventional gauges provide good overall accuracy (estimated error range of 9.7 to 21%) with a set-up cost of $20,000 per site and operational costs of $25,000 per year. The expected error for the prototype gauge is slightly higher with values ranging from 13 to 23%, but projected costs are significantly less than a conventional site.

Methods

Siting

Runoff stations were positioned at the edges of fields in grassed waterways on private farms. Considerations for siting included year-round access, estimated peak discharge, slope, and whether the station would impede tractors, harvesters, and other vehicles. Lead technicians in each state coordinated with project participants for choosing suitable monitoring locations. Monitored catchments varied in size, climate, cropping patterns, soils, and slope to provide a diverse and robust field test. Typical monitored catchments ranged from 5 to 40 acres and were located near Platteville, WI; River Falls, WI; Dyersville, IA; Fort Dodge, IA; Ames, IA, and Rochester, MN.

Training and Outreach

Three training sessions were hosted by UW-Platteville Pioneer Farm Research staff early in the project. These sessions provided all of the critical information to those who would be involved with siting, installation, operation, and data analysis. The sessions included a visit to the first field installation to demonstrate installation and setup methods and considerations, a presentation and discussion about the gauge components, and a trip to the hydraulics lab to demonstrate station operation during flow conditions.

Six field days were hosted by UW-Platteville, the Minnesota Department of Agriculture, the Iowa Soybean Association, and UW-Extension. During these field days, the project and associated equipment was explained and demonstrated, farmers discussed their roles, and the public was provided an opportunity to engage with project participants to learn about runoff monitoring and the goals of the study.

MHXL Flume

The modified HXL (MHXL) flume was developed by UW-Platteville Pioneer Farm Research. The primary objective for developing this flume was to limit water depth while maintaining flow capacity sufficient for edge-of-field monitoring. This was achieved by modifying the geometry of the flume and by allowing for controlled overtopping conditions. Five cubic feet per second (cfs) of flow in a 0.375-foot MHXL flume is about half the depth of the same flow in a 2-foot h-flume. One foot of stage in a 2.5-foot h-flume is 2.41 cubic feet per second (cfs) of discharge, while one foot of stage in a 0.375-foot MHXL flume (overtopping) is 11 cfs of discharge. By reducing maximum stage, installation and maintenance costs are reduced with smaller soil berms and less ponding and hydraulic pressure upstream of the station. To prevent runoff water from bypassing monitoring stations, each flume was attached to a vertical plywood

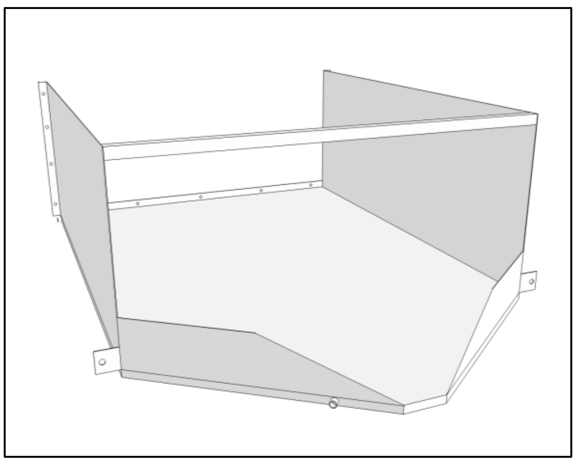

Figure 2. Modified HXL flume with attached water jacket and approach section.

wing wall that was partially buried and tamped into place. Soil berms were installed beyond each wing wall to direct all runoff water through the flume for monitoring and sampling.

Flume Heater

Beneath the flume, a thin fluid jacket with threaded inlets and outlets was welded in place to allow for heated antifreeze circulation. A portable propane camping water heater and pump was used to heat and circulate antifreeze on-demand to reduce labor associated with station preparation in late winter when in-flume ice buildup becomes frequent during the freeze-thaw cycle. Manually chipping ice from flumes typically requires 1-2 hours and accidental damage to the flume and other equipment is a risk. The integrated heater was designed to quickly melt the bond between the flume floor and walls so that the ice could be lifted out after 10-20 minutes of run time.

Stage Sensor

Maxbotix HRWL-WR sensors were wired into a custom weather proof enclosure and mounted above the flume and tailwater to monitor stage. The in-flume sensor is mounted upstream of the flume in the attached approach section to account for the extended drawdown curve of the water's surface during overtopping conditions. The tailwater sensor is used to detect and correct for submergence. The sensor has a resolution of 1 mm, digital output, and an accuracy of 1%.

Figure 3. Sensor with custom weather proof housing

Datalogger

The datalogger was developed by UW-Platteville Pioneer Farm Research and the Electrical Engineering department. The first generation dataloggers lacked an on-board user interface and were wired and assembled by students. Three units were field-tested in Wisconsin for several months in 2012, but problems associated with quality control and lack of a user interface led to rapid development of the second-generation system.

Figure 4. First generation datalogger

On the second-generation unit (used for the remainder of the project), a 2-row lcd screen and 3x4 keypad was added to provide a live display and on-board user interface. The second-generation datalogger also featured greatly improved wiring, plugs, and receptacles for simplified installation and component replacement. Contracted engineering firms developed the enclosure and assembled the dataloggers. These units were pre-programmed for edge-of-field monitoring and provided users with limited selectable variables such as flume type and size, greatly simplifying installation and setup. The interface featured an always-on display of live stage and total accumulated flow and also included menus to calibrate sensors and sample pump, download data, and adjust the date and time.

Figure 5. Second generation datalogger with lcd screen, keypad, and threaded cable connectors

Sample Pump

The prototype gauge was equipped with an APT Instruments SP300 peristaltic pump that was controlled by the datalogger. The datalogger continually measured accumulated flow and triggered a sample each time that the user-selected sample interval was met. For instance, if the user selected a sample interval of 100 cubic feet, then the sampler would trigger about every five and half minutes with a discharge rate of 0.3 cubic feet per second. The sample volume is determined during pump calibration and was typically between 100 and 200 mL. Clear vinyl tubing was attached to the pump to collect samples out of the flume and into a six-gallon plastic pail resulting in a flow-weighted composite sample. After the event, representative sub-samples were collected by vigorously stirring the sample with a paddle to evenly suspend solids while opening a spigot at the bottom of the pail to fill a one-liter bottle. Samples were stored on ice until they arrived at the USDA ARS National Lab for Agriculture and the Environment in Ames, Iowa to be analyzed for sediment and nutrient content.

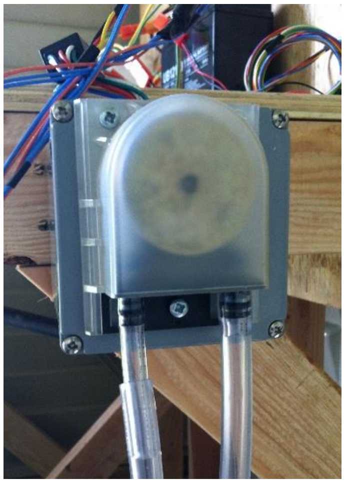

Figure 6. APT SP300 peristaltic pump

Backup Sampler

To provide a reliable backup sampler in case of power loss, passive single-stage siphon samplers were installed to sample at depths of 0.1’ and 0.2’. These samplers are comprised of a bottle with connected intake and vent tubes. The intake tube is placed in the flume, rises up to the desired sample depth, and then drops back down to the bottle, which is placed beside and below the flume. The vent tube connects to the bottle and is rises straight up to an elevation higher than the expected maximum stage. When stage in the flume reaches the sample depth, a siphon is initiated, once the bottle fills up, no water flows in or out.

Figure 7. Single stage siphon samplers photographed from above

Photographic Data

Stationary time-lapse digital cameras were used to automatically record daily field conditions, periodic agronomic practices, and continuous flume stage and conditions. The time-

Figure 8. Timelapse and motion triggered trail camera (left). Sample timelapse image (right).

lapse camera was aimed upslope at the contributing farm field and provided a continuous record of field conditions by taking one photo per day. The motion-triggered trail camera was also pointed upslope, had a 60-foot range, and was reliably triggered by passing tractors and implements to record the type and timing of agronomic practices. The flume stage camera was pointed at the flume and staff gauge and was triggered every 5 minutes to capture a continuous record of known stage values and accompanying conditions.

Power Supply

Power was provided by a combination of solar panels, charge controllers, and deep-cycle batteries. A 20-watt solar panel was mounted on a post near the station facing south. The solar panel cables were routed to a 10-amp charge controller. The battery and datalogger were connected to the battery and device terminals on the charge controller.

Precipitation Gauge

A Stratus RG202 manual precipitation gauge was used to record on-site precipitation. This unit has a maximum capacity of 11 inches and is accurate to 1/100th of an inch. This gauge was serviced upon each site visit, with precipitation data recorded in the field log.

Figure 9. Stratus RG202 precipitation gauge

Equipment Enclosures

Stations built in Wisconsin and eastern Iowa were housed within a 10x8 metal garden shed with sliding doors. The shed provided protection for the equipment and staff from the elements. Stations in Iowa and Minnesota housed electronics and sampling equipment in a plastic or steel storage box while the flume, sensors, and other equipment was installed without an enclosure.

Station Visits

Stations were visited at least once per month during dry periods to conduct routine maintenance and data collection. After runoff events, stations were visited to collect samples, make observations, and collect data. During the winter season, stations were visited before anticipated runoff events to remove snow and ice from the station and its components to allow for free-flowing conditions and sampler functionality. Every effort was made to visit runoff stations during runoff to validate data and observe equipment while in operation. Routine maintenance included mowing, checking and adjusting flume levelness, calibrating stage sensors, dealing with pest activity, checking and replacing batteries, collecting images and resetting cameras, and maintaining clean flumes and approach sections.

Evaluation

During the active monitoring period, field technicians documented observations of prototype gauge performance. This qualitative evaluation was used to make improvements upon both the prototype equipment and methods.

In-line stations were installed where the experimental equipment was in a series with an existing conventional edge-of-field monitoring site. The in-line sites provided the opportunity to compare prototype and conventional station operation and results, while also providing a useful complement of equipment for field days and training.

Figure 10. Wisconsin in-line installation with soil berms to prevent run-on between stations. The prototype (right) was positioned upstream of the conventional station (left)

In addition to the in-line installations, seven in-situ stations featured conventional monitoring and sampling equipment alongside prototype equipment both using the same MHXL flume to compare stage sensor accuracy and sampling results of each system. The conventional equipment was comprised of an APG ultrasonic stage sensor, Campbell Scientific CR200X datalogger, portable ISCO sampler with four composite sample bottles, and a tipping bucket rain gauge. Conventional equipment did not include tail water or photo monitoring.

Results

Runoff Monitoring Capacity Building

Training sessions were hosted at UW-Platteville Pioneer Farm to provide project partners with the necessary information to install, operate, and maintain prototype equipment and analyze discharge data. For many in attendance, these training sessions were their first exposure to edge-of-field runoff monitoring equipment and techniques. The training was later used to begin their first attempts at runoff monitoring in their local communities, increasing the capacity of their programs and increasing awareness of runoff monitoring in their communities. In one instance, the field technician receiving the training was the farmer and Soil and Water Conservation

District staff member who was both installing and operating the equipment on his own property. In total, thirty people attended the training sessions to increase the capacity of their local monitoring and outreach programs.

Farmer Involvement

Participating farmers were encouraged to attend and participate in public field days and were reimbursed for their time and travel expenses. Farmers were typically very interested in the data being generated and were willing to answer questions and discuss their role during field days. Participating farmers received annual reports of data generated from the project and were provided with an explanation of the results. While farmers typically came away with a positive experience and valued the data after the project ended, the consensus indicated that the level of effort was too high to operate an edge-of-field station without assistance.

Figure 11. Public field day on August 29, 2013

Siting

Proper siting of edge-of-field runoff monitoring stations affects data quality regardless of the complement of equipment. The best results were generated from stations installed in deep grassed waterways with greater than three percent slopes, however fields available for runoff monitoring do not always have an ideal monitoring location available. Installations in shallow grassed waterways sometimes limited the length of soil berms extending from wingwalls if participating farmers weren't willing to have them extend beyond the waterway into their fields. At such stations, bypass was routinely observed during runoff events. Stations installed on nearly flat slopes experienced excessive submergence during snowmelt as staff was sometimes unable to sufficiently clear deep snow downstream from the flume.

Datalogger

Production of a working prototype was underway at the beginning of the project. Students in the UW-Platteville Electrical Engineering department were assembling dataloggers and wiring sensors and pumps to begin field testing. After the first units were installed and tested for several months, the failure rate was too high to further deploy and use the initial system for the field test. The backup power system was designed to switch to a smaller backup battery when voltage was detected to be too low. While this makes sense, the implementation of the switch did not factor in momentary voltage drops caused by the sample pump starting. Dataloggers would trigger the first sample of a runoff event causing a momentary voltage drop and switch over to the smaller battery for the remainder of the runoff event as the primary power can only be restored during a field visit. This resulted in power failures and data loss since the smaller batteries didn't have the capacity to serve as primary power sources during runoff events. Without a live display, laptops were carried into the field and connected to the prototype dataloggers to check stage, adjust settings, and collect data. With primary and backup dataloggers at each station, field visit times became too long. Sensors used on the first generation system proved to be too unreliable for field use. Finally, the complexity of the assembly introduced too many errors into the datalogger and wiring.

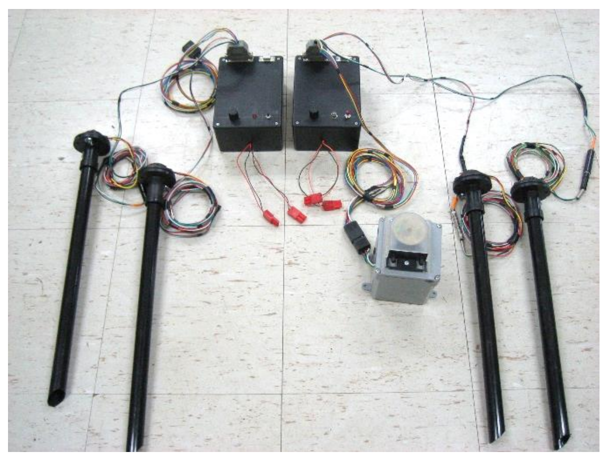

Figure 12. First generation electronics kit including primary and backup dataloggers and sensors, sample pump, and wiring harnesses

After the initial testing period, second generation dataloggers were rapidly developed, assembled, tested, and deployed widely for the remainder of the project. The live display and user-interface greatly reduced routine station visit times and improved technician's ability to detect malfunctions. The user interface also improved the setup and installation process since no external device (laptop) was needed to access setup menus.

Despite across the board improvements over the older datalogger, this unit still had some weaknesses. The built-in storage capacity was chosen during a very early stage of development and later became limited by additional parameters saved and growth of the program file size. The datalogger simply stops saving new data once the memory fills up and no on-screen warning is displayed. During field testing, data needed to be collected every two weeks or so during active runoff periods to prevent data loss. Data storage was sufficient to last 2-3 months during periods with brief runoff events since data is logged less frequently during dry conditions. Exacerbating the problem, technicians not only needed to remember to collect data frequently, they needed to remember to erase data after collection was complete in order to free up memory for new data.

Without removable memory or remote access, a laptop computer was needed to collect data. The program, Hyperterminal was used to interface with the datalogger through its serial port. Both the serial port and the software interface were confusing and difficult to use. Laptop computers available during the study period typically did not have a built-in serial port, so a USB adapter was used in its place. The adapters did not reliably work and often required users to restart the computer to restore functionality. The Hyperterminal interface did work, but required too many steps and was not intuitive to field staff. More hours of training were spent on learning data collection than any other procedure. Simply exchanging a removable storage card would have saved many hours in the field and reduced the instances of lost data.

Stage Sensors

The stage sensors used on the prototype gauge were very comparable to the stage sensors used on the conventional system. Since the accuracy of the conventional ultrasonic sensor has not been thoroughly tested, linear regressions for both sensors were generated using runoff events with known stage values generated from stage camera photographs (1,313 data points) taken during flow (Figure 13). Each sensor's results plotted with comparable coefficients of determination (R^2) and nearly 1:1 slopes, indicating that each sensor provides stage measurements that match observed stage within a 95% confidence interval. Since discharge

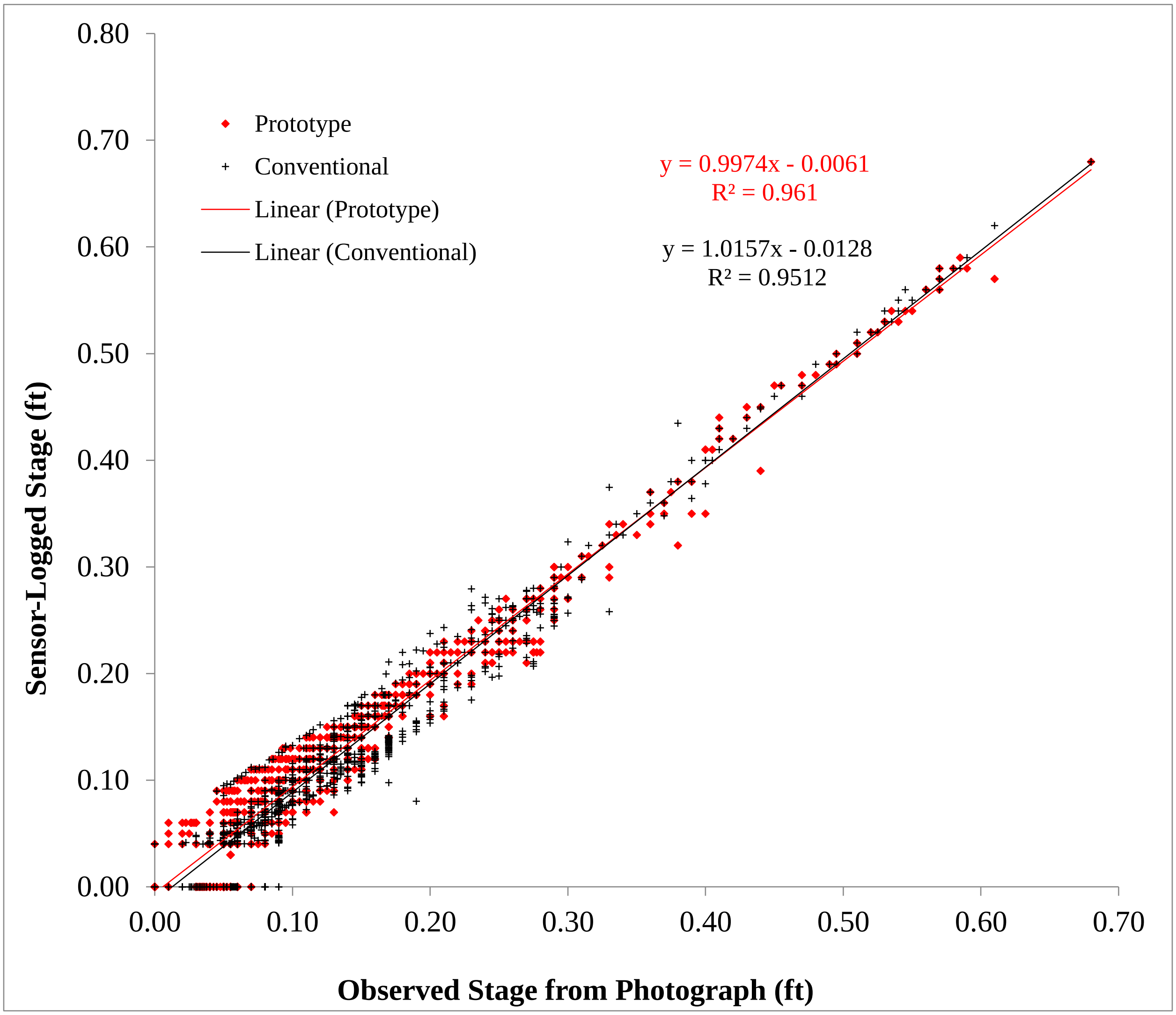

Figure 13. Linear regressions of observed stage and both prototype and conventional sensor stage

estimates are derived directly from stage data, this analysis indicates that both ultrasonic sensors will provide discharge estimates with approximately equal amounts of error.

MHXL Flume Field Observations

The MHXL flume reduced both installation and labor costs. The low-profile of the MHXL flume resulted in soil berms that were smaller in both height and length than what would have been required for equivalent H-flume installations. The integrated heater proved to be a major time-saver for removing ice of any thickness. Ten to twenty minutes after starting the heater, the bond between the flume and the ice would be melted free and the ice could easily be removed. Conventional flumes required hours of manual labor to break and remove ice in small pieces. The propane RV shower heater was prone to damage caused by mice and openings were covered with hardware cloth to keep mice out.

Figure 14. Thick ice easily removed after running the flume heater for ten minutes

MHXL Flume Lab Evaluation

Three 0.125’ MHXL flumes were precision machined and tested at University of Minnesota St. Anthony Falls Laboratory (SAF) in order to develop rating curves for the MHXL flume series. Laboratory tests included installation of the three flumes in series and subjecting flumes to multiple flow rates to determine the stage discharge relationship. Discharge was measured using time capture techniques as well as measurements from pre-calibrated in-line flumes (1.0’ and 2.5’ H-flumes). Seven discharge rates were utilized to establish the stage-discharge relationship for the low-flow portion of the flume (<=0.125’ stage), and 11 discharge rates were used to establish the stage-discharge relationship for the high-flow portion of the flume (>0.125’ to 0.5’ stages). Plots of data with polynomial regression trend lines indicate a strong relationship between stage and discharge and are included below (<=0.125' stages R^2 = 0.9958, >0.125' stages R^2 = 0.9986).

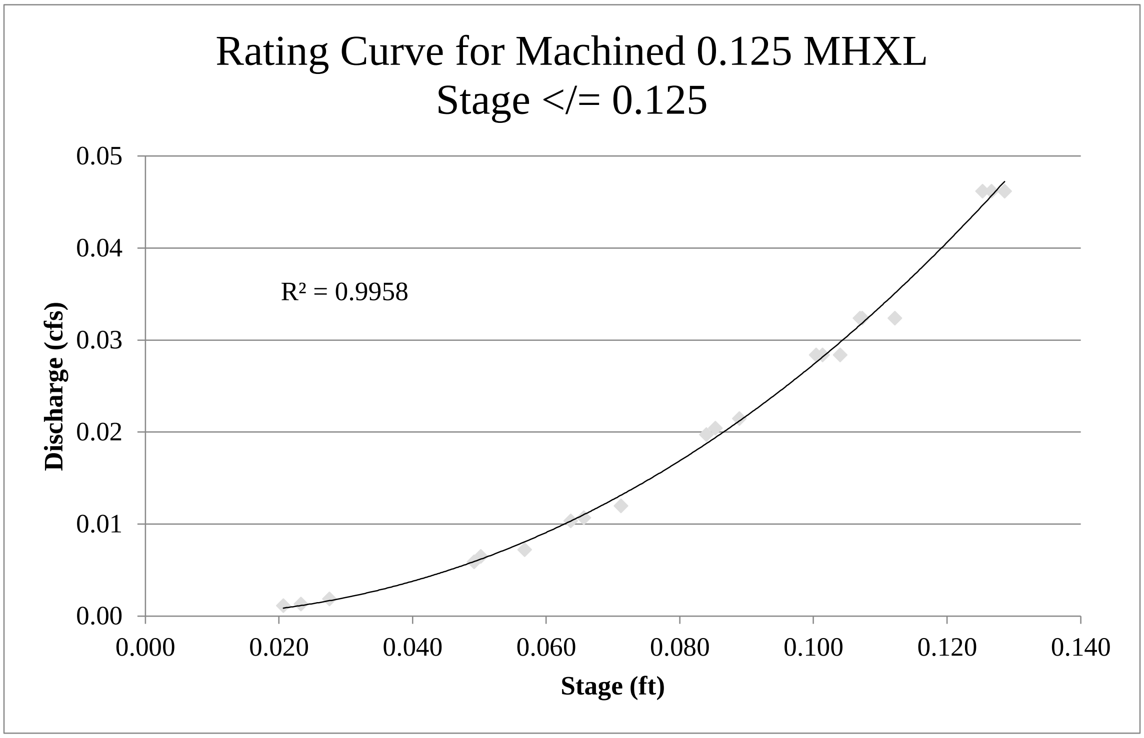

Figure 15. Rating curve for machined 0.125 MHXL flume for stages less than or equal to 0.125 feet

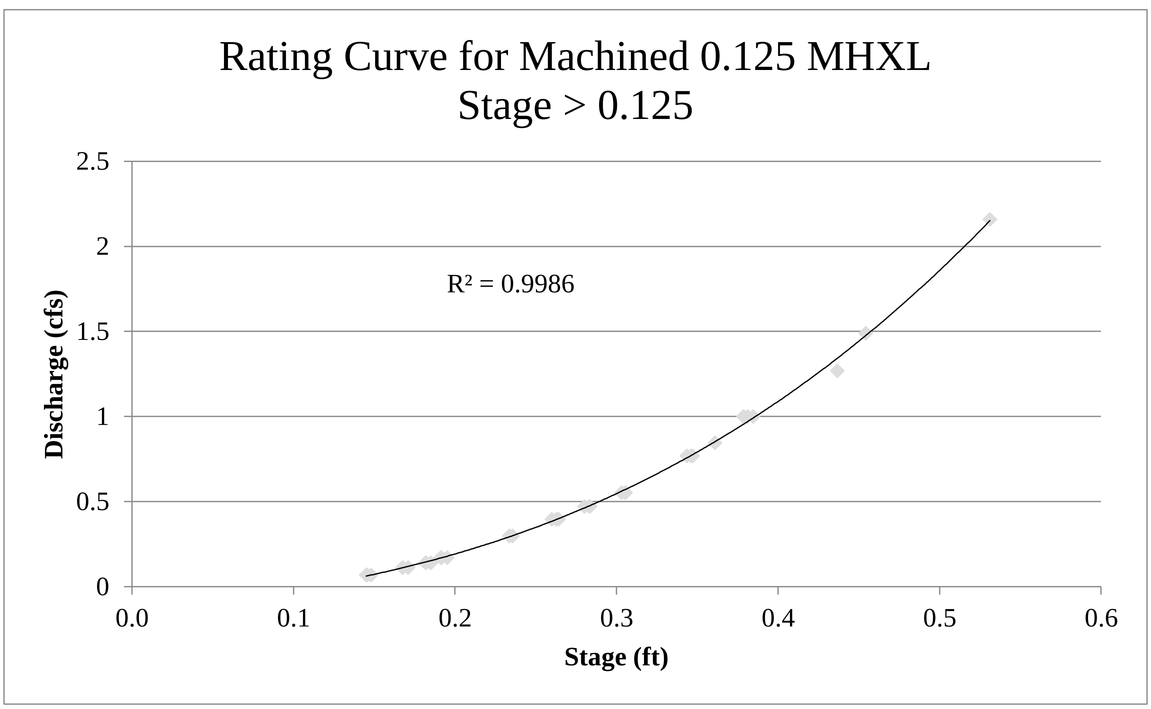

Figure 16. Rating curve for machined 0.125 MHXL flume for stages greater than 0.125 feet

In an effort to reduce cost, alternative flumes were constructed using state-of-the-art CNC metal cutting and bending techniques. This manufacturing technique reduce cost of flumes by approximately 60%. Several of these flumes were evaluated at the SAFL to determine accuracy and precision of discharge estimates.

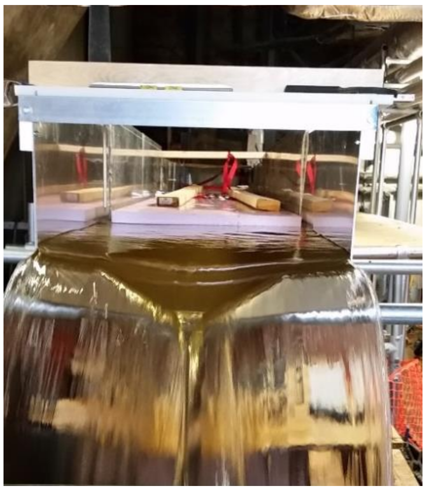

Figure 17. MHXL flume flowing at St. Anthony Falls

In order to determine accuracy and precision of flume discharge estimates, 138 pairs of stage and discharge measurements were obtained from 12 prototype flumes. The stage values were used to determine estimates of discharge using a scaled version of the 0.125' rating curve. This data was compared to measured discharge obtained using time capture techniques for low discharges and flume (1.0' and 2.5' H-flumes) measurements for higher flows. Figure 18 illustrates that the low-cost MHXL flumes produced precise estimates of discharge ($R^2 = 0.9968$)

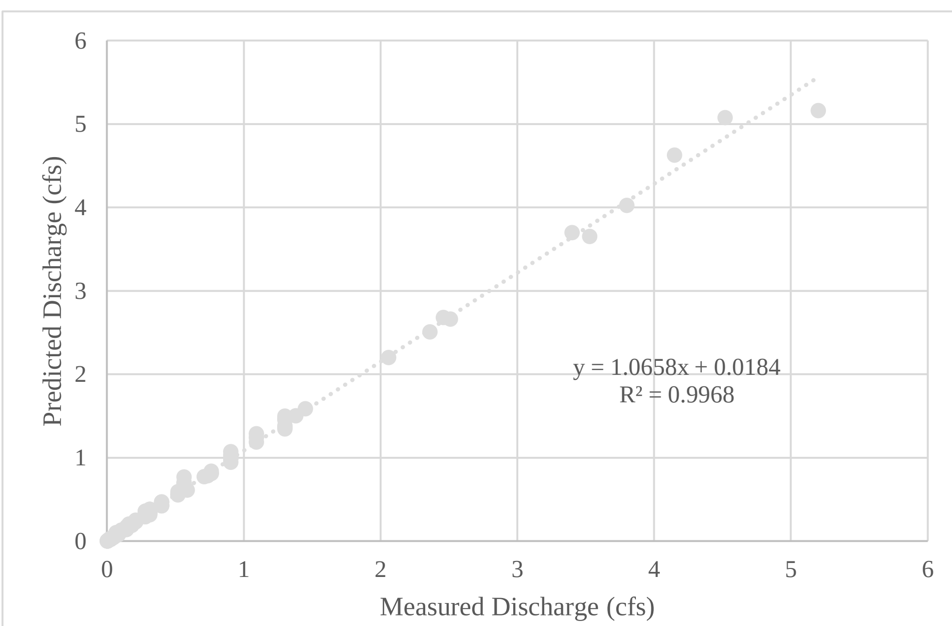

Figure 18. Linear regression of measured discharge against predicted discharge (based on scaled 0.125' MHXL rating curve

but the results were less accurate than the more expensive machined flumes and generally underestimated discharge (slope of the line = 1.0658).

While results are encouraging, lab and field test results indicate that at high discharge rates flow within the flume becomes turbulent and difficult to gauge- this condition is exacerbated with below-grade installations. Such conditions may be resulting in underestimation of discharge rates.

In-Line Comparisons

Comparing two edge-of-field runoff systems installed in-line with one another proved extremely difficult in practice. When designing the installation, many considerations must be made to prevent one station from affecting the results of the other. Both flumes must receive the same volume of runoff approaching at roughly the same velocity in order to make a valid comparison of results. Properly designing and maintaining such a setup required dramatically more effort than anticipated.

Figure 19. Low quiescent flow (left) and high turbulent flow (right)

The in-line setup in Wisconsin was installed in a waterway with minimal relief, as a result, the stations needed to be about 200 feet apart such that ponding at the downstream flume would not back up into the upstream flume. The waterway in between was bermed to prevent run-on that would increase flow at the downstream flume. Unfortunately, the snow distribution prior to the first and largest runoff event directed runoff water over a berm near the upstream station allowing runoff water to bypass the

Figure 20. Wisconsin in-line station with bypass

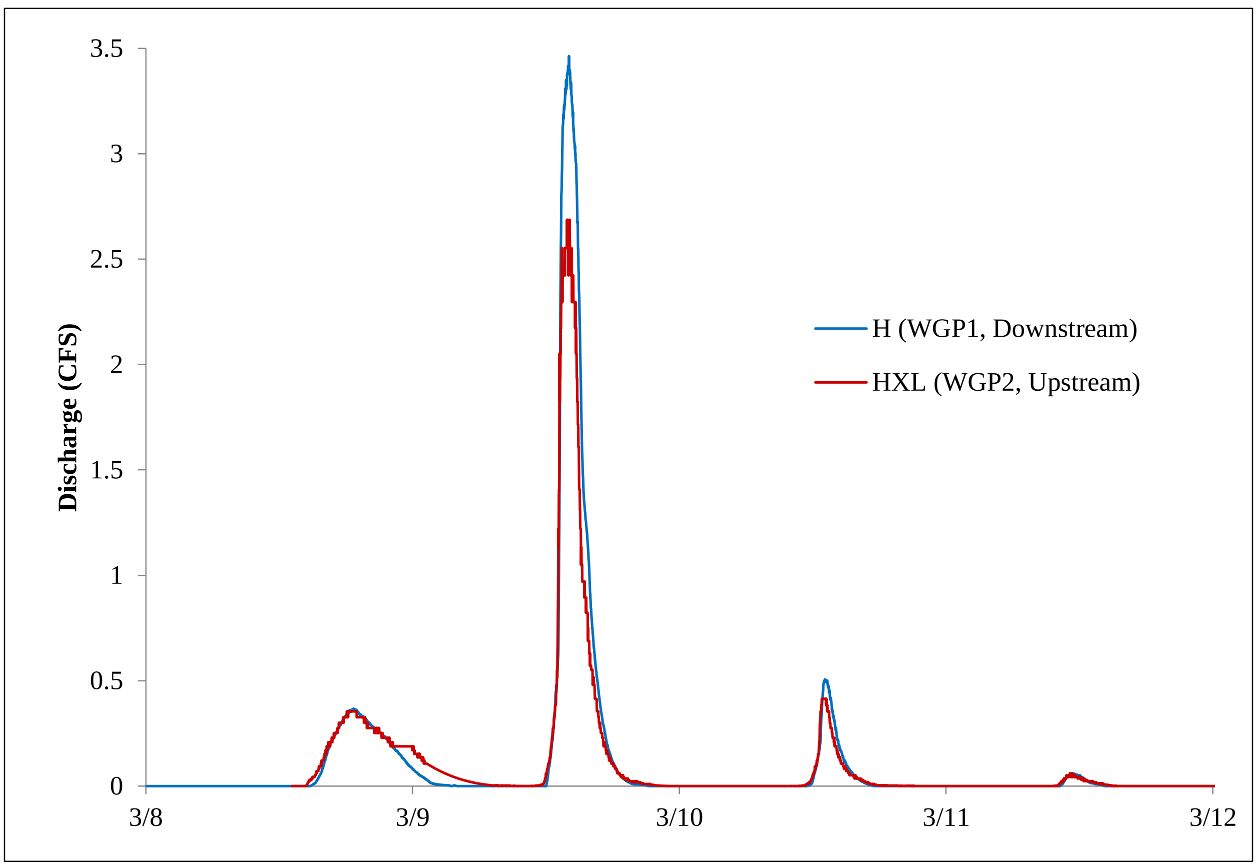

Figure 21. Discharge hydrograph of Wisconsin in-line stations during the 2015 snowmelt runoff event

prototype gauge and flow through the conventional gauge downstream until the issue was discovered and corrected. The narrow shoveled path through the snow upstream from the prototype station coupled with high volume resulted in high-velocity water flowing into the prototype flume. This flume was also installed below-grade, further accelerating the water and increasing turbulence. The downstream channel through the snow was much wider, allowing runoff water to slow down and spread out before reaching the at-grade conventional h-flume. All of these issues were corrected after the first runoff event, however only one other runoff event occurred.

In Minnesota, the flumes for the in-line stations were placed close together with a wood channel between them. However, the upstream portion of the channel was not sealed to the upstream h-flume. It was left open to prevent runoff from backing up water and submerging the upstream flume. This design leaves open the possibility of runoff water spilling out the back of the channel and bypassing the lower flume, particularly under high flows. A scale-model laboratory simulation of this setup indicated significant leaking of water between flumes, but the amount was not consistently proportional to flow. The channel between flumes was then

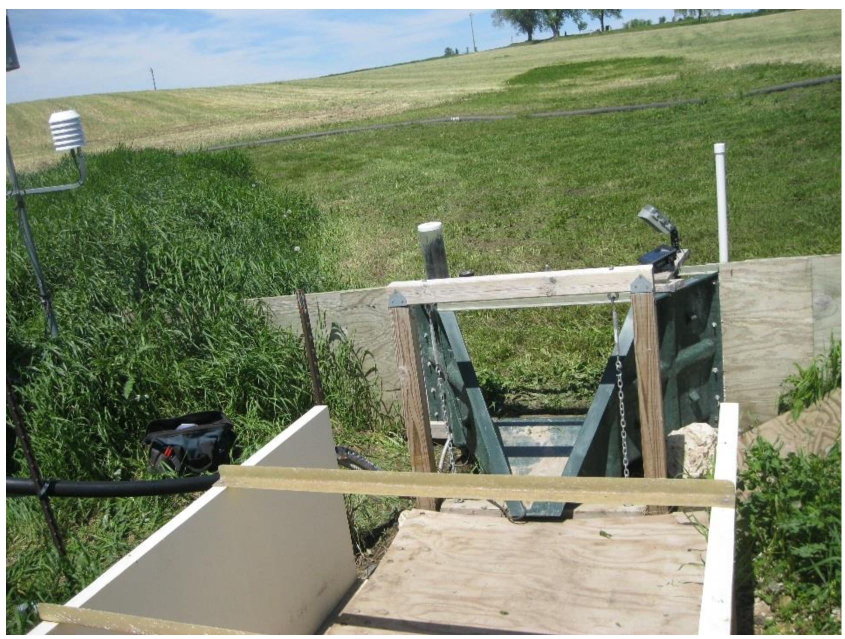

Figure 22. Minnesota station with in-line flumes. Upstream h-flume with open-back channel

removed in the winter months, leaving open the possibility of both bypass and run-on between stations.

Errors and Problems Documented at In-Situ Stations

Errors and other issues were documented by field staff for both the prototype and conventional equipment during the data collection period (Table 1).

Table 1 Observed sources of error for both the prototype and conventional monitoring systems

Prototype Monitoring System		**Conventional Monitoring System**	
Issue or error	**Number of occurrences**	**Issue or error**	**Number of occurrences**
1. Sensor reading erroneously high (1.60 -1.87 feet)	9	1. Erroneously high readings (1.47 to 1.52’)	7
2. Changing the offset was displayed on the datalogger but no observable effect on the data being recorded	2	2. Erroneous and erratic main sensor values ranging from 0.34-1.31’	6
3. Data display reading different stages than what is being recorded by the datalogger	9	3. Stage values were reported as “NAN” or “not a number” indicating an issue with the ultrasonic sensor	1
4. Blown fuses causing the system to not record data and / or datalogger lost power and started recording the date and time at 1/1/2000 00:00	4	4. No samples collected during runoff due to submergence conditions	8
5. Random drop in stage	3	5. Discharge estimates inaccurate due to submergence conditions	30
6. Raw sensor reading is bad (reading 0098 or 1640)	1		
7. Datalogger recording one hundredth of the raw sensor value (e.g., Raw value = 1480, sensor reading 14.80 feet)	1		

Prototype Monitoring System		**Conventional Monitoring System**	
Issue or error	**Number of occurrences**	**Issue or error**	**Number of occurrences**
8. Cracked pump tubing during season….missed samples on 2 events)	5		
9. Erroneous and erratic main sensor values ranging from 0.79-1.6	48		
10. Datalogger randomly stopped recording data (sometimes values still appeared on the datalogger screen)	8		
11. Sensor not reading what was below it	1		
12. Sensor zero point changed on its own	1		
13. Datalogger stopped recording any data and showed the values of "65:65:65 65/65/65,-0001,-0001, 0.00,0.00,0"	2		
14. Datalogger displayed "?!#, etc." after plugging in to download	1		
15. Pump fell apart and broken pieces caused the system to pull too much power, blow the fuse, and render the system inoperable	1		

Submergence Correction

Monitoring tail water proved an effective method of detecting flume submergence conditions. When submergence conditions were detected with elevated tail water stage, the datalogger reduced flow estimates once the submergence reached 54%, reducing sample frequency as designed. However, late in the project the correction factor in the datalogger program was found to be incorrect such that the discharge estimate was being over-corrected resulting in under-sampling under these conditions. Discharge estimates were easily corrected using logged stage and tail water data and the proper correction equation. Conventional stations were not capable of estimating discharge under submergence conditions and field technicians turned off conventional samplers during these periods and logged zero discharge. Some submergence conditions lasted for multiple days in a row and accounted for the majority of snowmelt export, so this feature was found to drastically improve discharge estimates at stations vulnerable to submergence.

Sampling

The APT Instruments SP300 pump was reliable in the field. Pump failure requiring replacement was very rare. The only issue encountered early on was that the silicone pump tubing did not have sufficient durability for the busy snowmelt season and was replaced with more durable Norprene tubing. Concentrations from 18 runoff events where both the prototype and conventional samplers each collected at least one liter of sample (from the in-situ comparison stations) were analyzed and mean concentrations are shown in Table 2.

Linear regressions for each of the constituents are plotted in Figure 23.

Table 2. Mean constituent concentrations in mg/L for 18 runoff events

Constituent	Prototype	Conventional
Ammonium	2.2	2.9
NO2+NO3(N)	2.2	2.1
Suspended Sediment (SS)	662	751
Total Phosphorus (TP)	1.7	1.9

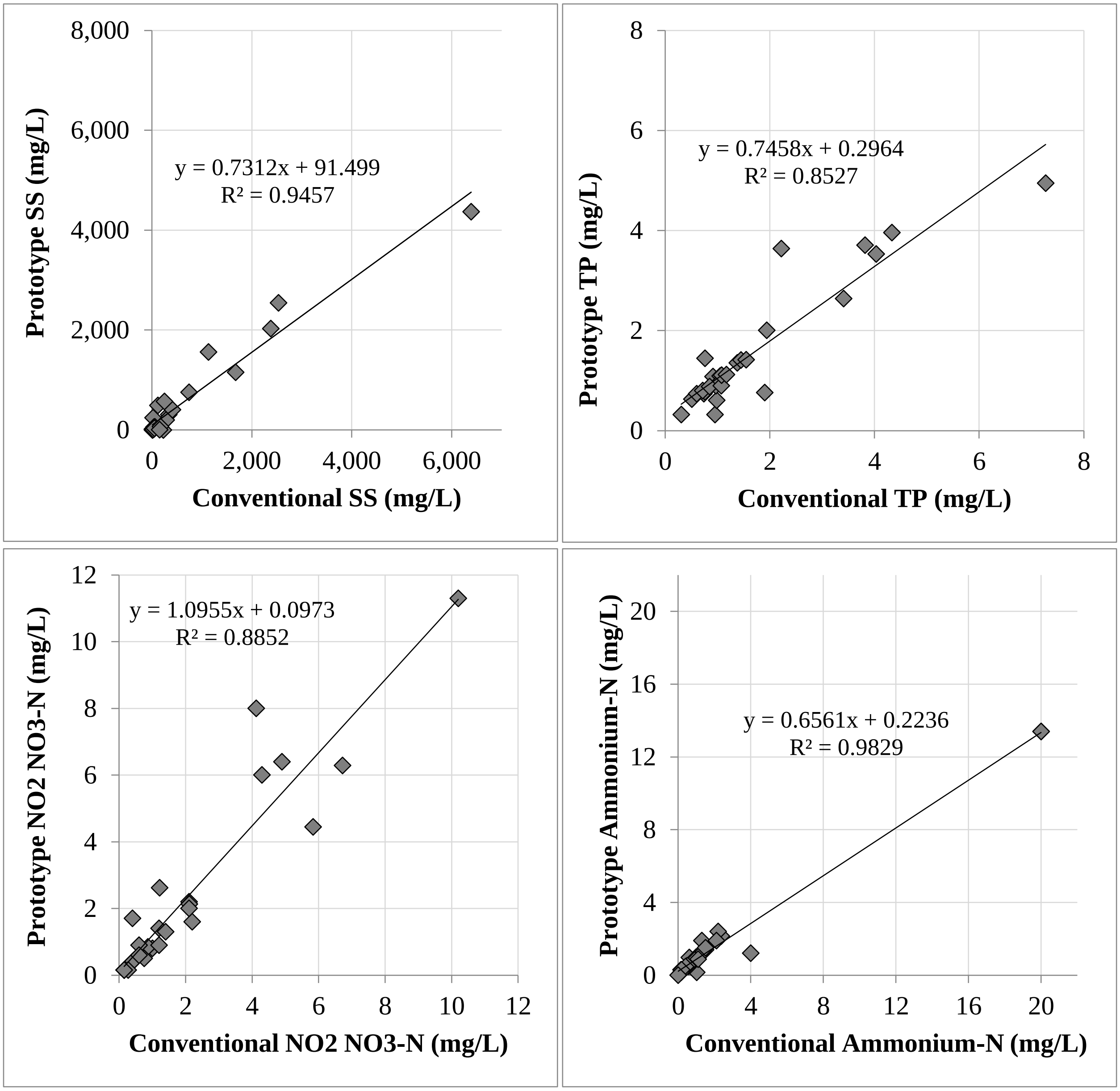

Figure 23. Linear regressions of tested constituent concentrations from prototype and conventional samples

To further investigate, a laboratory trial was conducted to compare water quality data from the APT Instruments pump (CIG) to samples collected by industry standard automated samplers (ISCO) and grab sampling techniques. The trial was conducted at the UW-Platteville Environmental Engineering Hydraulics lab. Evaluations were based on several water quality parameters, including: nitrate plus nitrite (NO_2^-/NO_3^-), dissolved reactive phosphorus (DRP), total phosphorus (TP), ammonium (NH_4^+), total Kjeldahl nitrogen (TKN), total nitrogen (TN), and turbidity.

Prior to conducting the laboratory trials, soils were collected from the UW-Platteville Pioneer Farm to create a synthetic runoff. Soils were collected from the top 5 cm of the soil surface of cultivated fields. The collected soil was then dried and sieved. The sieved soil was then added to the recirculating flume in the UW-Platteville Environmental Engineering Laboratory. The recirculating flume consists of a collection tank, constant head tank, approach section, and flume (1.0 H-flume). Stage depth in the flume was determined using a 60 mm point gauge (Armfield). Agitation/circulating pumps were added to the collection tank to maintain soil particles in suspension during the experiment.

Figure 24. Point gauge measurement of water surface (left), h flume and approach during high flow trial (right)

After addition of soil to the recirculating flume, water flow was adjusted until a 0.2 ft steady-state stage was established. After obtaining steady-state flow, replicate samples (2) were collected simultaneously from each the CIG and ISCO Samplers and two grab sample collected from the end of the H-flume. After sample collection, flow was increased in increments of 0.1 ft and another round of samples were collected at each flow depth. Samples were refrigerated after collection prior to transport to the UW-Stevens Point Water and Environmental Analysis Laboratory for analysis. The graphs below illustrate interquartile ranges and mean values for all constituents by sampler type. The charts indicate that the CIG sampler produced similar results compared to the grab samples, and concentrations from samples collected with the ISCO sampler tended to be slightly higher in concentration than the CIG and grab samples. Results of Analysis of Variance statistical test indicate that the type of sampler had a significant ($p=0.05$) effect on sample TKN and TN concentrations.

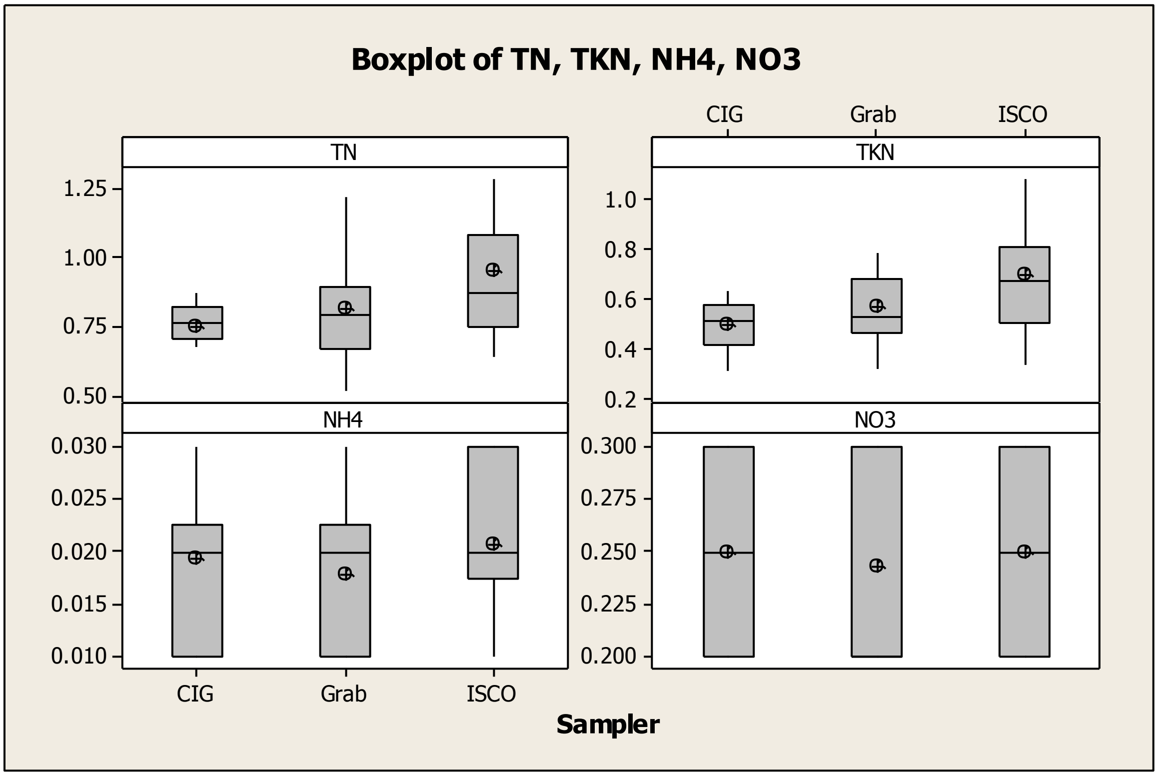

Figure 25. Boxplot of TN, TKN, NH4, and NO3 concentrations

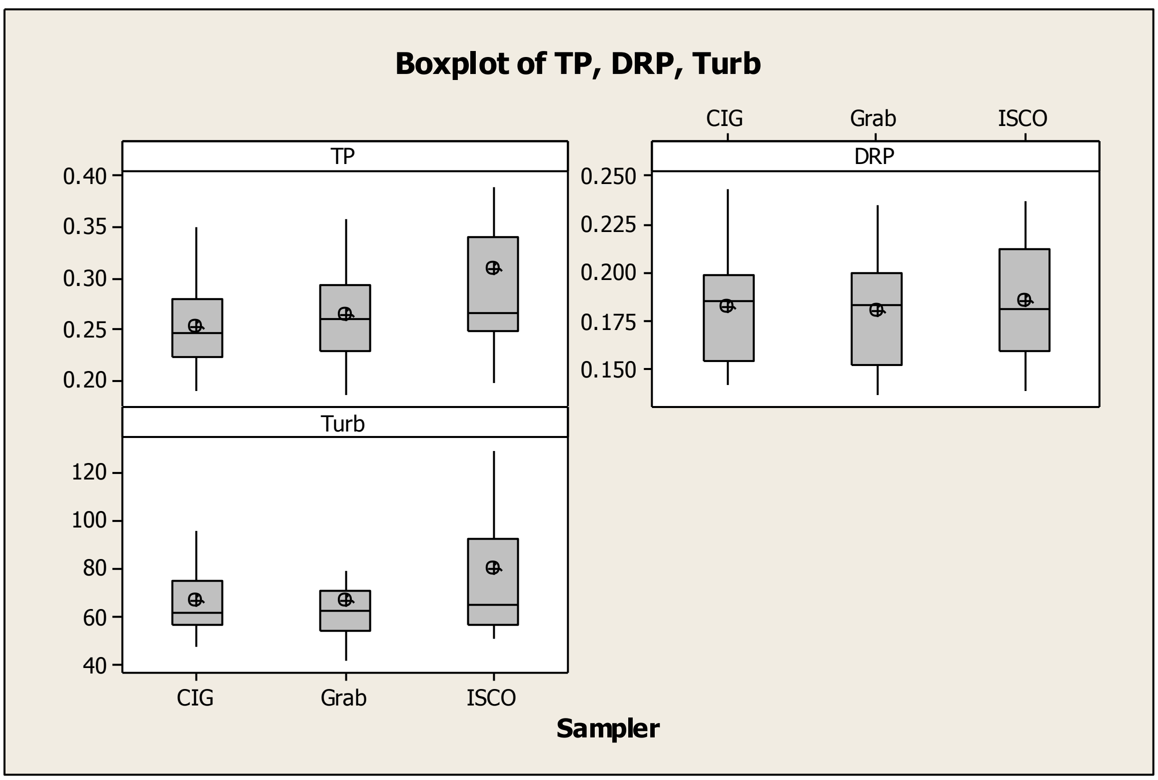

Figure 26. Boxplot of TP, DRP, and turbidity concentrations

Mean concentration for samples from each sampler are included in Table 3 by parameter. Values with the same superscript indicate significant differences. Paired t-test analysis of sample concentrations indicated that the ISCO produced significantly (p=0.05) higher TKN, TN, and turbidity concentrations when compared to grab samples. The ISCO sampler concentrations for TKN and TN were also significantly higher than CIG sampler concentrations. There were no significant differences between CIG and grab sampler concentrations. One potential explanation for the differences in sample concentrations is that the ISCO sampler is collecting more bed load sediment from the bottom of the channel because it has a faster intake velocity than the CIG sampler, and the bed load is producing a biased sample.

Table 3. Nutrient and turbidity mean concentrations from each of three sampling methods. Matching superscript indicates statistically significant differences.

	Parameter						
Sampler	**DRP**	**TP**	**NO3/NO2**	**NH4**	**TKN**	**TN**	**Turbidity**
			-------------------- (mg/l) --------------------				
CIG	0.18	0.25	0.25	0.19	0.50^{b}	0.75^{b}	66.9
ISCO	0.19	0.26	0.25	0.18	0.70^{a}	0.95^{a}	80.1^{a}
Grab	0.18	0.31	0.24	0.21	0.57^{ab}	0.81^{ab}	66.6^{a}

Backup Sampler

Passive samplers worked as expected during the warm seasons and captured samples from all but the smallest events. The samples are not representative of the entire event, but they provide some water quality information in when electronics malfunction. While they did work, they were very difficult to access and replace, adding significant time to field visits. If the samplers did not seal properly, water would continually flow through them during runoff events, creating a sediment trap and biasing the sample. The biggest problem with passive samplers was submergence.

Figure 27. Passive samplers submerged after a runoff event

This was especially a problem at stations with gentle slopes. In winter, bottles would become submerged under water and then freeze in place, so they were inaccessible until spring.

Passive samplers were in place throughout the study period but were primarily used as a back-up system in case the automated sampling system failed to collect water. Samples from seven runoff events were analyzed to compare the results from the automated sampler to the passive sampler. Table 4 provides a summary of the analysis for the comparison between the automated sampler and the passive sampler.

Table 4. Statistical analysis of the mean loads between the automated sampler and passive sampler

Analyte	**Mean of Event Loads (pounds)**		**Number of Events**	**p-value**	**Statistically significant at α =0.05?**
	Automated Sampler*	**Passive sampler***			
Suspended Sediment Concentration	516 (294)	1,244 (1,040)	7	0.37	No
Total Phosphorus	0.52 (0.19)	0.78 (0.49)	7	0.42	No
Nitrate – Nitrogen	1.1 (0.7)	0.6 (0.4)	7	0.16	No
Ammonia	0.3 (0.2)	0.2 (0.2)	7	0.22	No
*Values in parentheses indicate the standard error					

No statistical differences were found between the loads of the automated equipment and the passive samplers. Although no statistical difference was found, the mean loads for the SSC collected by the passive sampler were 58% higher and total phosphorus was 33% higher. Conversely, the nitrate-nitrogen load and ammonia loads were less than the automated sampler by 47% and 21%, respectively. These differences are likely the result of the discrete nature of the samples. While there was no statistical difference between the passive samples and the automated samples, the reliability problems combined with the relatively large percent differences in concentrations indicate that more representative flow-weighted samples from the automated system provides samples that are better suited for estimating event loads.

Precipitation

The precipitation gauge provided a basic measurement of total rainfall, but the data generated does not quantify rainfall intensity. While the gauge is designed to measure snowfall, the plastic was prone to cracking over the winter months if pooled water froze in the cylinder. For that reason, the gauge was typically uninstalled during the winter season. For observational studies and adaptive management, this record is sufficient, however for research purposes, a tipping bucket rain gauge is recommended. In hindsight, the precipitation record could have been greatly improved if installed at a nearby cooperator's residence so that it could be checked more frequently.

Photographic Data

Data provided from photographs provided both critical validation of data and as well as difficult challenges. Daily timelapse imagery provided by the Wingscapes TimelapseCam was the easiest to manage as the cameras reliably triggered each day and did not have power problems when connected to 12-volt power. However, the daily images provided only field conditions, rarely capturing agronomic activities. The motion-triggered cameras were triggered by passing field equipment, providing a more complete record of agronomic practices. However, these cameras failed more frequently, especially after being in the field for a year. They also were prone to recording hundreds or even thousands of images caused by grass blowing in the wind, birds, and other natural movements. Images of flumes with staff gauges taken every five minutes provided very valuable stage validation data used to document the accuracy of the stage sensor. Images of the flume during flow identified turbulence, ice, submergence, and other factors that affected overall data quality. However, the Wingscapes Birdcam Pro (selected for its low cost, weather-proofing, built-in timelapse options, and LED flash) simply wasn't well-suited for long-term use. The camera was not capable of operating on 12V power alone, and the internal batteries only lasted about 2-4 weeks, even with 12V input. Continuously collecting data from three cameras per station generated hundreds of thousands of images requiring a large time commitment to transferring, sorting, culling, and extracting numerical data. Hundreds of gigabytes of storage were required to keep the images on file. The stage camera generated the most images, so typically only one image was saved from days with no runoff and the other 287 images were deleted.

Conclusions

This project successfully engaged farmers and the general public in edge-of-field runoff monitoring, improved the capacity of organizations beginning new monitoring efforts, and tested the prototype edge-of-field monitoring gauge. Field test results were used to drive further development to address weaknesses, reduce labor inputs, and improve data quality (Appendix A).

Despite attempts to reduce labor inputs and simplify station operation, diligent field staff are needed to gather usable data. Station visits must be made once per month at a bare minimum year round to perform routine maintenance and ensure station readiness for runoff. After runoff events, samples must be collected within 24 hours to ensure high integrity and prevent holding time effects on water chemistry. Every effort must be made to observe and document runoff events on-site to validate data and system function. Extensive training is not necessary to successfully operate the prototype gauge, but dedicated field staff are needed to make the effort worthwhile.

After initial improvements were made and assembly errors were identified, the prototype gauge and its components typically functioned as expected and provided discharge and pollutant export data that was comparable to conventional systems.

This project is a crucial step towards lowering barriers to edge-of-field monitoring and improving tools for adaptive management. Feedback from farmers indicates that while they are very interested in the results of edge-of-field monitoring stations, they do not have the resources to operate the stations without help. However, the prototype gauge provides a monitoring and outreach tool for organizations with limited resources to engage with the agricultural community.

References

Harmel, R. D., R. J. Cooper, R. M. Slade, R. L. Haney, J. G. Arnold (2006). Cumulative Uncertainty in Measured Streamflow and Water Quality Data for Small Watersheds. *Transactions of the American Society of Agricultural and Biological Engineers*, 49(3): 689-701.

Appendix A

Continued Development of Prototype Gauge

	PERFORMANCE OF PROJECT PROTOTYPE	UPDATES
DATALOGGER	Limited data storage, data loss	SD Card Logging
	Live display saves time	Remote Server Data Upload
	User interface eliminates laptop requirement for setup and operation	Improved User Interface (Figure 28)
	Confusing data collection interface	Web Display of latest 24 hours of data (Figure 29)
	Laptop required for data collection	Remote Pump Control
	No remote access, field visit required to determine status	
FLUME	Reduced installation costs with smaller berms	Flume design has been modified to create a greater cross-sectional area at high flow rates, however design has not yet been lab tested
	Requires at-grade installation and limited approach slope	Aluminum construction using CNC bending and cutting reduces weight and resists corrosion
	Steel construction was too heavy, vulnerable to rust	
FLUME HEATER	Heat system worked well but welded-on liquid jacket added significant fabrication costs	Improved lower cost design of the liquid jacket
	Water heater was sometimes damaged by mice	Heater enclosure designed to keep rodents out of heater
STAGE CAMERA	Consumer-grade camera not reliable for long-term operation	Multiple alternatives tested: tablet, smartphone, eyefi SD card, Arduino camera, indoor and outdoor IP cameras (Figure 30).
	Photos provide highly-valuable data validation and outreach tools	
	Insufficient data validation for data quality assurance	
SAMPLER	Silicone pump tubing has a short lifespan	
	Sampler reliability is good overall	

PASSIVE SAMPLERS	Functioned well in above-freezing weather	
	Difficult to access	
	Not functional in freezing weather, bottles freeze in place	
SENSOR	Good overall accuracy and reliability	Sensor triggers enabled to minimize cross talk between sensors.
	Intolerant of focus tubes	
	Occasional erroneous data output	
TIMELAPSE CAMERA	Good overall reliability	
MOTION-TRIGGERED TRAIL CAMERA	Consumer-grade camera not reliable for long-term operation	

Figure 28. Current generation datalogger with improved feature set

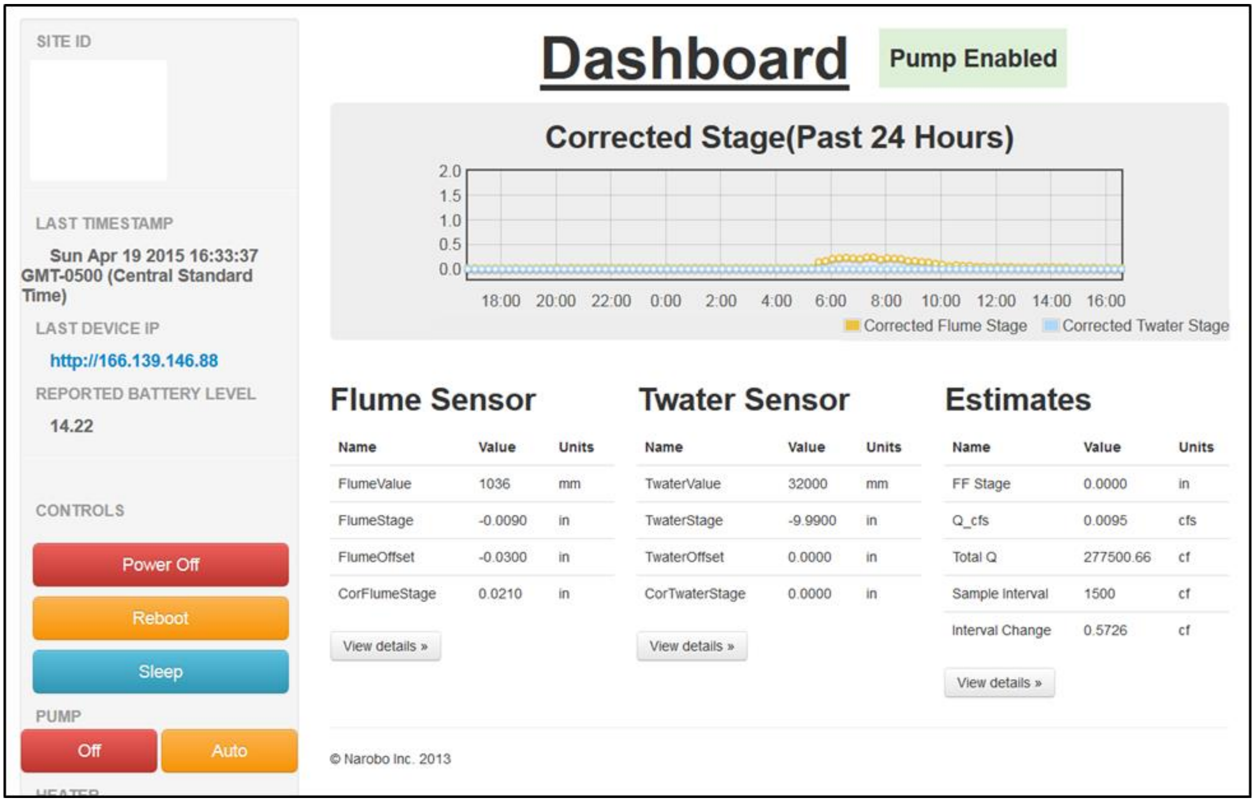

Figure 29. Online dashboard with recent data and remote controls

Outdoor IP Camera	Indoor IP Camera
 	 

Figure 30. X. IP cameras in use to remotely monitor stations in real time and validate data