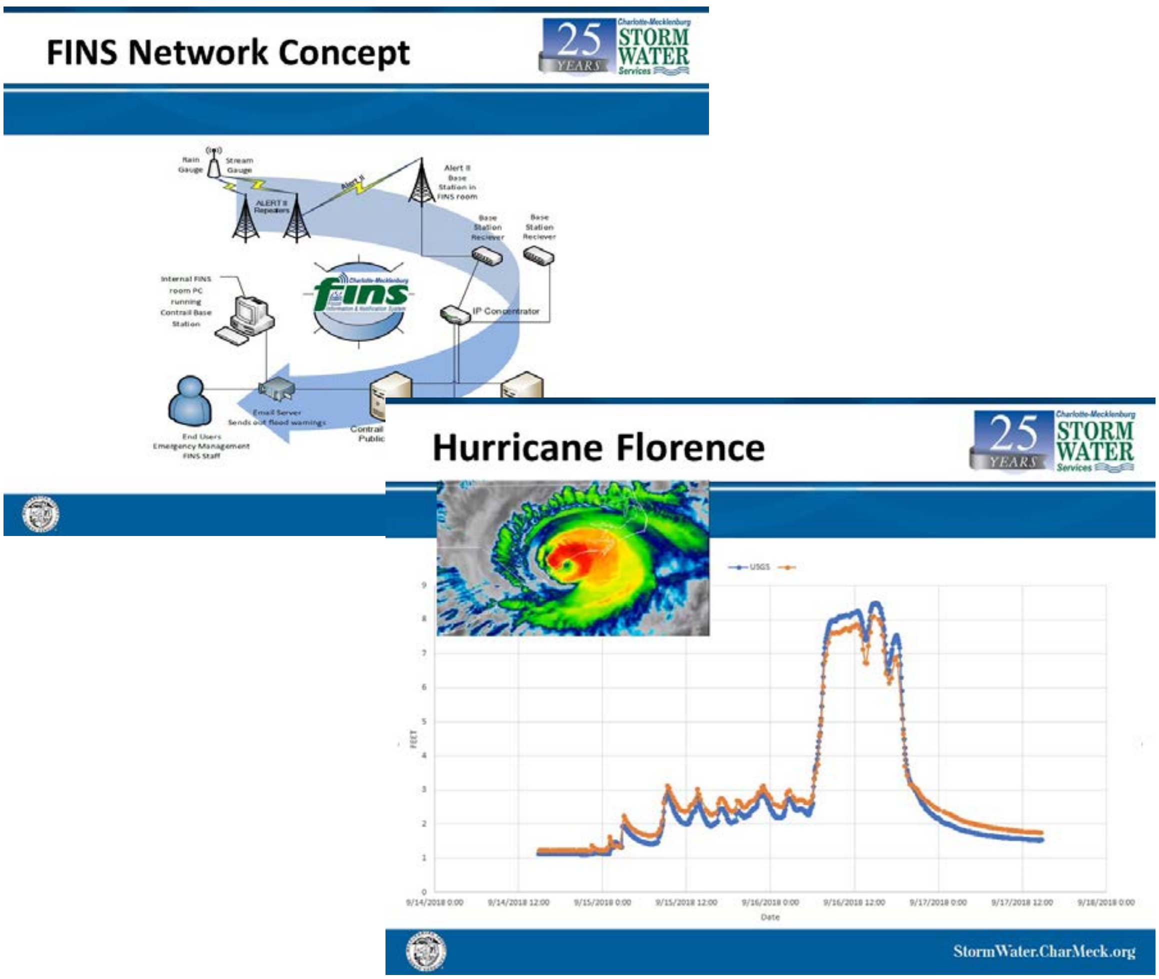
Low-Cost Flood Sensors: Performance Analysis

A partnership between Charlotte-Mecklenburg Storm Water Services and the U.S. Department of Homeland Security Science and Technology Directorate



May 2020

This report has been prepared to satisfy Deliverable 5.B of the U.S. Department of Homeland Security Office of Procurement Operations S&T Acquisition Branch contract 70RSAT18CB0000022.

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

EXECUTIVE SUMMARY

This report details the installation and operation of low-cost flood sensors (LCS) in Mecklenburg County during Option Year 1 of the stated contract. Charlotte-Mecklenburg Storm Water Services (CMSWS) received 93 LCS from the vendor and deployed them at sites previously identified during the site selection analysis (CMSWS, 2019). Two of the sites were co-located with an existing U.S. Geological Survey (USGS) stream gage for quality assurance and quality control purposes.

PROJECT SUMMARY

Installation of the LCS began in July 2019 and was completed in September 2019. Upon installation, most of beta (second generation) LCS units performed reasonably, however battery life and communication challenges persisted throughout 2019. These challenges caused the vendor to perform multiple firmware updates and, in some cases, remove problematic equipment from the field. The testing period for the beta LCS extended through February 2020.

Upon installation, CMSWS initiated an operation and maintenance (O&M) protocol that consisted of several activities designed to monitor performance, including regular site visits, status checks of data transmission and correcting equipment issues with the vendor.

One of the primary functions of the LCS is to support the generation of warnings and alerts to inform emergency responders of flood conditions endangering life and property. CMSWS integrated the LCS into the existing Flood Information and Notification System (FINS) to expand the warning and alert capabilities to additional sites.

RESULTS

The accuracy of the LCS exceeded the expectations of CMSWS. The accuracy of the units was approximately equivalent to the manufacturer specifications of 0.04 feet, which was determined through comparison with co-located USGS gages and field verification measurements during baseflow. The accuracy of the LCS did not appear to diminish over the testing period and validation measurements were consistently within expected tolerance. Although not as scientifically accurate as a USGS gage, the LCS clearly provided a more than adequate level of accuracy for general flood monitoring and the generation of flood warnings.

After the firmware updates, the units were transmitting data for approximately 90% of the testing period. Lapses in transmission were attributed to low battery voltage, site-specific damaged equipment and vandalism. Approximately 22% of the beta LCS units experienced lapses in data transmission due to in-stream head unit equipment damage caused by in-stream debris, fallen trees and vandalism.

Testing of the warning and alert capabilities of the LCS data was highly successful.

Overall, the beta LCS units performed effectively in Mecklenburg County. This is largely the result of CMSWS' active O&M program to monitor the performance of the sensors, collect validation measurements, maintain site conditions and repair any damage encountered. It is critical that any community using LCS implement a comprehensive O&M program to ensure the equipment is functional when needed during emergencies.

INTRODUCTION

In April 2018, Charlotte-Mecklenburg Storm Water Services (CMSWS) contracted with the U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) to test Low-Cost Flood Sensors (LCS). The project is part of the DHS S&T Flood Apex Program, which is designed to reduce fatalities from flooding events, reduce property losses from future events, support community flood resiliency- and provide flood predictive analytics tools.

The project aimed to further the goals of the Flood Apex program by developing and documenting tools for flood risk management that can be leveraged and transferred to other communities to manage and reduce flood risk and to enhance Mecklenburg County's existing Flood Information and Notification System (FINS). The LCS portion of the project was intended to be implemented over the course of three (3) years with portion specific goals and deliverables associated with each year.

- Year 1 (Base Year): Deploy and evaluate 75 alpha (first generation) sensors from three private vendors (25 sensors from each vendor) and report the performance to DHS;
- Year 2 (Option Year 1): Deploy and evaluate approximately 93 beta (second generation) sensors from a single private vendor selected by DHS from the pool of three alpha sensor providers;
- Year 3 (Option Year 2): Fully integrate the beta sensors with the existing FINS system to provide automation of data and displays to include real time risk scoring, losses avoided and inundation mapping. Additionally, Mecklenburg County will provide communication portability research to integrate sensor output with additional systems and technologies.

This document presents CMSWS' Option Year 1 (OY1) assessment of the LCS performance and demonstration results based on the deployment of the 93 beta sensors at 93 locations in Mecklenburg County, North Carolina. The beta sensors were deployed at a variety of locations throughout Mecklenburg County representing multiple use-cases (see CMSWS 2019a). The 93 sensors were integrated into the existing FINS system, which is cooperatively supported by CMSWS and the USGS Cooperative Water Program. This network (see Figure 1) consists of 54 USGS stream gages, 72 rain gages and 25 alpha (first generation) sensors all transmitting data to the CMSWS FINS server (see Figure 2). One of the main functions of FINS is to generate and transmit flood warnings to emergency personnel, the media and general public.

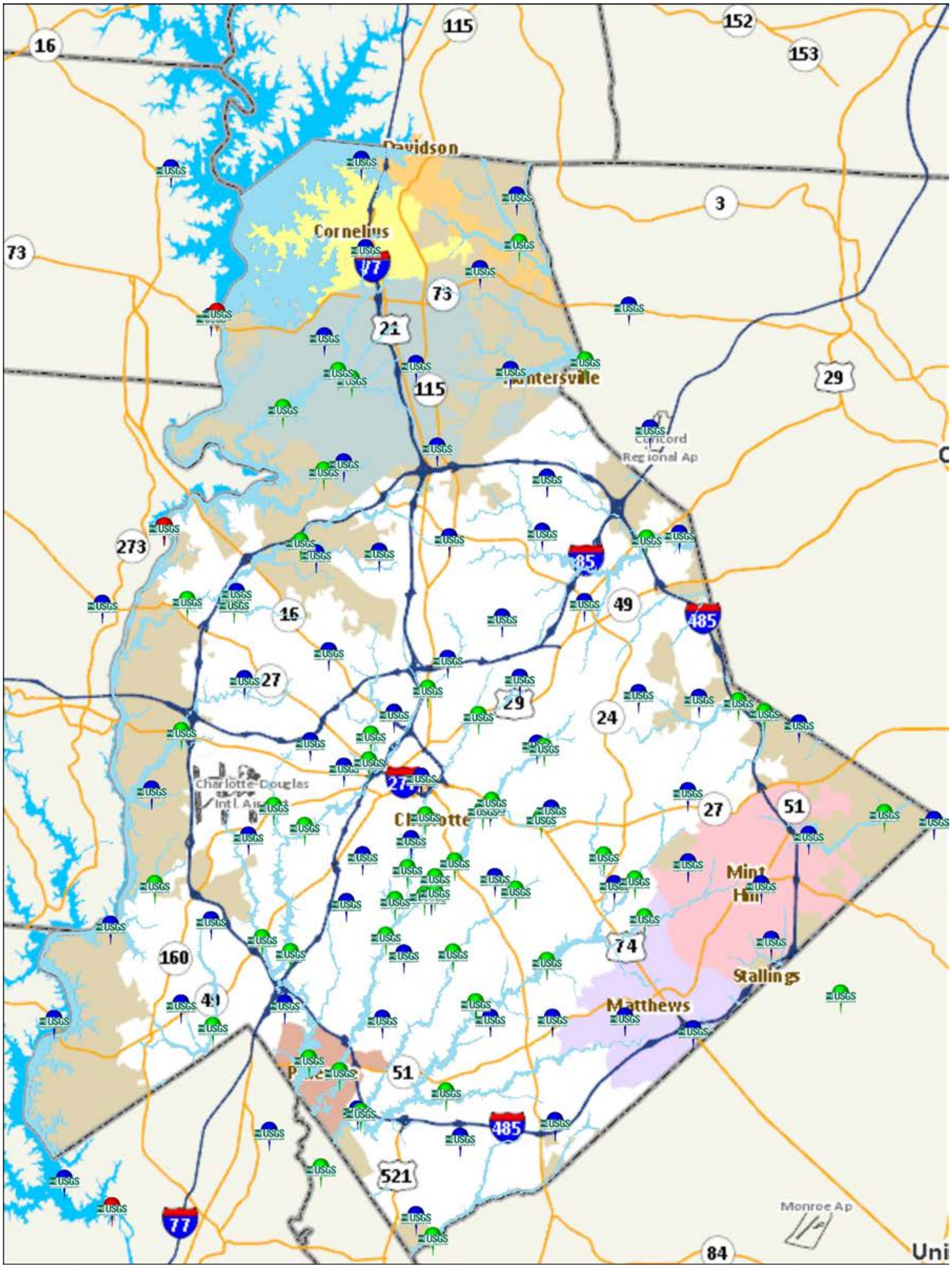


Figure 1: Existing FINS USGS Stream Gage Network

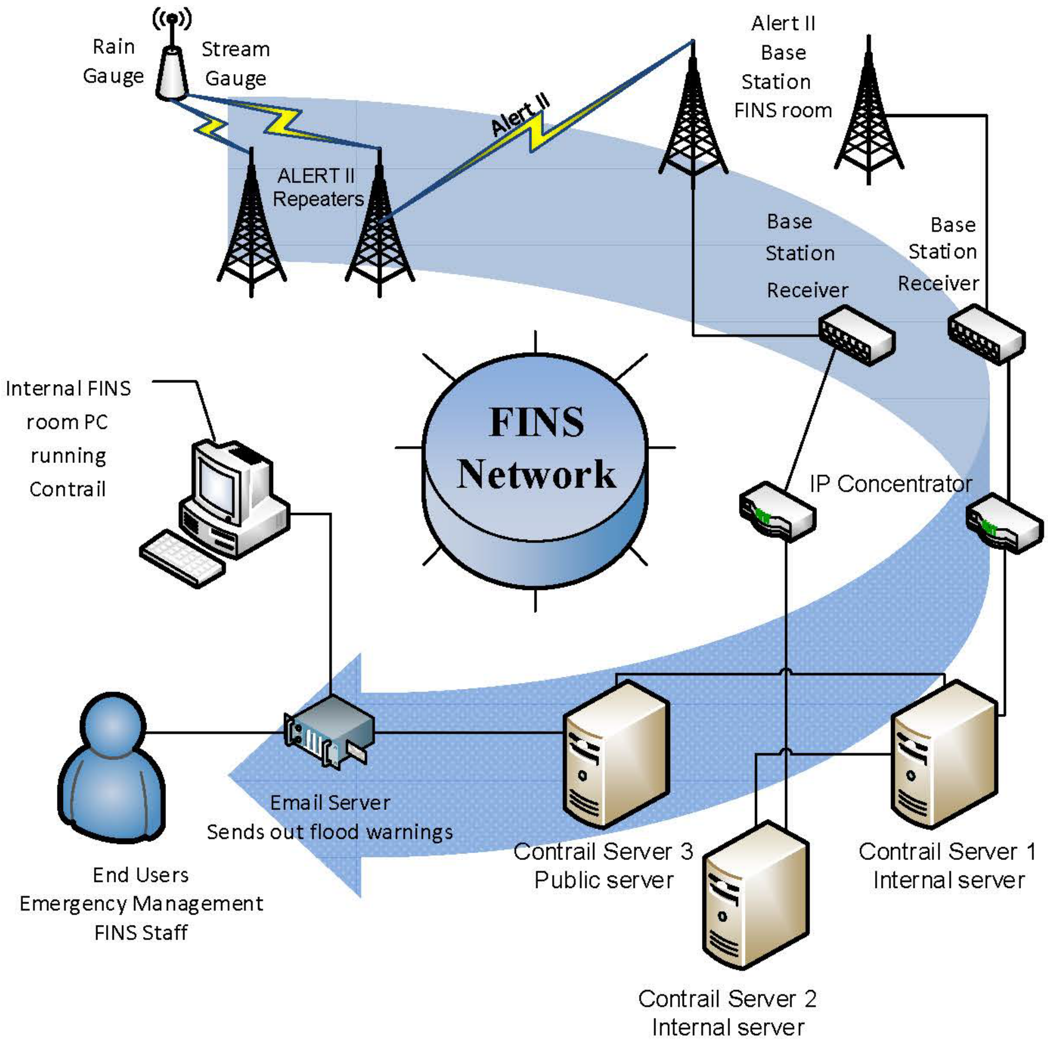


Figure 2: FINS Technical Concept and Data Architecture

During OY1, 93 beta sensors were delivered to CMSWS from the vendor. On July 8, 2019, CMSWS began the installation of these sensors at the sites. These additional sites helped extend coverage of the FINS network in the following categories:

- Unmonitored flood risk
- Stream-road crossings
- Critical infrastructure
- Capital Improvement Project (CIP) sites
- Rapid deployment
- USGS validation
- Public demonstration

Testing over 2019 and 2020 aimed to determine the suitability of the LCS for monitoring flooding in an urban setting. Specifically, the LCS were assessed on the following criteria:

- Suitability of the LCS for generating automated flood warnings through integration with CMSWS' existing FINS network.
- Reliability of the LCS when exposed to long term field deployment. It is critical that equipment used to monitor flood hazards be reliable and is functional when needed in a crisis or emergency.
- Accuracy of the LCS data in relation to USGS gages and field measurements.
- Durability of the LCS when deployed in an urban setting. Field equipment is subjected to natural and manmade hazards, it is important that the LCS be able to continue to function despite these hazards.

1 Sensor Alarms and Notifications

1.1 Flood Threat Notifications

In the base year, CMSWS documented how flood threat notifications function in FINS to increase CMSWS' ability to identify flood threats and send notifications (see CMSWS 2019).

Over the past 20 years, CMSWS has developed a system of flood warnings that have been implemented in FINS. The FINS software continually monitors site-specific incoming water level data and compares it to the elevation of at-risk infrastructure and property. A group of three warning elevations are typically established for every site and are known as 'alert', 'investigate' and 'emergency' levels. A description of each warning is provided below:

- "Alert" level – this level of warning is intended to make the target groups aware that a flood event is possible.
- "Investigate" level – this level of warning is intended to make the target groups aware that a flood event has been identified and appropriate action needs to be taken to further investigate the warning site.
- "Emergency" level – this level of warning is intended to make the target groups aware that a flood event is occurring and structures near the flood sensor are being impacted.

CMSWS has worked closely with emergency management personnel to establish the warning levels. They are determined through evaluation of site conditions (e.g. elevation of bridge deck) and past flood history. If a threshold elevation is exceeded at a site, FINS automatically notifies emergency responders and technical staff via email and text. Emergency responders have been trained in the interpretation of the warning levels and apply tactical knowledge of the threat to determine an appropriate response.

1.2 Identify Alert Thresholds

LCS beta sensors have site-specific threshold mean sea level (MSL) elevations identified. Each sensor is equipped with GPS capability that provides location (latitude and longitude) and elevation. CMSWS determined that the accuracy of the elevations provided by the LCS did not meet programmatic needs to establish warnings. To address this situation, CMSWS conducted elevation surveys of each LCS site using highly accurate GPS equipment. During the survey, the elevation of the in-stream unit was determined along with the elevation of infrastructure and buildings to be monitored. Figure 3 presents a sample alarm in FINS for an LCS monitoring a stream crossing. In this example, the warning level has been exceeded and the software initiated a warning message to the appropriate recipients. The warning message provides the alarm name, alarm level, site name and location and the sensor type being monitored.

Rule	LEVEL Road Surface – Briar Creek @ Perth Ct – ALERT (1211)
Level	Warning
Site	Rapid Deploy FMB071 (071)
Sensor	Level – MSL (5) was

Figure 3: Example Alarm in FINS

Figure 4 presents a hydrograph generated in FINS from incoming LCS data. It shows the alert (warning and deploy) elevations or thresholds (top left in MSL) compared to the real-time stream level (also in MSL). If LCS are relocated in the field, thresholds can easily be updated in FINS or new thresholds can be added. This is particularly important for rapid deployment units, which need the capability of being deployed and transmitting data to FINS in a matter of hours.

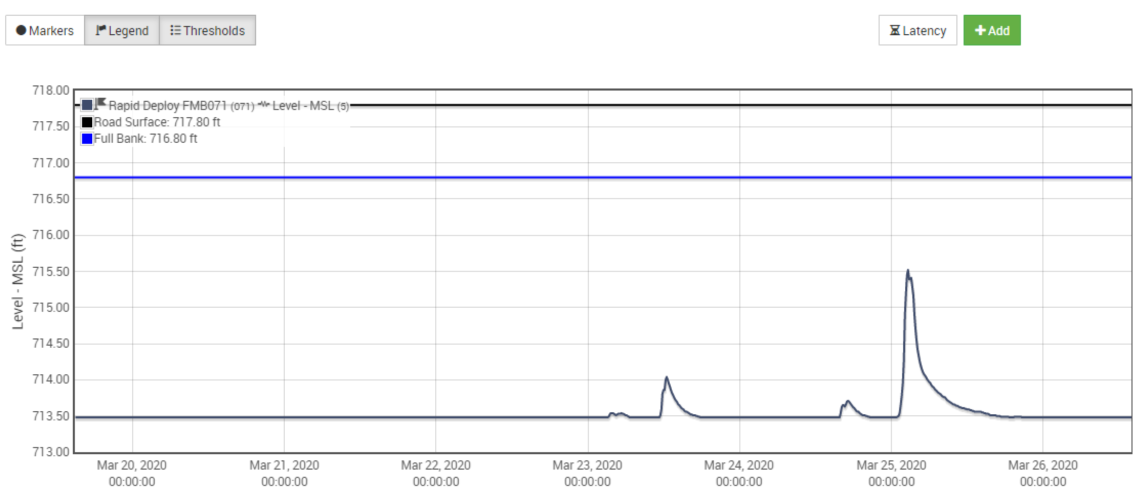


Figure 4: Sample FINS hydrograph showing water level and alert levels

Figure 5 presents an example of the notification messages sent by FINS. This notification contains detailed information that informs the recipient of which parameter(s) triggered the notification along with the location and the alarm date and time.

This is a message from the Charlotte-Mecklenburg FINS at 2020-09-02 01:22:08 EDT A flood ALERT is in effect for the area near Stewart Creek at Freedom Drive at map code J-27. Consult your SOG for instructions.

THREAT STATUS:
Contrail observed sensor 1, Gage-Height ft. @ STEWART CREEK at MOREHEAD STREET, current value is 10.114. This is >= threat threshold of 9.4 feet.
In the last 10 min, Contrail observed sensor 1, Gage-Height ft. @ STEWART CREEK at MOREHEAD STREET, had a change > threat threshold of 0 feet.

CONTRAIL LAST REPORTED:
Sensor 1, Gage-Height ft. @ STEWART CREEK at MOREHEAD STREET, last reported at 2020-09-02 01:20:00 EDT with a value of 10.114.

CLICK HERE FOR DETAILS https://contrail.mecknc.gov/dashboard/?dashboard=ad644ed9-48d3-4531-a261-8941fbbb0bfb

Do not reply to this message. It was generated by an automated system that cannot respond.

Figure 5: Example FINS Notification Message

Each individual alarm notification includes a predetermined target group. These target groups can be modified in FINS to make sure the correct target group(s) receive the alarm notifications and that the information provided is suitable for determining the appropriate response. For example, an alert notification for a road crossing sent to a fire captain may trigger a non-emergency response to visually inspect the site, whereas an emergency notification may trigger an immediate deployment of equipment to block the crossing.

1.3 IDENTIFY TARGET GROUPS

Target groups are broadly defined as those individuals or groups to be made aware of a threat of flooding. In Mecklenburg County, first responders and Emergency Operations Center (EOC) staff are included in all flood warning alarms along with CMSWS staff. News media and social media outlets are included with this target group in order to inform the public. Other groups and individuals with general interest or an interest in a specific stream or site (such as nearby residents or business owners) are included in flood warning alarms based on location.

At the request of emergency management (EM), flood warning messages from FINS do not go directly to the public or social media. EM recognizes that flood sensors have the potential to transmit invalid measurements that could trigger "false alarm" flood warnings potentially causing panic or unnecessary action. EM uses in-house, proven methods to communicate flood warnings to the public.

With the exception of a rapidly deployed LCS (used for ad hoc purposes), all sensors identified at flood warning sites will have the appropriate target group identified and assigned to the flood warning alarms. Target groups for rapidly deployed LCS are limited to CMSWS staff and first responders. If a rapidly deployed LCS becomes a permanent site, the target groups will be updated with appropriate recipients. Table 1 presents the target groups identified in Mecklenburg County, how they are identified and the best communication method(s) to be employed.

Table 1: Target Groups for Warnings and Associated Communication Methods

Target Group	How members of the group are identified	Communication methods to be employed
First Responders	CMSWS public liaison will contact all local emergency responders and request they submit all email addresses and mobile numbers for first responders.	Email address and mobile numbers will be grouped together, so all members of this target group will receive the same flood warning message simultaneously.
Citizens at immediate risk of flooding	First responders dispatched to the area experiencing flooding conditions will use third party software and social media to notify citizens.	Physically going door to door of homes and businesses. Placing barricades on flooded roads or send wireless emergency alerts (WEA) to all active smart mobile devices in the area.
Emergency Operations Center Staff	All staff checked-in at the EOC during an emergency event are assigned to their area of expertise streamlining communication from the field.	Two-way radios, face to face interaction, email address and mobile numbers are grouped together, so all members of this target group will receive the same flood warning message simultaneously.
News Media and Social Media	CMSWS public liaison will reach out to all News and Social media groups that have coverage in the areas where LCS are installed.	Email addresses will be grouped together, so all members of this target group will receive the same flood warning message simultaneously. Messages for Social Media groups will automatically be posted to appropriate app or website.
CMSWS Staff	A CMSWS staff member is always on call and available to assist EM 24/7.	All flood warning messages and FINS IT network messages are reviewed by CMSWS on call staff.

1.4 Use of LCS for Flood Warnings

CMSWS has successfully integrated LCS data into existing FINS software to significantly expand areas of the County now monitored for the threat of flooding. Flood warning notifications triggered by LCS data function the same as existing FINS warning notifications, but the notifications are only sent to CMSWS staff. EM and other target groups will be added to the LCS flood warning notifications as the need arises.

2 Sensor Demonstrations

CMSWS conducted demonstrations of the LCS equipment to several stakeholder groups concerned with flood notifications in order to solicit feedback from local and regional groups regarding the possible use of LCS in other communities. The demonstrations also provided an opportunity to make others aware of the technology and ease of installation.

Figure 6: Demonstration of LCS at Fall Floodplain Institute.

October 16 – 18, 2019: Fall Floodplain Institute, NC Association of Floodplain Managers – Cherokee, North Carolina

CMSWS staff participated in a workshop as part of the Fall Floodplain Institute and presented details of the DHS Flood Apex Program to conference attendees. At the conclusion of the presentation, attendees were invited outdoors to a nearby creek where CMSWS staff performed a live demonstration of how to install a LCS. They also shared a synopsis of the lessons learned from the previous year's experiences installing these sensors.

November 14, 2019: All Hazards Advisory Committee Conference, Charlotte-Mecklenburg Emergency Management Office (CMEMO) – Charlotte, North Carolina

- Josh McSwain participated in the All Hazards Advisory Conference and presented identical details of the DHS Flood Apex conference as Appendix A, regarding how CMSWS is incorporating these LCS into the existing FINS network.

CMSWS has been invited to present at two events listed below, but due to the COVID-19 restrictions, both conferences have been postponed to the fall of 2020.

- May 5 – 8, 2020 Alert Users Group – Ventura, California
- June 7 – 11, 2020 Association of State Floodplain Managers – Fort Worth, Texas

3 LCS Deployment Timeline

CMSWS received 93 beta LCS from the vendor in July 2019. They were deployed at sites selected during the Base Year of the contract (see CMSWS 2019a) using techniques developed by CMSWS and the vendor (see CMSWS 2020). Data presented here includes all measurements collected from the time of installation until February 29, 2020.

3.1 LCS Deployment and Testing

The following outlines the LCS project milestones, which are also presented graphically in Figure 7.

3.1.1 Installations

- Primary: July 8, 2019 – September 5, 2019 (85 units)
    - FMB69 was installed on January 19, 2020, due to a storm drainage improvement project that prevented earlier install
- Rapid Deployment: January 29, 2020 – February 8, 2020
    - Rapid Deploy FMB090 - Sixmile Creek at Providence Country Club - January 29, 2020
    - Rapid Deploy FMB079 - Sixmile Creek at Tom Short Rd - January 29, 2020
    - Rapid Deploy FMB071 - Briar Creek Watershed @ Perth Court - February 5, 2020
    - Rapid Deploy FMB062 - SE End of Riverside Dr - February 8, 2020

3.1.2 Firmware Updates

- 2.10 - July 8, 2019
- 2.12 - Jul 15, 2019 – August 8, 2019
- 2.15 - August 21, 2019 – August 22, 2019
- 2.16 - September 19, 2019
- 2.17 - September 19, 2019
- 2.24 - December 3, 2019 – December 5, 2019

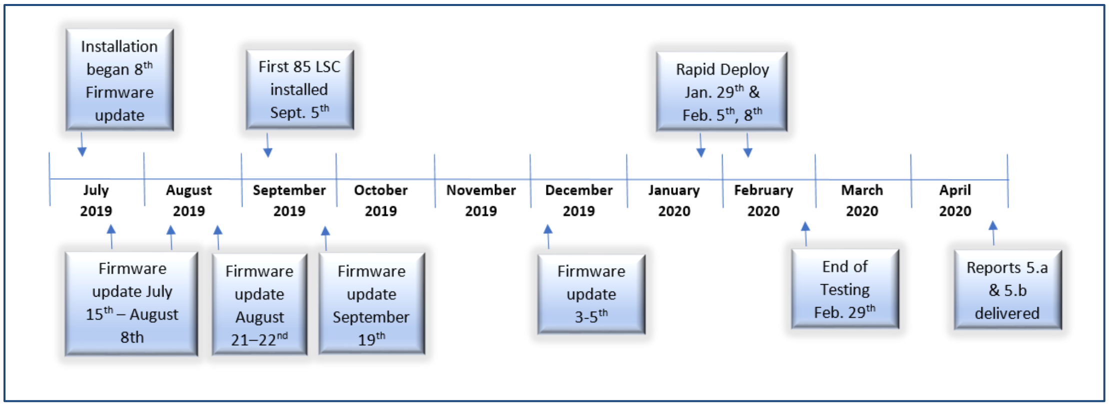


Figure 7: LCS Project Milestone Timeline

3.2 DATA INTEGRATION

CMSWS tested the following three methods for receiving data transmitted from the beta LCS:

- Method 1: Transmit LCS data directly to the vendor's cloud server where CMSWS staff could use a secure login to view the data.
- Method 2: Build upon the Method 1 by creating a data transfer app on the vendor's cloud server to forward the data directly to the CMSWS FINS server.
- Method 3: Transmit LCS data directly to a CMSWS FINS server.

Figure 8 shows the configuration of the data integration of a LCS and CMSWS FINS server as described in Method 3.

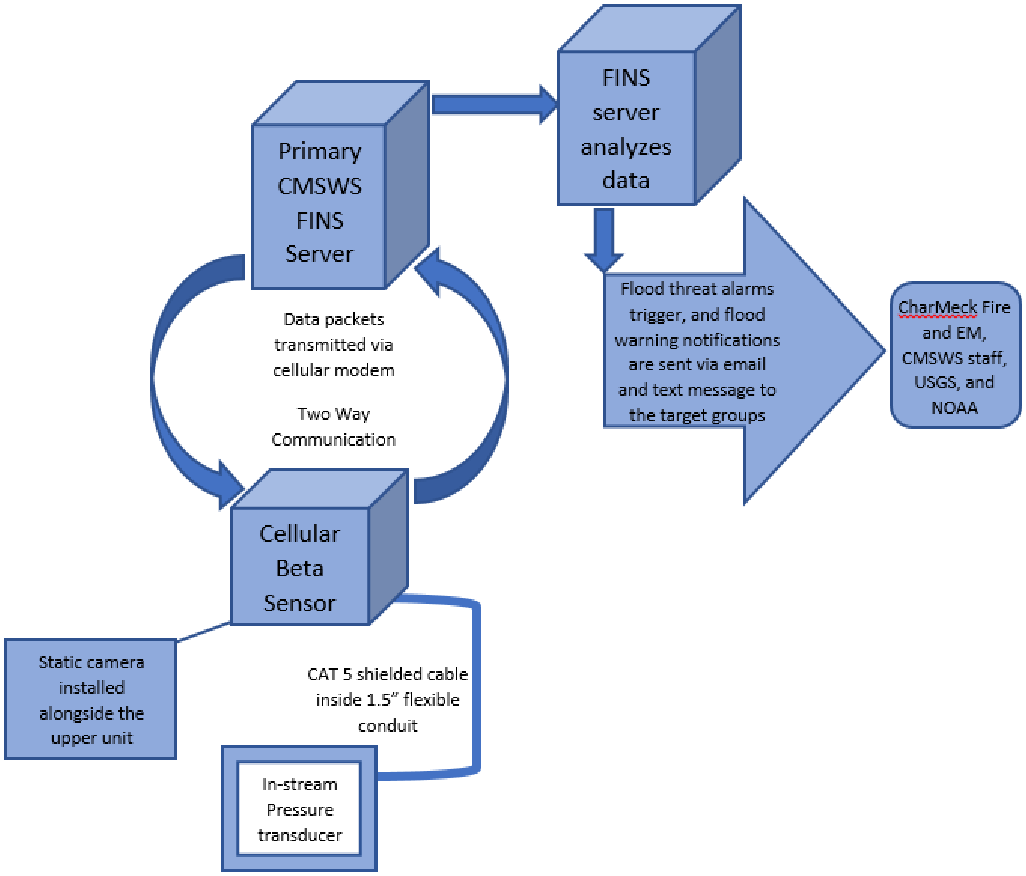


Figure 8: FINS Digital Communication Path

4 Sensor Performance

4.1 Data Quality

4.1.1 Firmware Updates

Installation of the vendor's beta sensors began in July 2019 and was completed in September 2019. During the evaluation period (July 8, 2019 to February 29, 2020), the beta sensors performed effectively after several firmware updates. Initially, the equipment needed three separate firmware updates prior to field deployment and another two updates after installation was completed (a total of five firmware updates). Data continued to be transmitted from many of the LCS during the series of updates, but overall reliability was adversely affected. Following the final firmware update in December 2019 (firmware version 2.24), the LCS consistently transmitted accurate measurements.

4.1.2 FINS Compatibility

Compatibility issues between the FINS third-party software and the beta LCS were observed in late December 2019 and again in January 2020, but this is not representative of the LCS. CMSWS worked with the FINS software provider to identify the problem and implement a solution. Since implementation, FINS and the beta LCS have communicated consistently with no data loss from operational sensors.

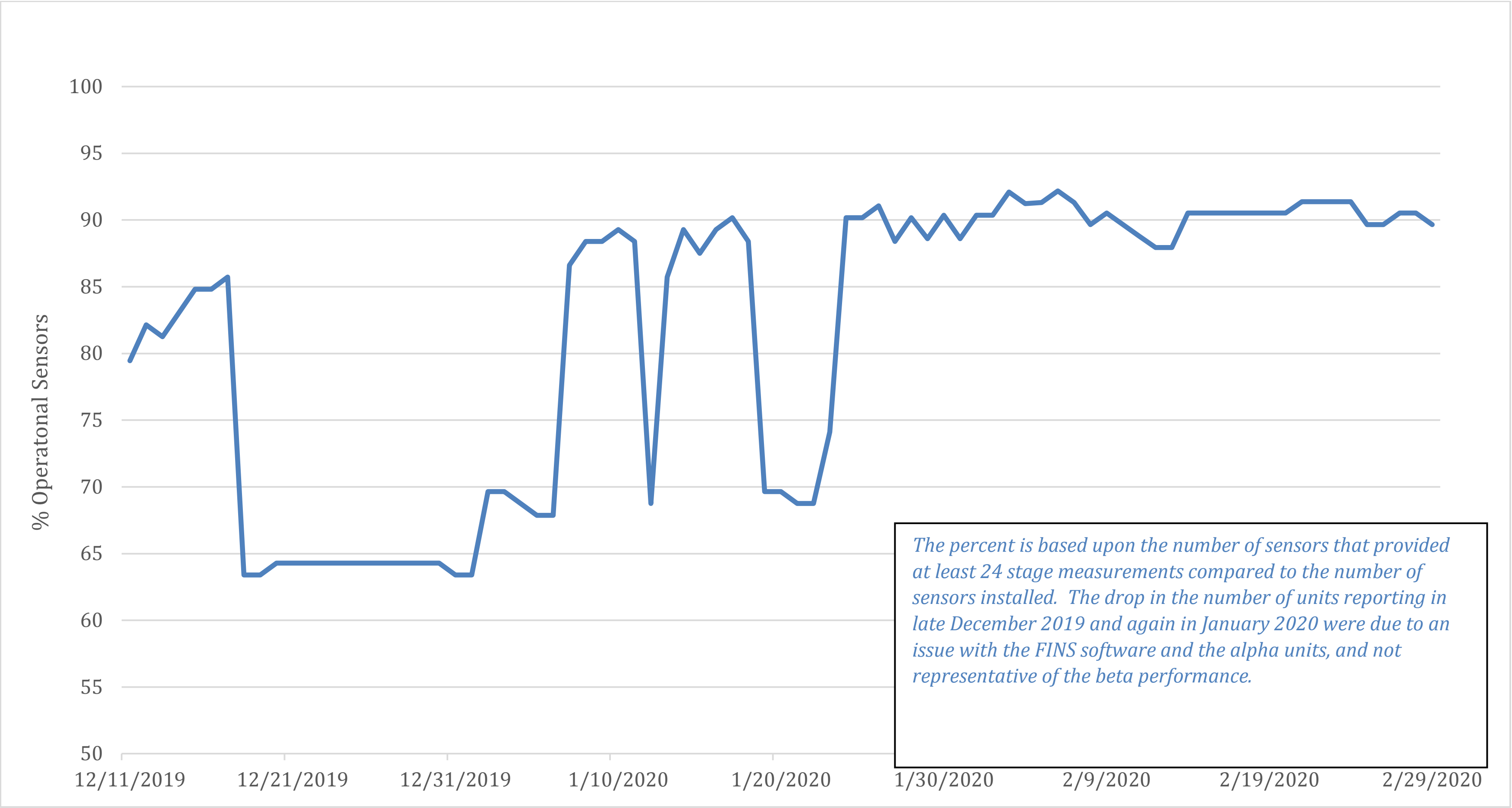


Figure 9: Percent of operational LCS after the installation of the latest firmware (December 11, 2019 – February 29, 2020)

4.2 USGS Accuracy Comparisons:

During the base year, CMSWS installed three alpha LCS at existing USGS gauges for accuracy comparisons. In Option Year 1, CMSWS installed three additional sites for comparing the beta units with USGS gages. The following observations were made:

- The LCS beta sensor located on Torrence Creek (FMB7) performed within the manufacturers stated accuracy tolerances (±0.5" or 0.04') when compared to the USGS measurements for that location (Figure 11). This assumes that the USGS gauges are accurate to their specifications of 0.01' or 0.2% of stage, whichever is greater.
- The other five co-existing locations could not be correlated with the USGS equipment due to different hydraulic dynamics of the creeks. The LCS at FMB7 is the only site where the equipment was installed within 3' of the USGS equipment. Some sites were as far apart as 100' from the USGS equipment, opposite sides of the creek, in different pools or have supplemental flow entering between the two pieces of equipment. These factors can contribute to slightly different stages being recorded and direct comparisons could not be made. However, it should be noted that hydrographs prepared from LCS data tracked nearly the same as the USGS generated data.

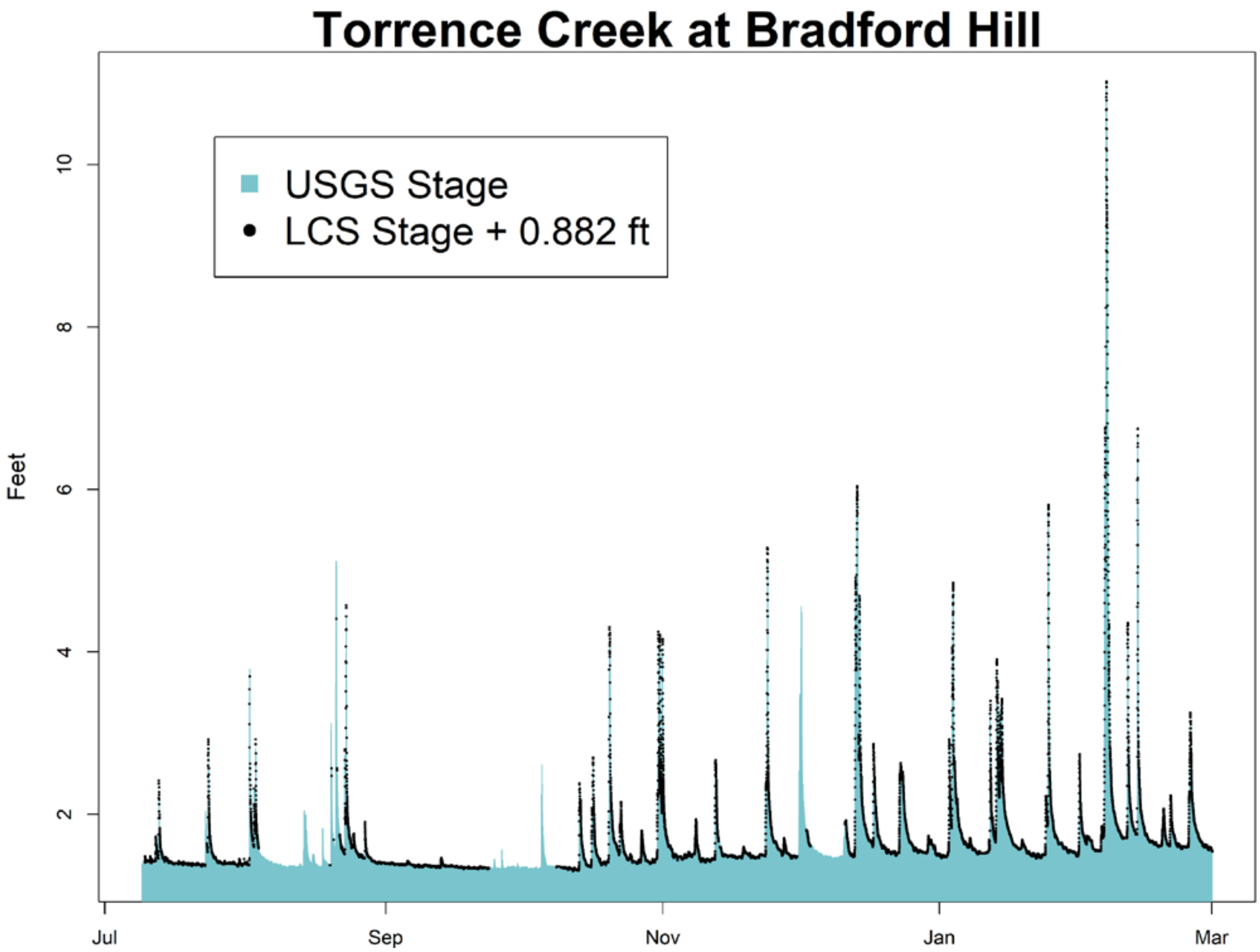


Figure 10: Comparison of USGS stage gauge 0214265808 and FMB7 for Torrence Creek at Bradford Hill Lane from July 8, 2019 to February 29, 2020

4.3 Data Validation Measurements

While conducting the routine maintenance on the LCS, CMSWS staff collected validation measurements of the water level above the LCS. These values were recorded and entered into the inspections database (Appendix B). The measurements were generally collected during baseflow conditions and do not represent flooding conditions. However, the USGS comparisons show that these sensors perform well during these higher stage events . Statistical comparison of the difference between the recorded stage and the measured stage was performed. The median difference for the validated measurement for all sites was 0.035 feet, which is nearly equivalent to the 0.04 feet of accuracy reported by the manufacturer (Table 2). The validated measurement was calculated from the LCS beta sensors that were operational during the evaluation period.

Table 2: Summary statistics for residual differences among the LCS sites during the evaluation period. All measurements are expressed as differences in feet.

Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
-0.4658	-0.0033	0.0350	0.0497	0.0933	0.6800

The accuracy of the LCS exceeded the expectations of CMSWS. The accuracy of the LCS did not appear to diminish over the testing period and validation measurements were consistently within expected tolerance. Although not as scientifically accurate as a USGS gauge, the LCS clearly provided a more than adequate level of accuracy for general flood monitoring and the generation of flood warnings.

4.4 LCS Reliability

For a flood warning system to work well, a community must have a reliable and accurate data stream. If a community is not confident in the data its hardware is providing, they cannot effectively protect their citizens. Further, operating a network of 116 sites is no easy task. The LCS network that CMSWS integrated into their existing flood warning network operated at approximately 90% reliability following the late firmware update. Although CMSWS has not been able to maintain 100% reliability with the LCS network, most problems cannot be contributed to the hardware itself. Section 5 of this document highlights some of the challenges encountered with the operation and maintenance of the LCS network. Overall, the reliability of the LCS units is good and should improve in time with more product enhancements from the vendor.

4.5 Warning and Alert Performance

Section 4.4 explains the reasons why a community must have a reliable and accurate data stream, but it is equally important to have reliable flood warning notifications. CMSWS conducted a performance test for flood warning notifications using both alpha and beta LCS. First, flood alarms were written in FINS software for LCS co-located with a USGS stream sensor. This allowed CMSWS to compare flood alarm notifications triggered by data transmitted from the USGS sensor and data transmitted from the LCS. This scenario was tested through several storm events during the OY1 testing timeframe. CMSWS determined that the LCS successfully sent flood notifications concurrent with a USGS sensor flood notifications for a rate of 100% successful. Due to the difference in reporting time intervals, the flood notifications were received a few minutes apart from each other. Encouragingly, both sensors identified the same flood events and flood thresholds.

In addition to comparing flood notification performance with USGS sensors, CMSWS also created flood warning alarms and notifications at 22 additional LCS sites. After analyzing the flood notifications sent from these 25 sites, CMSWS determined the overall LCS warning and alert performance rate of 94% successful based on timely delivery, identifying flood thresholds accurately and delivering the notification to the appropriate target group. The small percentage of flood notifications that did not perform successfully had simple errors in the alarm parameters.

5 Operation and Maintenance

In order to guide the integration of the LCS into CMSWS' pre-existing FINS network, CMSWS personnel developed an operation and maintenance (O&M) plan (reference Appendix B). CMSWS technicians conducted daily reviews of incoming LCS data to the FINS network. Staff documented LCS sites for follow-up that abruptly stopped reporting or showed erroneous data. Technicians conducted routine monthly site visits and additional visits after a rain events greater than 1 inch.

During the visits, technicians evaluated general site conditions noting signs of physical damage to the head unit, data communication cable and/or in-stream sensor (see Table 3). Typical site maintenance included clearing debris along the cable line and at the in-stream sensor. CMSWS developed a low-profile in-stream sensor mounting bracket; however, debris continued to accumulate around the in-stream sensor. Additional site maintenance included vegetation control to maintain optimal solar exposure for the head unit and to maintain a safe working space for the technicians.

Table 3: Sample Inspection Tracking Tool for Operations and Maintenance

Insp #	Site	Notes	Validation Depth (ft)	Insp Date Time	Inspector
230	FMB10 (Paw Creek @ W side of Toddville Rd)	Firmware 2.10 Update	N/A	07/08/19 12:00 AM	[Name]
242	FMB14 (Irwin Creek @ W side of Oaklawn Cemetery)	Dry Installation	N/A	07/08/19 12:00 AM	[Name]
570	FMB44 (Little Sugar Creek @ Freedom Park walk bridge across from Discovery Place Nature Center)	Cleared debris. Lower sensor observed ripped from mounting bracket. Sensor reattached. Needs concrete anchors.	0.16	09/18/19 11:25 AM	[Name]
601	FM25 (Little Sugar Creek @ Baxter St)	All good	0.21	09/11/19 04:05 PM	[Name]
770	FM19 (McMullen Creek @ Providence Rd)	secured sensor to bracket; cleared debris	0.4	10/18/19 11:05 AM	[Name]

During monthly O&M inspections, technicians collected validation measurements of the in-stream sensor. These validations were later compared to data from the sensor to ensure the in-stream sensor was reporting stage levels within the vendor specific range of accuracy. All O&M activities were then logged in a data management system.

During OY1, CMSWS personnel observed several types of damage that required repairs to be made to the unit. Out of 93 sensors, 15 head units and five in-stream units (approximately 22%) were damaged during the reporting period. The most common damage/repairs were:

- Eight (8) instances were documented in which pests were observed inside the head unit causing issues with the unit reporting data to CMSWS.
- Three (3) antennas were observed to be broken, stolen or detached from the head unit.
- Five (5) in-stream sensors were replaced due to damage by debris or pressure transducer failure.

- Four (4) head units have been found dislodged from their mounting brackets, two (2) of which were related to vandalism and found in the creek, one (1) was due to a falling tree, and the fourth was due to a car accident that hit the guard rail where the mounting pole was located behind.
- Approximately 10 instances were documented during which battery voltages were below the vendor-specific threshold of being able to report data to CMSWS. Battery failure was associated with prolonged cloud cover and/or reduced solar exposure due to vegetation cover.
- Three (3) CMSWS signs indicating Flood Monitoring and a contact number were observed bent, removed and/or otherwise vandalized and required replacement.

To prevent these issues, CMSWS implemented modifications to the O&M plan to reduce damages to the LCS at existing and future sites. New practices included:

- Antennas: The application of an adhesive on antennas to deter unscrewing antennas by unauthorized individuals. To the extent possible, head units were mounted inconspicuously behind signage/poles/away from sidewalks to reduce visibility to the public.
- In-Stream Sensors: In-stream sensors were re-installed at sites where abnormal debris accumulation was observed. Technicians moved the location of the in-stream sensors to locations where the accumulation of passing debris was reduced. This was a trial and error process; however less debris was generally associated with faster moving baseflow. Additional hose-clamps and/or zip-ties were used to secure the in-stream sensor to the mounting bracket, and in-stream sensors were better protected using rip-rap barriers on the upstream side at sites with abnormally high debris accumulation.
- One flaw that CMSWS has observed in the beta sensors is the mounting design of the in-stream sensor. The beta design of the in-stream sensor only allowed one mounting bolt to be used and this contributed to in-stream sensors being damaged by debris during high flow events. The vendor worked with CMSWS to improve on this design and they have incorporated these changes into their newest lower sensor that is going into production.
- Head units: Locking cable-ties were installed to deter vandalism of head units at sites with previous vandalism or where the head units were clearly visible to the public. Most importantly, units were placed away from sidewalks, roads and other transportation corridors whenever feasible.
- Batteries: Additional attention was given to ensuring maximum solar exposure for the head units, and units were installed in a location to generate enough solar power for the unit regardless of the season and subsequent foliage density.
- Signage: Signs have been replaced in areas where vandalism has been prevalent. No further action has been taken to deter vandalism of signage.

Overall, the durability of the LCSs have met the expectations of CMSWS. Approximately 22% of the units experienced damage that prevented proper functioning at some point during the test period. Individual units have experienced damage from vandalism, in-stream debris and fallen trees. Some of the damage was preventable, notably better positioning of the in-stream sensors and installation of the head units at inconspicuous locations. The damage rate reinforces the need for an active O&M program that routinely conducts desktop evaluations and site visits for each LCS. Without an active O&M program, CMSWS expects that approximately 50% of the LCS would be inoperable within 1 year. Deploying the LCS without an O&M program will likely result in a significant number of inoperable units during a flood emergency.

6 CONCLUSIONS

In general, the LCS met the expectations of CMSWS and were effectively deployed at the various use cases. The results of the test period were favorable, particularly when the costs of the LCS are considered. The following conclusions were drawn from CMSWS' experience during the testing period:

1. The LCS beta units provide data suitable for generating flood warnings, achieving a 94% success rate during testing. Care must be taken to train recipients on the data, particularly first responders and emergency management staff, so that proper action is taken.
2. The LCS beta units provide data that meets or exceeds the needs of CMSWS. Comparisons with USGS gauge data and field validation measurements confirmed the manufacturer's specified level of accuracy. Accuracy of the units is more than suitable for the generation of flood warnings as well as other uses of water level elevation data, such as losses-avoided calculations and illicit discharge detection.
3. The LCS beta units were reasonably reliable after multiple firmware updates were completed. The LCS network has been reporting data 90% of the time after the last firmware update. This network reliability should increase with product enhancements from the vendor and implementing lessons learned from the O&M program.
4. The LCS beta units were somewhat durable. Approximately 22% of the units experienced some sort of damage during the testing period that prevented the transmission of data. With experience, this number could likely be reduced to the 10-15% range. The damage rate reinforced the need for an active O&M program monitor performance and conduct repairs.

Overall, the LCS beta units have proven to be a valuable enhancement to the FINS network. The speed and flexibility of installation, accuracy and simple functionality were positive attributes, particularly when cost is considered. A diligent and active O&M program is critical to offset damage rates and to ensure reliability rates do not decline to unacceptable levels.

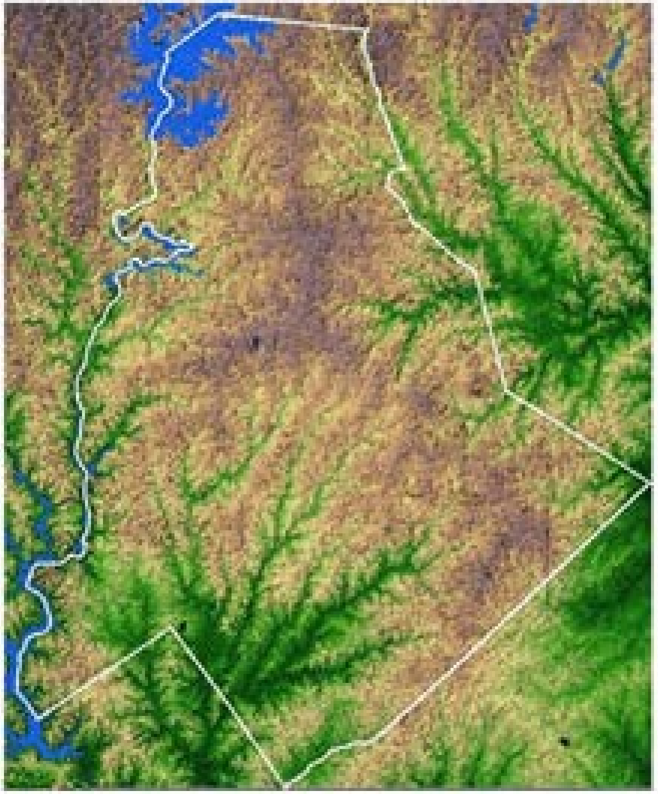
APPENDIX A: INNOVATIONS IN LOW-COST STREAM SENSORS PRESENTATION

Innovations in Low Cost Stream Sensors

Charlotte-Mecklenburg Storm Water Services

Low-Cost Flood Sensor Project

I. Pre-deployment Plan
II. Field Installation
III. Sensor Functionality
IV. Sensor Performance
V. Creek Demonstration



Flood Apex Program

Homeland Security

Science and Technology

Rethinking America's Costliest Disaster

Program Overview

The Department of Homeland Security's Flood Apex Program was created at the request of the Administrator of the Federal Emergency Management Agency (FEMA) to bring together new and emerging technologies designed to increase communities' resilience to flood disasters and provide flood predictive analytic tools to FEMA, state and local governments, and other stakeholders.

Key Objectives

- Reduce fatalities and property losses from future flood events.
- Increase community resilience to disruptions caused by flooding.
- Develop better investment strategies to prepare for, respond to, recover from and mitigate against flood hazards.

Approach

The Flood Apex Program will deliver these objectives by:

- Building on existing programs and efforts at the federal, state and community levels;
- Operationalizing new methods and technologies; and
- Empowering communities with the right data and decision support tools to enable pre- and post-event flood resilience planning.

National Flood Decision Support Toolbox

The effort will culminate in a National Flood Decision Support Toolbox ("the Toolbox"), which will contain a suite of knowledge products, data sources, models and visualization tools to support decision-making before, during and after flood events.

Charter Goals

The Flood Apex Program will create a decision support system-of-systems for community risk assessment and resilience planning to save lives, reduce property losses and enhance community resilience to disruptive events.

- **Goal 1:** Leverage existing data sources to create multi-domain representations of critical community functions using an integrated, systems-of-systems approach.
- **Goal 2:** Enhance collaboration and coordination around disaster risk reduction.
- **Goal 3:** Identify indicators of community resilience and opportunities to introduce advanced technologies.
- **Goal 4:** Empower communities with a decision support tool to enable both pre-event, scenario-based risk planning and adaptive recovery in the post-event environment.
- **Goal 5:** Enable faster decision-making and more efficient mutual aid in the operational theater for warnings and evacuations.

Five Flood Apex Research Tracks

Work under the program follows five activity tracks, each of which will contribute products and decision tools to the Toolbox over the four year life of the program (2016 – 2020).

Reduce Flood Fatalities

- Automated, geo-targeted alerts and warnings integrated with the National Weather Service (NWS) "Turn Around, Don't Drown" (TADD) campaign.

Reduce Uninsured Losses

- New tools and outreach efforts to encourage uptake of flood insurance.

Improve Mitigation Investment Decisions

- New decision tools to maximize the benefit of mitigation investments.

Enhance Community Resilience

- Standard operating procedures (SOPs), outreach and decision tools to integrate resilience as a core concept in flood risk management planning.

Improved Management of Flood Support Data

- Integration of data, models and decision tools into the Toolbox.

1.1 Pre-Deployment Plan

- March 2017 – The beginning of Flood Apex Project
- Project team begins grant proposal
- None Disclosure Agreement (NDA) signed
- Detailed sensor presentation from each vendor
- Municipal ownership and encroachment
  - August of 2017, grant was approved by Mecklenburg County Board of County Commissioners.
  - March of 2018, CMSWS submitted an execution of a grant memo to County Managers office.
  - June of 2018, Mecklenburg County Board of County Commissioners approved taking ownership of the LCS from the DHS.
  - June of 2018, Right-of-Way encroachment agreement with the City of Charlotte DOT was signed by the Mecklenburg County Attorney
- Vendor provided sensor equipment examples

1.2 Site Selection

Alpha Sensors (Year 1)

- 25 sites and 75 LCS, 5 mesh networks with 4 to 5 LCS per network, all sites within 2,500 feet of one another.
- Each mesh network has unique physical and geographic attributes, (urban, rural, heavy tree canopy, etc.).
- Detailed assessment of each site was conducted, located underground utilities and cleared brush and in-stream debris

Beta Sensors (Year 2)

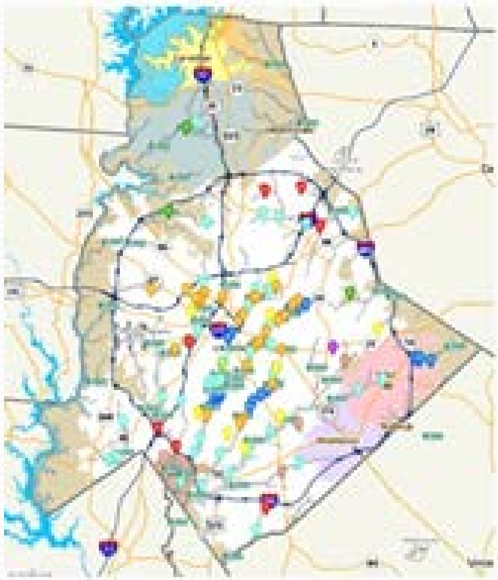
- 95 sites and 95 sensors for CMSWS benefit
- Examples of sites selected include: mitigation areas, overtopped roads, minor system CIP, high hazard dams, gaps in FINS coverage.
- Alarms and Notifications in Contrail

Charlotte-Mecklenburg STORM WATER Services

1.3 Extending Current Flood Monitoring

Existing FINS Network
50 USGS Gauges =
46.2% of Flood Risk Monitored

Base Year 1 :
50 USGS Gauges +
25 Alpha Sensor Sites =
51.2% of Flood Risk Monitored



Option Year 1:
50 USGS Gauges +
25 Alpha Sensor Sites +
93 Beta Sensor Sites =
96% of Flood Risk Monitored

1.4 Maintenance and Inspections Database

Operation and maintenance activities along with inspection information for the LCS was stored in a new module added to an existing database.

II. Field Installation

2.1 Site Preparation

- Initial site visits
  - Solar Requirements
  - Vegetation management
  - Safety
  - Measurements

2.2 Sensor Installation Design Plans

STORM WATER

2.3 Installation Procedures - Communication Units

2.3 Installation Procedures – Communication Units

STORM WATER

2.3 Installation Procedures – Communication Units

Vendor 1 βeta Communication Units

2.3 Installation Procedures – Lower Sensors

2.3 Installation Procedures – Lower Sensors


Vendor 1 & Vendor 2 Lower Sensors


Vendor 3 Lower Sensor

2.3 Installation Procedures
- Lower Sensors – Vendor’s βeta

2.3 Installation Procedures - Lower Sensors – Vendor's βeta

2.4 Installation Lessons Learned – Vendor 1

Pros:

- Small size
- Plug & play cables
- Mounting adaptability
- Cable is direct burial

Cons:

- Pre-determined cable lengths
- Radio mesh network is limited
- Bird resting spot
- Network dependency

2.4 Installation Lesson Learned – Vendor 2

Pros:

- Instream sensor is rugged
- Plug & play wiring
- Cellular independence
- Unistrut mounting

Cons:

- Bulky equipment
- Pre-determined cable length (200')
- Cable was hard to work with

2.4 Installation Lessons Learned – Vendor 3

Pros:

- Field configured cable lengths
- Quick mounting

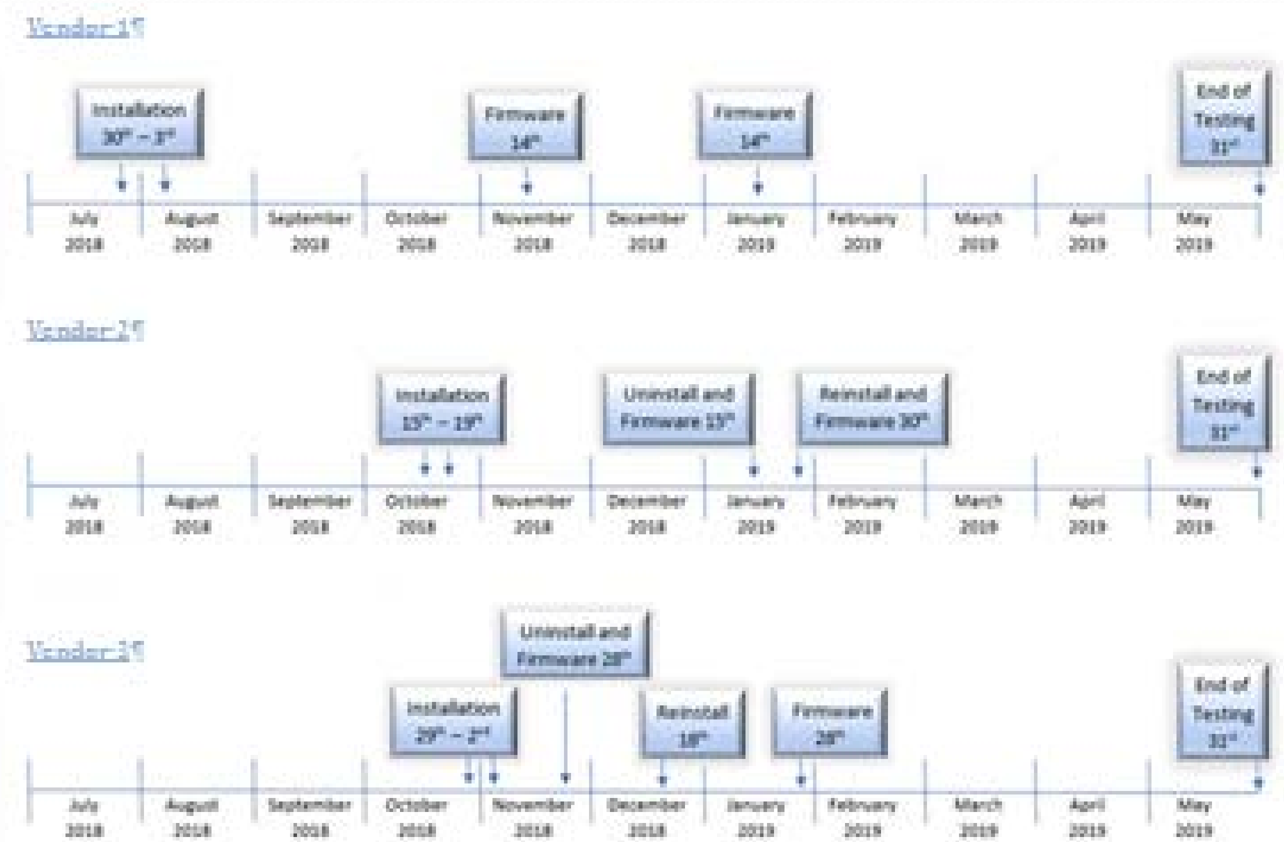
Cons:

- In-stream sensor design
- Quality control

III. Sensor Functionality

Hurricane Florence – Flooding of Little Sugar Creek 9/17/2018

3.1 Functionality Timeline

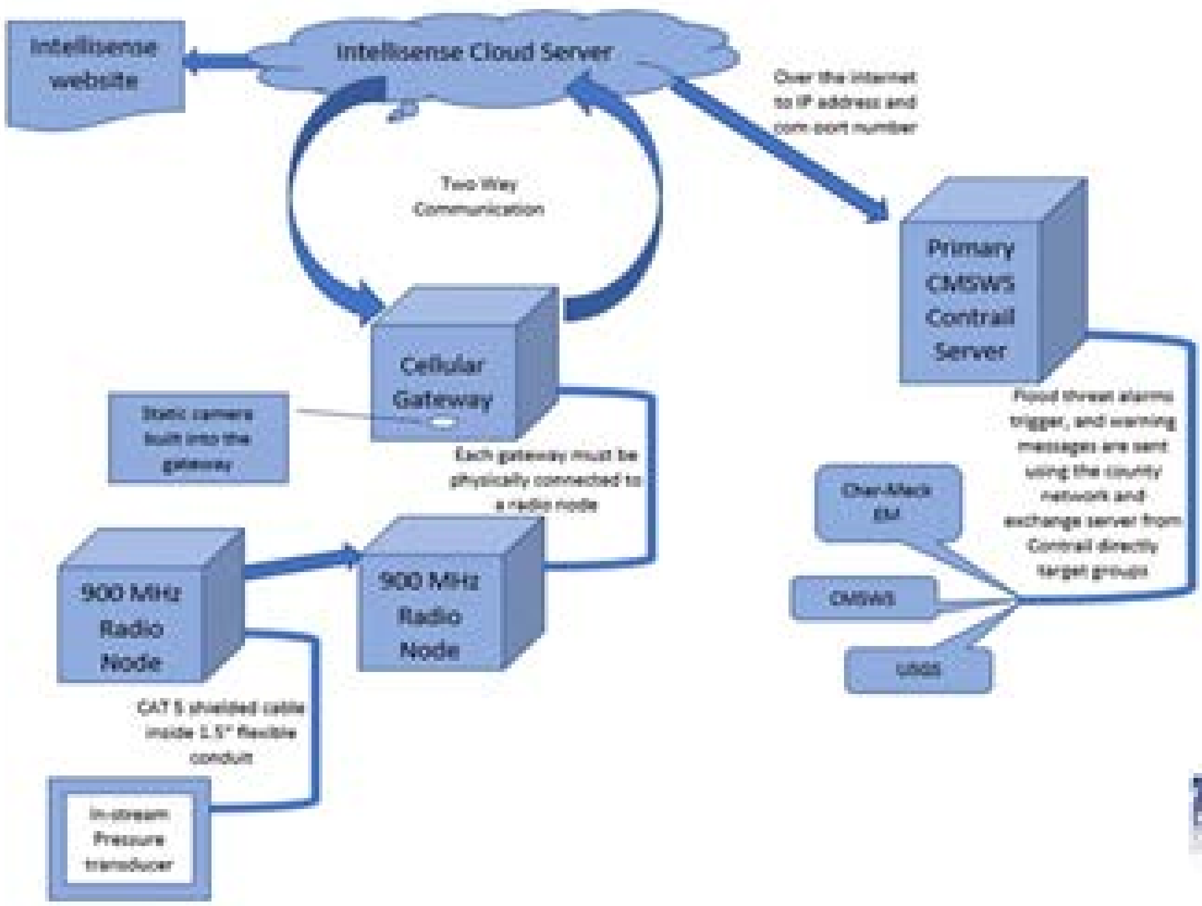


3.2 Operation & Maintenance

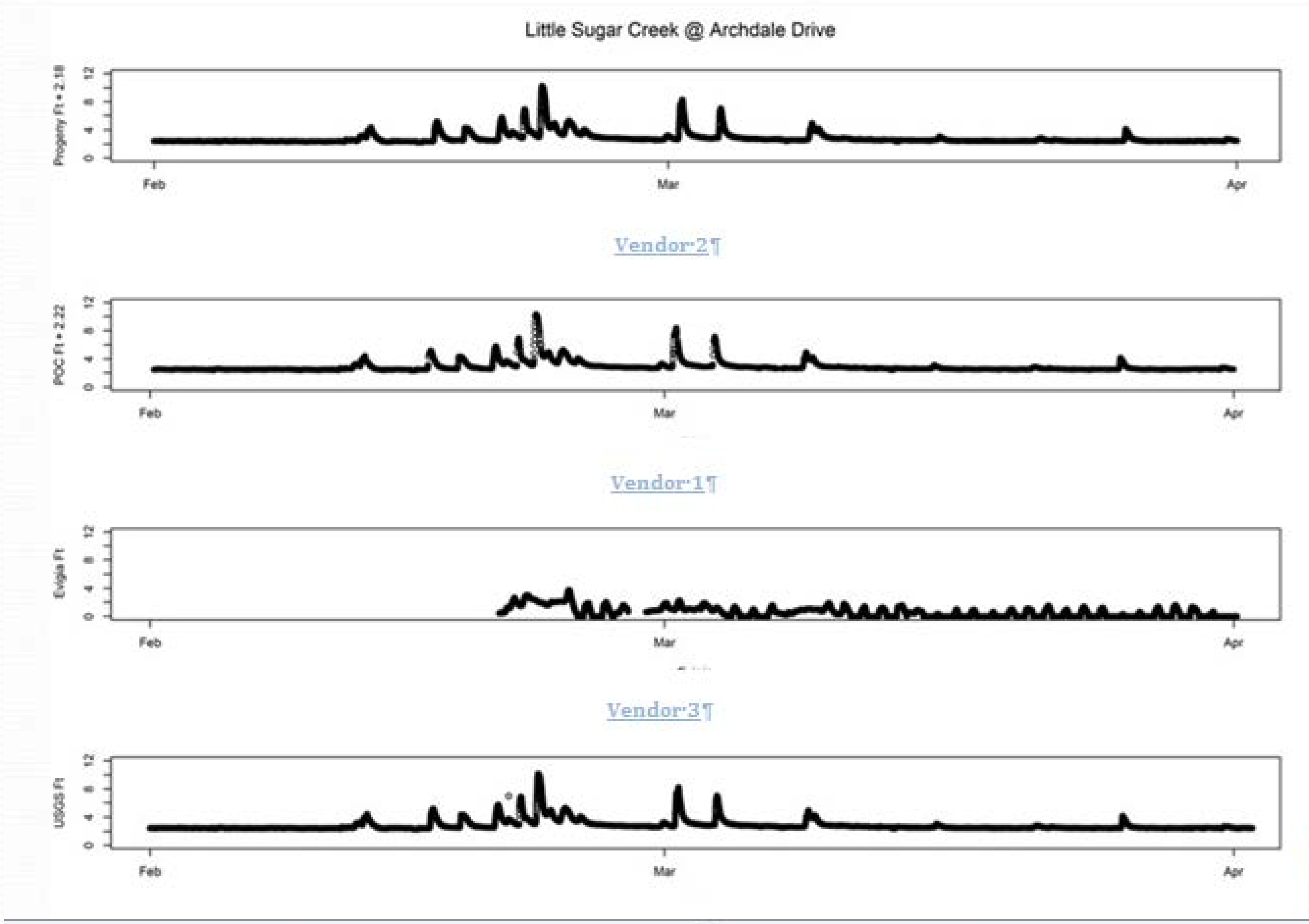
Photo of Storm debris blockage

- All vendors performed firmware updates
- Removing debris
- Replacing damaged items
  - Lower sensors
  - Solar panels
  - Antennas
- Validation measurements

3.3 Data Integration – Vendor 1



Flood Sensor Performance February - April



APPENDIX B: OPERATION AND MAINTENANCE (O&M) PLAN

REFER TO LCS VENDOR SPECIFIC INSTRUCTIONS AND MODIFY O&M CHECKLIST AS NEEDED

General O&M Plan for CMSWS Personnel:

1. **Daily**:
   a. Check data communication server for alerts or alarms
      i. Ensure all units are geographically present on the server
      ii. Ensure battery levels are adequate to maintain unit's reporting frequency
      iii. Ensure stage is reporting at sites where applicable*

      *Dry installation sites will show a stage of 0" outside of storm events

      iv. If any of the aforementioned criteria present issues, investigate further with site visits
2. **Monthly:**
   a. Conduct monthly site visits
      i. Refer to "Physical O&M Plan Inspection Checklist" below
      ii. Conduct validation measurement at lower sensor, documenting site, date, time and measurement

         Example:

         Site: FMB1 **Date:** 1/1/20 **Time:** 12:00 PM

         Validation Measurement: 0.05"
   b. Insert validation measurement into a data management system (if applicable)
      i. This data is used as a means of conducting Quality Assurance/Quality Control (QAQC) for the flood sensors

Physical O&M Plan Inspection Checklist:

1. Head unit:
   a. Structure to which Head unit is Mounted:
      i. Ensure that the structure is secure
   b. Mounting Bracket
      i. Ensure mounting bracket is securely attached and is southern facing

c. Head Unit
    i. Ensure that head unit is securely attached to mounting bracket
    ii. Inspect for signs of vandalism
        1. Damage to solar panels
        2. Missing or broken antennas
        3. All cables are properly inserted into their designated ports
    iii. Inspect for signs of pest in or around the head unit
        1. Address accordingly

2. Data Communication Cable:
a. Cable
    i. Ensure that data communicate cable is plugged into unit
    ii. Ensure majority of data communication cable is protect inside conduit
        1. Storm events can cause cable to become exposed
    iii. Check for damaged/exposed wires
b. Conduit
    i. Ensure conduit is securely attached to head unit mounting structure
    ii. Check for damage to conduit

3. In-stream Sensor:
a. Pin
    i. Ensure pin is securely driven into creek bed or deployed location
b. In-stream Sensor
    i. Ensure in-stream sensor mounting bracket is securely attached to in stream pin
    ii. Ensure in-stream sensor is securely attached to mounting bracket
    iii. Check in-stream sensor for signs of physical damage
    iv. Ensure conduit is securely attached to in-stream mounting bracket
    v. Check in-stream sensor data communication cable is protected inside of conduit

4. Additional Inspections:
a. Cameras
    i. Ensure camera is properly secure
    ii. Ensure camera cables are plugged in and undamaged
b. Signage

i. Ensure signage is properly secured and visible

c. Vegetation

i. Ensure all vegetation around the head unit is removed

ii. Ensure all vegetation posing a health hazard (i.e. Poison Ivy) is removed from the site