Homeland Security

Science and Technology

Report of Findings

Kentucky Division of Water

Critical Infrastructure and Flood Risk Management Innovation for Dam Safety Monitoring

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1 Executive Summary

The Kentucky Division of Water (DOW), in cooperation with the Department of Homeland Security Science and Technology Directorate (DHS S&T), was awarded a phased project to establish a means of monitoring critical infrastructure, particularly dams, as part of the DHS S&T Flood Apex Program. The initial project phase dealt with researching appropriate methods to assess dam-related failure modes and available technology to develop warning thresholds for dam-related incidents. In the second phase of the project, DOW utilized water level sensors to serve as a replicable, cost-effective, and efficient solution that can be applied to dams and other critical infrastructure where flood risks may be lesser known on a wide scale across Kentucky (and the nation).

DOW tested and installed an extensive number of water level sensors at high and moderate hazard dams, many of which are remotely located and have little or no existing instrumentation. These efforts have allowed DOW to assess dam-related warning needs in critical areas of the Commonwealth in order to develop prototype warning thresholds that will ultimately lead to enhanced warning for dam owners, emergency management professionals, and other related stakeholders to better prepare for and mitigate dam-related incidents. In the future, DOW plans to extend implementation to differing use cases including levees, low water crossings, and municipal stormwater applications to address pluvial flooding.

As a result of utilizing sensors from multiple vendors, DOW has identified the need for a centralized data management platform. This will provide a single user interface to organize large amounts of data from multiple sensor vendors to streamline communication of dam-related hazards, namely floods, in warning and alert delivery. This statewide monitoring program intends to increase warning and response time in order to reduce risks to lives and property and ultimately build community resilience to flood events of all types, including dam inundation.

2 Introduction

DOW, in conjunction with DHS S&T Directorate's Flood Apex program, conducted a phased project to establish a means of monitoring dams with the end goal of the monitoring system being to alert effected communities and property owners of potential dam failure.

In the first project phase, four dams were selected for study based on the amount of available information and existing instrumentation available at each dam. Identifying existing data about the dams established a baseline that was used for comparison with the instrumentation being evaluated. The first phase focused primarily on instrumentation research, testing, and evaluation of selected instrumentation for accuracy and reliability. The initial project phase leveraged alpha sensors provided to DOW by DHS S&T and industry-standard sensors as a control.

The second phase primarily focused on dam instrumentation research. Potential dam failure modes were assessed, and included scenarios such as overtopping, slope instability, internal erosion/piping, vandalism, and lack of maintenance. Research was performed on possible instrumentation to monitor for these failure modes. Criteria to select the instrumentation was developed and included the number of risks/failure modes addressed, cost, difficulty of installation, difficulty of automation, required maintenance, and the applicability to typical DOW dams, many of which do not have existing instrumentation.

The second phase also included the purchase and installation of Internet of Things (IoT) flood sensors provided through a DHS S&T research grant to monitor pool elevations, a commercially available low-pressure transducer to monitor pool elevations and to serve as a control for IoT sensors, flow monitors in toe drains to monitor internal erosion, and a drone equipped to collect survey data and imaging of the dam to monitor for seepage and movement of the dam over time.

The remaining phases of this project included development of the instrumentation into a prototype dam incident warning system, operation and performance evaluation, and dissemination of best practices. Means of dissemination include internal communication within DOW, Kentucky Association of Mitigation Managers (KAMM) and US Army Corps of Engineers Silver Jackets among others. These best practices will be applied to other dam locations in the Commonwealth that have limited information and/or instrumentation. These tools are intended to increase warning and response time, ultimately reducing risks to lives, infrastructure and property.

The prototype dam breach warning system includes development of a single dashboard that allows users to view current and historical water levels at the monitored dams in Kentucky. In addition, the system will provide users a subscription service to alerts when water levels reach a certain threshold or when water level changes that surpass a given rate are detected.

After selecting the initial four pilot sites and testing the instrumentation, additional sensors were provided by DHS S&T for follow-on testing. The sensors provided by DHS S&T were installed at additional dam locations and testing was continued to refine methods and procedures for the prototype dam inundation warning system. Based on the results of the testing, many of the alpha and beta level sensors provided for the project possessed significant reliability issues. Due to the importance of the program, additional commercial sensors are planned to be tested to find more reliable sensors and monitoring software.

3 Phase 1: Site Pilot

The first phase of the project involved the analysis and selection of the initial dams to be used for testing. Utilizing the criteria defined below, dams were evaluated and a selection of dams that were ideal for the initial round of testing were identified.

3.1 Site Selection

Fourteen high hazard dams were selected as potential pilot sites for further evaluation based on knowledge of the dam inventory and dam risks. These potential pilot sites represented a mix of ownership (both state and local), and construction type (earth fill and rockfill), and were within 1.5 hours of travel from Lexington/Frankfort. The sites were ranked by evaluating for:

- Travel Time
- Failure Risk
- Population at Risk
- Existing Instrumentation / Available Data

The intent was to select a pilot site where pertinent information was already available to limit the amount of data collection required to identify and monitor for potential failure modes. Information about the dams was collected and the sites were ranked based on this information as shown in Table 1. This table shows the dams that were evaluated and the criteria used to evaluate these dams. Four dams were selected from this list for initial testing.

Table 1 Potential Pilot Site Ranking

Rank	Name	Owner	Stream	City	County	Travel Hours	Year Complete	Type	Height (ft)	NID Storage	Failure Rank[1]	Life Loss Rank[1]	Existing Instrumentation	Failure Potential or Known Historical Issues	Datasets Available	Notes
1	Freeman Lake/ Valley Creek MPS No. 4	Local	Freeman Creek	Elizabethtown	Hardin	1.5	1966	Earth	44	1830	53	2	16 piezometers on crest and downstream bench of dam	Potential clogging in west toe drain, Maintenance issues (vegetation, wave wash protection)	Record drawings, Yearly inspection reports, Instrumentation readings	Stantec data and experience, existing piezometers no inclinometers
2	Guist Creek Lake Dam	State	Guist Creek	Shelbyville	Shelby	0.8	1961	Earth	60	13510.7	N/A	N/A	Instrumentation is no longer working	Wet areas and maintenance issues	Record drawings for dam improvements (1994), Inspection reports, Emergency Action Plan	Dam has an existing high-water alarm
3	Clements Lake Dam	State	Evans Branch	Morehead	Rowan	1.3	1950	Earth	44	677.75	69	1	None	Seepage, clogged toe drain, erosion on upstream slope	Summary of stability analyses, Inspection reports, H&H analysis	Immediately upstream of Morehead State University, high downstream population at risk, warning time is less than a minute
4	Willisburg Lake Dam	State	Lick Creek	Willisburg	Washington	0.75	1968	Earth	77	3223.4	64	71	Instrumentation is no longer working	Maintenance issues (vegetation), spillway capacity issues	Construction drawings, Inspection reports, H&H analysis, geotechnical investigation report	Geotechnical information available
5	Banklick Creek FRS NO 3	Local	Banklick Creek	Erlanger	Kenton	1.5	1980	Earth	112	0 (Flood Control)	22	10	Instrumentation is no longer working	Erosion, sloughing, and maintenance issues (vegetation, material placed in emergency spillway)	Inspection reports, H&H analysis, Instrumentation layout	Piezometers are installed on the dam
6	Boltz Lake Dam	State	Eagle Creek	Dry Ridge	Grant	1	1956	Earth	71	1800	33	61	None	Principal spillway blocked with vegetation/siltation/debris, possible sinkhole, spillway capacity issues	Inspection Reports, H&H analysis	Lower downstream population at risk than other dams considered
7	Loch Mary Reservoir Dam	Local	Clear Creek	Earlington	Hopkins	3	1950	Earth	27	4200	5	12	None	Maintenance issues (hole, vegetation, deterioration of wave wash protection, spillway concrete), spillway capacity issues	Inspection Reports, H&H analysis, historic breach analysis	Travel time high
8	Renfro Dam	State	Little Renfro Creek	Renfro Valley	Rockcastle	1	1968	Earth	72	6107	39	15	None	Maintenance issues (vegetation), spillway capacity issues	Inspection reports, H&H analysis	Exploring warning system as part of a permit modification; Construction ongoing and planned
9	Olive Hill Reservoir Dam	Local	Perry Branch	Olive Hill	Carter	1.5	1957	Earth	47	340	18	17	None	Seepage, maintenance issues (sloughing, vegetation, material placed in emergency spillway)	Inspection Reports, H&H analysis	Travel time high
10	Wood Creek Lake Dam	State	Rockcastle River	East Bernstadt	Laurel	1.4	1969	Rockfill	163	44000	60	20	None	Seepage, possible spillway capacity issues	Record Drawings for dam improvements (1992), Inspection reports	Ongoing transportation projects in area
11	Mill Creek Lake Dam	State	Red River	Pine Ridge	Powell	1	1964	Earth	55	1840	66	21	None	Wet area and maintenance issues	Inspection Reports, H&H analysis	Travel time high
12	Beech Creek Dam	State	Beech Creek	Manchester	Clay	2	1963	Earth	67	1600	31	25	None	Water being pumped onto upstream face and other maintenance issues, spillway capacity issues	Inspection reports	Construction ongoing and planned
13	Lake Peewee Dam	Local	Greasy Creek	Madisonville	Hopkins	3	1953	Earth	32	8900	57	28	None	Maintenance issues (vegetation, slide)	Inspection Reports, H&H analysis	Travel time high
14	Lexington Reservoir 3	Private	West Hickman Creek	Lexington	Fayette	0.25	1902	Rockfill, Earth	40	2087	N/A	N/A	None	Slide in 1970's (repaired), no recent inspection reports are available	Record drawings for slide repair (1970's), Stability analysis associated with slide repair	Stantec data and experience; potential PR issue

[1]Failure Rank and Life Loss Rank represent the ranking of the dam compared to other State-Owned dams in terms of the likelihood of failure and the potential loss of life associated with a failure of the dam. These rankings were determined as part of a separate project in 2011 that reviewed information related to the condition of the dams and the population at risk downstream to develop a preliminary screening-level risk prioritization.

Four pilot sites were selected for initial tests by evaluating the data seen in Table 1 leading to the selection of the following four sites:

Freeman Lake / Valley Creek MPS No. 4, Hardin County

- Existing instrumentation (piezometers) that is routinely read and reported
- Recent re-construction (2000) with as-built and geotechnical information available
- Annual inspection records available
- Good working relationship between owner (City of Elizabethtown) and DOW

Guist Creek Lake Dam, Shelby County

- Existing instrumentation is no longer working
- Proximity to Lexington and Frankfort
- Significant maintenance issues that require regular surveillance
- State owned dam

Clements Lake Dam, Rowan County

- Immediately upstream of Morehead State University, high downstream population at risk, warning time is less than a minute
- Significant maintenance issues that require regular surveillance
- State owned dam

Willisburg Lake Dam, Washington County

- Large amount of construction and design information available, geotechnical subsurface investigation report available
- Significant maintenance issues that require regular surveillance
- State-owned dam

The four pilot sites are shown on a map below in Figure 1.

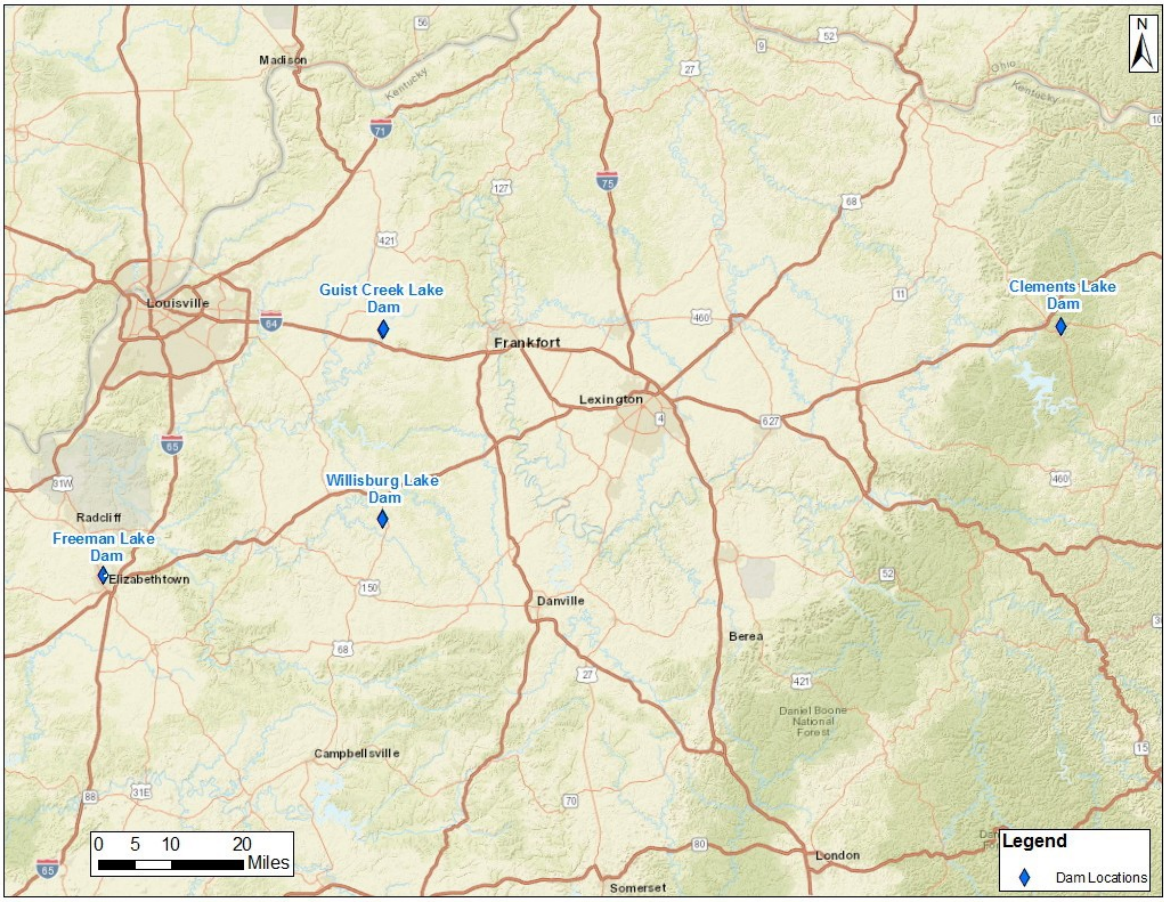


Figure 1 Pilot Sites

3.2 Risk Evaluation

For the four pilot sites, potential failure modes at the dams were reviewed. The intent was to identify general failure modes (applicable to most earthen dams) and develop a strategy to monitor for the failure modes, but not to perform a detailed potential failure mode analysis. The following failure modes were noted. These are listed in order of perceived likelihood of occurrence based on experience and history with dams in Kentucky:

- Internal Erosion/Piping
- Overtopping
  - Erosion/Headcutting in the Emergency Spillway
  - Dam Crest Overtopping
- Slope Instability
  - Static
  - Seismic
  - Rapid Drawdown
- Other
  - Sinkhole Formation
  - Maintenance Issues
  - Terrorism/Vandalism

4 Phase 2: Instrumentation

4.1 Instrumentation Overview

After the failure modes were identified, available instrumentation that can monitor for these potential failure modes was evaluated. Instrumentation reviewed included:

- Seepage Weirs
- Flow Monitors
- Soil Extensometers
- Vibrating Wire Piezometers
- In-Place Slope Inclinometers
- Low-Pressure Transducers
- Internet of Things (IoT) Flood Sensors
- Fiber Optic Sensing
- Drones
- Non-contact Water Level Sensors

A description of each type of instrumentation is summarized in Appendix D.

4.2 Instrumentation Selection

Criteria was developed to review the instrumentation and aid in selection of appropriate instrumentation. These criteria are listed and described below.

- Ability to monitor multiple failure modes – instrumentation that can monitor more than one failure mode was prioritized over instrumentation that only monitors one failure mode.
- Cost (purchase and Installation) – the overall cost of the instrumentation was estimated to determine its cost-effectiveness. Furthermore, cost of data service was included in cost determination
- Difficulty of installation – This was subjective and judged as low, medium, or high. Installation difficulty looked procedures including number of cable connections, mounting hardware, ability to attached pressure transducer underwater, and software setup.
- Difficulty of Automation – This was subjective and judged as low, medium, or high. Based on the vendors' provided dashboard for monitoring their sensors, how difficult was it to set up notifications and automation for sensor alerts.
- Required Maintenance – This was subjective and judged as low, medium, or high. How much routine maintenance was required, such as resetting system, replacing parts, cleaning, etc.
- Applicability to Kentucky State-Owned Dams – if successful, implementation of the instrumentation can be rolled out to other dams within the state's inventory. Therefore, whether the instrumentation can be able to be installed at a "typical" state-owned dam was evaluated.

Table 2 shows the evaluation of the instrumentation relative to these criteria. The rankings shown are subjective in nature and based on the experiences and background of the project team.

Based on this review, the recommendation was to install IoT Flood Sensors to monitor for overtopping, activation of the emergency spillway, and rapid drawdown/loss of pool. For testing and evaluating the accuracy of the IoT Flood Sensors, a low-pressure transducer that has been used successfully at dam sites was also recommended to act as a control.

Three vendors provided IoT sensors that were used for this project: Evigia, Intellisense, and Progeny. Each vendors' sensor used a pressure transducer probe to measure water pressure and convert the pressure to a corresponding depth. Although they provided the same data, each of the sensors used slightly different technologies, different form-factors, and had different installation procedures.

While using these systems, they were evaluated based on criteria from DHS S&T. Our evaluation of these sensors is covered in Section 4.6.2. In addition, stakeholders from five (5) state and local governments that have established flood sensor monitoring initiatives or are considering the installation of a sensor network to address several flooding related risks evaluated the sensors. While these stakeholders are all interested in early warning for flood alerts, each also has unique requirements, conditions and environments that will provide broad-use case test and evaluation scenarios to evaluate the performance of the flood sensors.

Lastly, the use of a drone was recommended for monitoring for Internal Erosion/Piping (seepage) and slope stability. This combination of instrumentation was viewed to be applicable at most of the dams regulated by DOW and was relatively cost effective.

Table 2 Instrumentation Selection

Instrumentation	Risk / Failure Monitoring	Cost	Difficulty of Installation	Difficulty of Automation	Required Maintenance	Applicability to DOW State- Owned Dams
Seepage Weirs	Monitors one failure mode (Internal Erosion/Piping)	Moderate cost	Medium	Medium	Medium	Medium – limited to dams with existing toe drains
Flow Monitors	Monitors one failure mode (Internal Erosion/Piping)	Moderate cost	Medium	Low	Medium	Medium – limited to dams with existing toe drains
Soil Extensometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $3,000 in material cost (assumes 3 sensors in series with cables run 500 feet) and $3,000 in installation cost[1]	Medium – requires shallow trench to install	Low	Medium	High – can be installed on any earthen dam to monitor for movement
Vibrating Wire Piezometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $1,500 in material cost (assumes 2 piezometers and cable run 200 feet) and $3,000 in installation cost[1]	Low for sites that already have piezometers (i.e. automating existing instrumentation) and High for sites that do not have piezometers (i.e. installing new instrumentation)	Low	Medium	Low – applicable to all earthen dams, however it is costly to install where there are not existing piezometers. Most state-owned dams do not have piezometers.
In-Place Slope Inclinometers	Monitors slope instability (due to static, seismic, or rapid drawdown)	Approximately $8,000 in material cost (assumes a 50- foot deep inclinometer) and $2,500 in installation cost[1]	Medium – can be installed in a day with a two-man crew	Low	High	Low – applicable to all earthen dams, however it is costly to install where there are not existing slope inclinometers. Most state- owned dams do not have this instrumentation.
Low-Pressure Transducers	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Approximately $1,500 in material cost (assumes a 50- foot deep inclinometer) and $2,500 in installation cost[1]	Medium – can be installed in a day with a two-man crew	Low	Medium	High – applicable to most state-owned dams for reading water levels
IoT Flood Sensors	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Approximately $1,000 each in material cost, approximately $3,000 in installation cost	Medium	Low	Medium	High – applicable to most state-owned dams for reading water levels
Fiber Optic	Monitors slope instability (due to static, seismic, or rapid drawdown)	Moderate cost	High	Low	Medium	High – applicable to most state-owned dams
Ultrasonic Sensors	Monitors three failure modes (Overtopping of Spillway or Crest) and Rapid Drawdown	Moderate cost	Medium	Low	Medium	High – applicable to most state-owned dams for reading water levels
Drone	Monitors slope instability (due to static, seismic, or rapid drawdown) and for Internal Erosion/Piping	$2,000 - $10,000 (equipment only) but can be used at multiple sites	Low	Medium	Medium	High – applicable to most state-owned dams

[1]Does not include cost of readout box (~$7,800 in materials and labor, can be used by multiple instruments)

4.2.1 Drone Selection

A DJI Mavic drone was purchased for this program. The drone was chosen due to the low cost along with the capabilities of the included camera. Additionally, other agencies within the Kentucky state government had positive experiences with DJI drones and provided the recommendation for the chosen product.

The drone provides the capability to quickly collect aerial imagery and accurate elevation data at the dams. These imagery and data can then be compared to historic data to identify changes and areas of interest. For example, if an area of dam was subsiding a few inches each year, this could be an indicator of issues to investigate further. The ability of an inspector on the ground to identify this small change is difficult, however comparing data in a year over year manner makes this change evident.

4.2.2 Drone Usage

In addition to the water level sensors, a drone was also used for evaluation and monitoring of selected dams. Modern drones can fly with little user input and collect very accurate imagery data quickly and reliably. DOW chose to investigate drone usage as an inexpensive way to routinely inspect dams for change.

Traditionally dams are inspected by personnel walking the dam and visually looking for defects. In addition, surveyors take topographic measurements of the dam and aircraft can be used to fly over the dam and collect photometric imagery and accurate topographic data using LIDAR. These methods are still used because of reliability and ability to accurate inspect the dam. These methods however are costly and time consuming. Due to recent improvements with drone technology that have drastically reduced the cost and improve the reliability and accuracy, DOW evaluated the use of drones to regular inspect dams and monitor for change.

A traditional, in-person inspection must be performed to both establish a baseline and comply with the state and federal inspection requirements. However, once the baseline inspection is performed, a drone may be used to easily monitor for changes.

Multiple drones were evaluated for cost, reliability, ease of use, and sensor quality. Modern, low cost drones do not use traditional LIDAR to collected topography, but instead use a high-quality camera and computer processing to create a topographic representation of the dam that is very similar to LIDAR. Drones use a three, four, or five band cameras to take a complete array of imagery of the dam from multiple angles. Automated photogrammetric procedures process the photos to create an accurate three-dimensional representation of the dam.

After evaluating the drones, DOW purchased a DJI Mavic model for approximately $2000. This is a low-cost model that is already used within Kentucky state government. DOW received assistance from other state agencies in training pilots and identifying software needs to utilize the drone. Multiple employees of DOW are trained as drone pilots and have received their FAA Part 107 certification for commercial flight.

The standard procedure for flying the dams involved the following steps:

1. Prior to the flight, a flight plan is developed. This flight plan shows the route of the drone and the pilot or pilots can determine how much coordination will be required if roads and or populated areas must be over flown. Flight plan software is updated based on current FAA data.

2. Situationally dependent coordination is initiated with dam owner and team required for flight. Based on the area to be flown a necessary number of safety spotters are identified for the inspection.
3. The team assembles at the dam and completes the flight plan. Ground referenced points are placed and surveyed if needed. The team monitors the imagery collected and if necessary collect imagery by flying additional autonomous and manual flights.
4. Post flight, the imagery is processed, and topographic data created. This topographic data is part of a holistic view of the dam, it is combined with other available data to analyze and inspect for changes at the dam.

More recently, after warnings published by DHS, DOW is evaluating other drones and manufacturers that are domestically produced., since there have been security concerns discovered with the DJI model. Since dams and water supply systems are considered critical infrastructure, and the consequences of failure can be quite high, DOW is working to migrate the drone inspection program away from DJI drones.

4.3 IoT Flood Sensor Application

The likelihood of dam failure is minimal, but with extremely high consequence. Many of the state-owned dams in the Commonwealth have little to no instrumentation and communities and property owners surrounding dams are typically unaware of any potential flooding risks. Due to the remote nature of many of these dams an issue may not be known until a state- or dam owner-initiated inspection is conducted.

The primary focus of the flood sensors is to promote hazard awareness and mitigation. The sooner hazards associated with dams can be identified and evaluated the more planning is possible for mitigation efforts including repairs, evacuation, and response. IoT sensors placed upstream and downstream of a dam will monitor water levels associated with the reservoir (lake) and of levels coming out of the dam. Any significant increase or decrease in water levels can potentially signify overtopping or a breach scenario and notifications in place or trigger warnings will alert the state to implement emergency actions. In the actual event of a dam breach, communities with appropriate warning systems may be given timely notice, saving lives and injuries by allowing people to evacuate promptly and responders to be ready when needed.

In addition to hazard mitigation, the sensors provided additional value. Many of the reservoirs that are monitored are used for water supply for local communities. In some cases, drought is a serious threat to community water supplies. The sensors provide an expedient and convenient method to monitor water supply via reservoir levels. Making this data public also provides a means to communicate with the community and encourage ownership in water conservation and utilization efforts. In another case, while a dam was being replaced, a temporary cofferdam was installed. The sensors allowed the contractor to monitor the cofferdam continuously during construction.

Although the sensors could measure water levels to sub-centimeter accuracy, measurements within a few centimeters of accuracy can achieve success for the warning system. Variations in water levels due to evaporative or groundwater effects are also not a concern for these purposes. The primary focus is on the trend of fast changes over short amounts of time.

Installation of the sensors used in this project was relatively simple and can be conducted in a few hours at most. Most of the sensors are installed on a ‘t’-post driven into the ground near the water intended to be monitored. The node, batteries, and solar components are installed on the t-post. The pressure transducer sensors are placed in the water and the cable is either buried or protected in conduit.

Implementation of tested IoT sensors with a low failure rate and minimal maintenance is the most advantageous. Many of these sensors are installed in remote locations and often require continual visits to the sensors for maintenance; the maintenance and operations of the sensors can come with significant cost. This highlights the need for DOW to continue to engage in beneficial partnerships to maintain the warning sensor system.

The low cost and ease of implementation of IoT sensors allows communities to better prepare for dam-related incidents by allowing investment in successful response and recovery strategies. By employing these types of systems, communities can contribute to their overall resiliency against dam-related risks and insurance costs by leveraging these systems for Community Rating System (CRS) flood insurance discounts.

4.4 Instrumentation Implementation

The selected instruments were installed at the pilot site and additional test sites. A summary of the instrumentation installed at each site is shown in Table 3. This table shows that the primary instrumentation purchased was the IoT Sensors. The Drone was purchased for use across the state.

Table 3 Instrumentation Implementation

Dam Location				
Instrumentation	Freeman Lake	Willisburg Lake	Guist Creek Lake	Clements Lake
IoT Sensors	10	6	6	6
Pressure Transducer and Data Logger/Readout Station	1	1	----	---
Drone	1 purchased (to be used at multiple sites)			

4.5 Calibration and Threshold Determination

For the installed instruments, trigger levels were set. When the data received during testing rose above these trigger elevations, a notification was sent via email to the project team for evaluation and verification.

Sensors deployed that detected water level (IoT Sensors and Pressure Transducer), water levels triggers were set to detect the following events:

- Water level above dam crest (overtopping)

- Water level within 1’ of dam crest (potential for overtopping)
- Water level above emergency spillway crest (emergency spillway active)
- Water level within 1’ of emergency spillway crest (potential for emergency spillway to become active)
- Water level more than 1’, 2’, and 5’ below normal pool (potential loss of pool)

To determine these trigger levels, as-built drawings of the dams were reviewed to determine the normal pool elevation, emergency spillway crest elevation, and dam crest elevation. Depths recorded when the instruments were first installed were assumed to be at the normal pool elevation. Elevations for the crest and emergency spillway were then correlated to depths for the instruments and used to set the trigger elevations. Additional triggers were set at the sites for upstream and downstream flood conditions that may impact surrounding structures. These elevations were set based on a review of available topography. For the testing phase, additional trigger elevations were also set at lower elevations to verify that the trigger notifications were functioning as expected. An example of trigger elevations set for Freeman Lake Dam are illustrated in Table 4.

Table 4 ***Freeman Lake Dam Elevations***

Dam Feature	Elevation	Alert
Crest of Dam	766.5	Overtopping
	765.6	1' Below Crest, Maximum Design Flood
	763.4	Potential Downstream Rehabilitation Center Flooding
	763.0	Potential Ring Road Flooding
	759.8	Significant Downstream Flooding (500-yr)
	759.0	Potential Upstream Residence Flooding
Emergency Spillway Crest	756.7	Emergency Spillway Crest Active
	755.7	1' Below Emergency Spillway Crest
Normal Pool	751.0	
	750.0	1' Below Normal Pool
	749.0	2' Below Normal Pool
	746.0	5' Below Normal Pool
Low Level Drawdown	722.0	
Principal Spillway	715.8	

4.6 Data Collection and Evaluation

All the IoT sensors collected and reported water levels on a regular basis. The reporting time could be modified for the sensors, but in general a reading was taken every five minutes and uploaded via cellular telemetry every 15 minutes.

The sensors all used pressure transducers to measure water pressure and calculate depth. These were connected to the sensor by cable and placed in the water below the expected low water line. The Progeny sensors also had the ability to monitor water level ultrasonically. This involved placing the sensor over the body of water with the ultrasonic sensor pointed down towards the water. We did not utilize the ultrasonic sensor for data collection, all our data was collected via pressure transducer.

In addition to water level, the sensors also collected other atmospheric readings. General all the sensors could collect the following additional data:

- Water Temperature
- Atmospheric Temperature
- Barometric Pressure
- Rainfall (with additional equipment)

Although all the readings were collected, through the course of this project, only water level was routinely monitored and analyzed.

4.6.1 Data Collection Methodology

Data for the various sensors was collected by cellular telemetry. The data was uploaded the vendors' respective servers and where it was accessible to viewed and download. We downloaded the data so that it can aggregated and compared. The individual sensor manufactures used different formats and storage systems for the data, so each had its own method for collection.

Initially Evigia used Grafana, an open source platform that allowed the data to be viewed on their website. According to Evigia there was no Application Programming Interface (API) access to read these data, so the data is manually downloaded on a weekly basis. Upon further investigation the Grafana platform exposes an API by default so if needed in the future DOW can access this data programmatically.

Through the course of the project, Evigia migrated from Grafana to a custom build web application for monitoring and collecting the data. This platform provided a more intuitive user interface and the most functionality of any of the vender provided dashboards.

Geokon does not provide telemetry or a dashboard for their sensors. They are partnered with Sensemetrics to provide telemetry and sensors are monitored through the Sensemetrics platform. This is a commercial platform that allows advanced monitoring and notifications from a variety of sensors. This serviced provides API access websockets for real time data access. This data was pulled on a 10-minute interval and stored in a consolidated database with other sensor data.

Intellisense uses Thingsboard, an open source platform that allows the data the viewed on their website. Thingsboard provides API access so this data was pulled every 10 minutes and stored in a consolidated database with other sensor data.

Progeny also uses a proprietary platform developed internally for displaying the data. Their website allows the user to view the data and download the data. This data was manually downloaded on a weekly basis.

4.6.2 Evaluation Criteria

For the purpose of a detailed plot comparison, sensor feeds were acquired from the four sensor vendors for four different sites across Kentucky over a seven-day period (February 14, 2019 – February 21, 2019). A series of figures was generated to compare water level readings among sensors at each site.

Daily total precipitation data were acquired from Kentucky Mesonet at Western Kentucky University (WKU) (https://www.kymesonet.org/) for four sites across Kentucky (Table 5).

Table 5 Selected Mesonet sites and approximate distances and directions from research sites

Research Site	Mesonet Site	Approximate Distance	Direction
Clements Lake	Rowan County MRHD	3.1 miles	Northwest
Freeman Lake	Hardin County CCLA	6.5 miles	Southwest
Guist Creek Lake	Shelby County WADD	7.9 miles	South
Willisburg Lake	Mercer County HRDB	17.7 miles	East

Acquired data were standardized in order to compare water level readings from different vendors at a given site because water level was reported differently by each vendor. Some of the sensors reported water level in feet while others reported in inches. In addition, the sensors were not necessarily calibrated to one another, for example if three sensors were places in 36” of water, one read 36”, one read 35” and one read 37”. When the water level rose by one inch, they all rose one inch higher (36”, 37”, 38”).

To account for variations in calibration, the units were standardized and then the initial water level value (very first reading) for each sensor was determined for the given time period, and the difference from this initial value was calculated for each data point (Data Point Value minus Initial Value). For Geokon sensors, all values were multiplied by 12 to convert from units of feet H_20 to inches H_20 prior to standardization.

Standardized (difference) values were intended to represent the change in water level (in inches) over time for a given sensor, with positive values corresponding to increased water level and negative values corresponding to decreased water level. Standardized values were plotted as a function of time to facilitate visual comparison of water level readings from different vendors at a given site.

The hourly running average of standardized values was also calculated by sensor to more effectively compare overall trends (increases and decreases) in water level among sensors – for a given hourly timepoint (e.g. 9am), all data collected within the previous hour (8am - 9am) were retrieved, and the mean of standardized values was computed. Running average values were plotted as a function of time with daily total precipitation values for reference.

Figures were visually inspected to (1) identify sensors with missing, highly variable, and extreme water level readings and (2) compare water level readings among sensors, with readings from Geokon sensors as the benchmark for comparison. A selection of these plotted data is included in Appendix A.

5 Follow on Sensor Testing

Following the initial testing of sensors, DHS S&T supplied an additional 133 beta sensors (38 from Progeny, 93 from Evigia, and 2 from Intellisense). “Beta” sensors had various improvements from “alpha” sensors; generally speaking, the “beta” sensors are one iteration away from production sensors. Using these sensors, DOW has made initial attempts to begin creation of the flood warning system across several dams. Due to additional issues with the beta sensors, DOW was not able to fully deploy the flood warning system as planned.

5.1 Follow on Sites

Additional dams were evaluated for installation of follow on sensors. A more substantial criteria was use for this round of installations. Once again, dams were selected based on proximity to the Lexington and Frankfort, KY region prioritizing high hazard and poor condition dams. In addition, dams for critical water supply and dams with newsworthy publicity were considered. Table 6 shows the breakdown of where the sensors were installed by type and condition. This table shows the variety of sensors installed around the state and variety of dams which were chosen for monitoring. Sensors were installed in the pool, usually near the dam, depending and the dam sensor were often installed in the outfall as well.

Reliability issues with the beta sensors continued to arise so a significant number were held in reserve as replacements. In addition, there was a significant cellular service costs associated with the sensors, to limit these extraneous costs and to ensure sufficient coverage for the study, not all sensors were installed.

5.1.1 Vandalism and Tampering

Based on experience with the alpha sensors, a few modifications were made when deploying the beta sensors. All the external antennas were attached using blue thread locking compound also known as, Loctite. This makes is more difficult to remove the antennas without the use of tools. Additionally, a label was applied to the sensor showing that is was for flood warning and giving contact information for DOW. Finally, to limit the concerns about surveillance, cameras were not installed on the sensors whenever possible. This was especially important with the Progeny sensors because it uses an off the shelf surveillance camera and it is very conspicuous on the sensor. These modifications mostly limited the vandalism issues.

5.1.2 Beta Sensor Evaluation

While using the sensors, each were evaluated for performance, reliability, and ease of use. The initial batch of sensors was formally evaluated for DHS and the results of this evaluation are contained in Appendix D.

The beta sensors were evaluated during use and the results are documented in the following sections.

5.1.2.1 Progeny Sensors

DOW received 38 sensors from Progeny Systems, 19 of the sensors had both cellular and satellite telemetry, while 19 had only cellular telemetry. Based on the ease of installation these were the primary sensors installed in the follow-on tests. The node was attached to uni-strut channel which is then attached in any variety of manners. The pressure transducer is a small two-inch square part with a mounting hole. These were attached to a standard eight-inch hollow concrete block to secure the sensor.

After initial installation of the Progeny beta sensors, DOW began to experience a significant failure rate. Of the 38 sensors, eight sensors failed within weeks of being activated. One of these may have failed to physical damage. Assuming one sensor failed due to physical damage, seven failed sensors out of 38 gave an 18% failure rate.

Table 6 Follow on Sites (As of 9/30/2020)

	Name	County	Owner	Hazard Potential	Assessed Condition	Progeny	Evigia	Intellisense	Common Name
1	Berea Reservoir	Madison	Berea College	H	POOR		1		
2	Boltz Lake Dam	Grant	Commonwealth of Kentucky	H	POOR		1		
3	Bullock Pen Lake Dam	Grant	Commonwealth of Kentucky	H	POOR	1	1		
4	Clements Lake Dam	Rowan	Commonwealth of Kentucky	H	FAIR	1			Eagle Lake
5	Corinth Lake Dam	Grant	Kentucky Transportation Cabinet	H	POOR		1		
6	Duncan Nave Dam	Jessamine	City of Nicholasville	H	POOR	2			Lake Mingo
7	Guist Creek Lake Dam	Shelby	Commonwealth of Kentucky	H	POOR	1			
8	Lake Reba Dam	Madison	City of Richmond	H	FAIR		1		
9	Martin Cnty Water Dist No 1 Dam	Martin	Martin County Water District	H	FAIR	2	1	1	Curtis Crum
10	Mitchell Hill Lake Dam	Jefferson	Louisville Metro Parks	H	POOR		1		Tom Wallace Lake
11	Olive Hill Reservoir Dam	Carter	City of Olive Hill	H	FAIR	1			
12	Red Lick Creek Mps 1	Madison	Berea Municipal Utilities	H	POOR		1		
13	Renfro Dam	Rockcastle	Kentucky Transportation Cabinet	H	POOR		1		
14	Taylor Fork Lake Dam	Madison	Madison County Fiscal Court	H	POOR		1		
15	Valley Creek Frs 12 – Buffalo Lake	Hardin	City of Elizabethtown	H	FAIR	1			
16	Valley Creek Frs 3 – Trooper Lake	Hardin	City of Elizabethtown	H	FAIR	1			
17	Valley Creek Frs 8 – Valley Lake	Hardin	City of Elizabethtown	H	FAIR	1			
18	Valley Creek Mps 4 - Freeman Lake	Hardin	City of Elizabethtown	H	SATISFACTORY	2			
19	Willisburg Lake Dam	Washington	Commonwealth of Kentucky	H	POOR	1			
20	Wood Creek Lake Dam	Laurel	Kentucky Transportation Cabinet	H	FAIR		1		
21	Game Farm (Upper)Dam	Franklin	Commonwealth of	S	POOR	2			Sportsmans Lake

			Kentucky						
22	Lake McNeely Dam	Jefferson	Commonwealth of Kentucky	S	POOR		1		
23	Lake Sympson Dam	Nelson	Commonwealth of Kentucky	S	POOR		1		
24	Long Run Park Lake Dam	Jefferson	Louisville Metro Parks	S	POOR		1		
25	Smokey Valley Dam	Carter	Commonwealth of Kentucky	S	POOR				
26	Williamstown Lake Dam	Grant	City of Williamstown	S	FAIR				
27	Williamstown Reservoir Dam	Grant	City of Williamstown	L	POOR				
28	Barren County - Low Water Crossings	Barren	Barren County High School	S	n/a				
29	Louisville Metro - Pluvial Flood Locations	Jefferson	Metropolitan Sewer District	S	n/a				
30	Marion County Sportsman Dam	Marion	Commonwealth of Kentucky	H	POOR		1		
31	Cedar Creek Dam	Lincoln	Commonwealth of Kentucky	H	POOR		1		
32	Fagan Branch Reservoir Dam	Marion	Lebanon Water Company	H	SATISFACTORY		1		
33	Lake Luzerne Dam	Muhlenberg	City of Greenville	H	UNSATISFACTORY		1		
34	Rice Lake Dam	Lincoln	City of Stanford	H	UNSATISFACTORY	1			
35	Liberty Reservoir Dam	Casey	City of Liberty	H	FAIR	1			
36	Campton Lake Dam	Wolfe	City of Campton	H	FAIR		1		
37	Pigeon Roost Creek MPS 1	Jackson	City of McKee	H	FAIR		1		Upper Mckee Reservoir
38	Tyner Lake Dam	Jackson	Jackson Co Water Association	H	FAIR		1		Lake Beulah Removed due to vandalism
39	Lake George	Crittenden	City of Marion	M	FAIR		1		
40	Providence City Lake	Webster	City of Providence	M	FAIR		1		
41	Beech Creek Dam	Clay	KDFWR	H	FAIR		1		Burt Combs Lake
42	Beech Fork Dam	Powell	Beech Fork Water District	H	SATISFACTORY		1		
43	Greenbriar Lake	Montgomery	City of Mt Sterling	S	FAIR		1		Mt Sterling Dam
44	Elkhorn Lake	Letcher	City of Jenkins	H	POOR		1		
						18	27	1	

One possible issue that arose with the sensors during testing was water infiltration into the telemetry node. Visually the nodes appeared very well sealed however regular inspections showed significant condensed moisture inside the units. Based on when and the weather conditions during which the sensors were installed, the moisture did not appear to be due to temperature and dewpoint changes.

Working with Progeny, identified a possible cause for the moisture issue. A field update was issued that was applied to the sensors. This involved using RTV sealant to seal two small pinholes in the camera connection. After applying this fix, moisture issues were still prevalent in the sensors. The team was unable to reach a conclusion as to whether the moisture was the cause of sensor failure or it was due to other causes.

Progeny supplied cameras for all their sensors. However, these sensors were installed without cameras in most cases because our use case did not require photography. The cameras for the Progeny sensors were large surveillance style cameras and DOW was concerned these cameras can draw undue attention to the sensor in rural areas.

5.1.2.2 Evigia Sensors

DOW received 131 sensors from Evigia. There were challenges encountered installing the Evigia sensors, so these were not widely installed during the initial follow on tests. These units demonstrated a difficulty with securing the pressure transducer under water. The pressure transducers for the Evigia units consisted of a section of pipe. There were no built-in mounting provisions. The suggested mounting method included hose clamps to secure the sensor to an object in the water. This object can be a post driven into the bed of the water source or a stand secured with sandbags. These methods required personnel to enter the water which created unnecessary safety risks.

The mounted node for the Evigia sensors was simplified due to the integral mount that held both the solar panel and the node on the single mounting bracket. The node for the Evigia units was completely factory sealed and had no provisions for external antennas. This was a great benefit for both durability and limited the theft of antennas that was a prevalent problem. DOW did not find any degradation in cellular receptions from the use of internal antennas.

DOW also experienced multiple failures modes with the Evigia sensors. Most of the failures experienced were firmware related and where fixed with firmware patches. Firmware updates cannot be performed locally by DOW, so all the sensors had to be shipped back to Evigia multiple times.

The first firmware issue caused the units to stop reporting water level. This was easily fixed by restarting the node; however, this required a person to physically disconnect and reconnect the power to cycle the unit. The firmware update for this can automatically restart the unit if it quit reporting water level.

The second update was not directly related to Evigia but was an issue with the cellular modems that were used. These required an update, or the modem will completely fail after a set period due to a clock issue.

The third required firmware update was regarding the pressure and temperature sensors inside the node. The update was essential for the sensors to continue functioning.

An interesting specification of the Evigia cameras came to light during the troubleshooting process. The cameras included their own cellular modem and transmit the photos on a separate signal from the sensor data. This was done so that the sensor readings are not slowed down while photos are transmitted. This process seems to work well, and no issues were encountered. This is something DOW must keep in mind if Evigia sensors are used in the future, as the additional cellular modem will increase monthly data charges if paid on a line-wise basis (as compared to paid simply on data usage).

5.1.2.3 Intellisense Sensors

DOW received two additional Intellisense sensors in June 2020. These were final manufacturing prototypes and were considered production ready sensors. As with the earlier sensors from this vendor these sensors were very reliable and accurate. The mounting brackets had multiple options for mounting. After mounting the bracket, the sensor was attached and can be locked to the bracket to limit tampering and theft. These have an external antenna that can be removed, as with other sensors with external antennas, blue thread locker was used to limit the ability to tamper with the antennas.

These sensors took a different approach to weather protection. Instead of completely sealing the electronics, these had openings on the bottom to allow water to drain and were sealed on the top to prevent rain from entering the sensors. The electronics were exposed to atmospheric humidity. More time is required to determine if this influences the long-term durability of the electronics. If the sensors were used in coastal, salty environment, or in an area with high traffic (such as stormwater-related situations), based on DOW's observations there can likely be a detrimental effect on the sensors.

6 Conclusions and Future Work

Based on numerous, documented reliability and installation issues, DOW was not able to fully implement a statewide early dam warning system. However, this is still a priority for DOW, and the agency is actively pursuing this goal via a FEMA Hazard Mitigation Grant Program (HMGP) application. The statewide warning system will include a single dashboard that allows users with various agencies to view current and historical water levels at the monitored dams in Kentucky. In addition, the users may subscribe to alerts when water levels reach a certain threshold or water level change is detected that surpasses a given rate.

In a future phase, DOW is planning to evaluate more low-cost commercial sensors and to work directly with Intellisense to test their production sensors. DOW will also leverage research conducted on other commercial water level sensors that are priced competitively with the sensors tested in this program. Based on the historical usage of these sensors, DOW expects to see higher reliability and equivalent accuracy to what was encountered in the project.

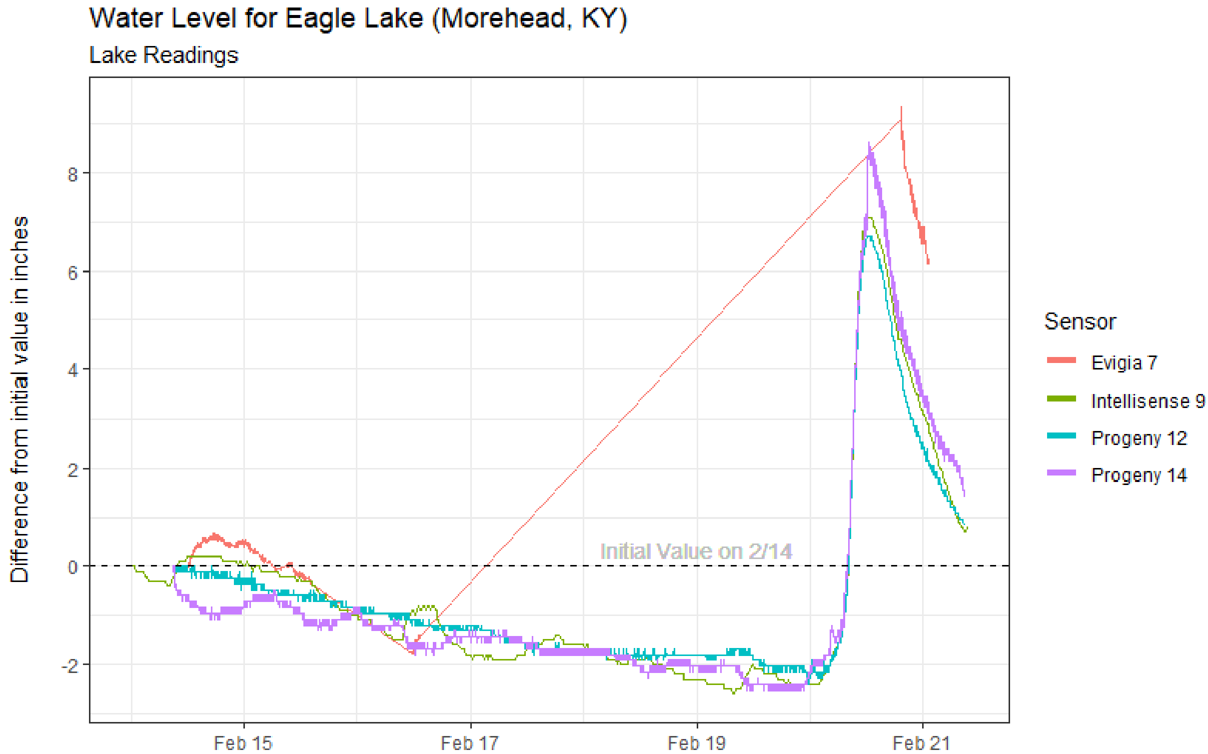
DOW plans to migrate to the OneRain Contrail platform for data management. This robust platform monitors the sensors and publicly publishing select data. This will fill the needs of DOW's statewide early warning system and allow for a central platform that can monitor sensors from various vendors in a single web location. The initial investment and maintenance of a single platform is costly and can require more IoT sensor testing prior to implementation; therefore, DOW will need a dependable network of sensors.

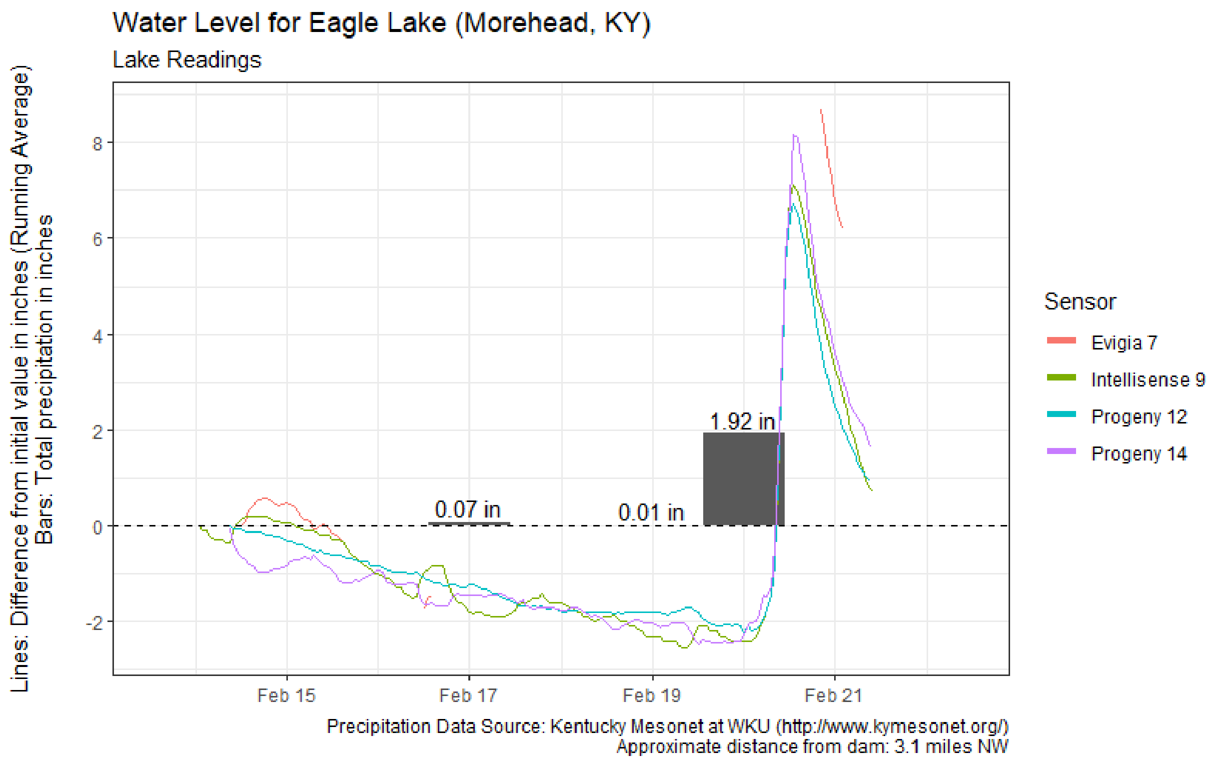
Further, DOW desires to continue to implement warning sensors for differing use cases including levees, low water crossings, and municipal stormwater applications to address pluvial flooding.

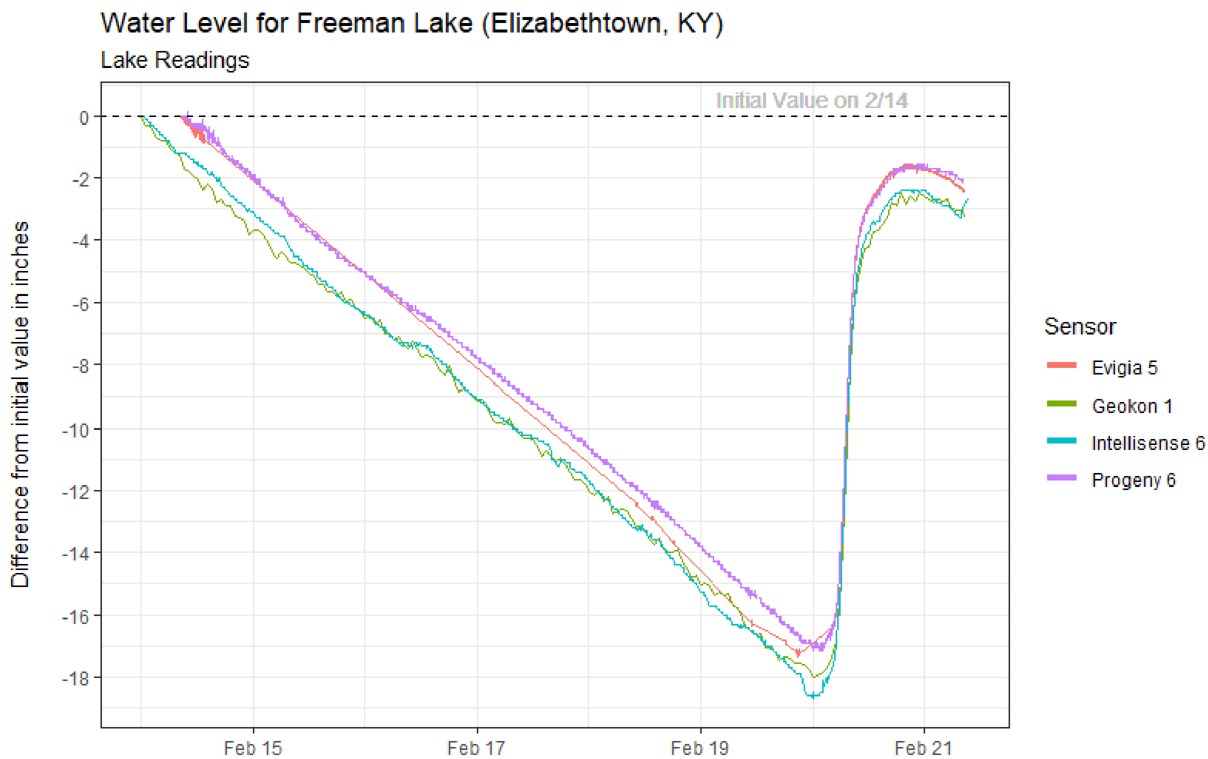
Similarly, DOW aims to extend the opportunity for sensor installation and warning systems to communities for sponsorship, operations and maintenance. Varying sized communities have been identified each of which have a local champion needed for successful execution:

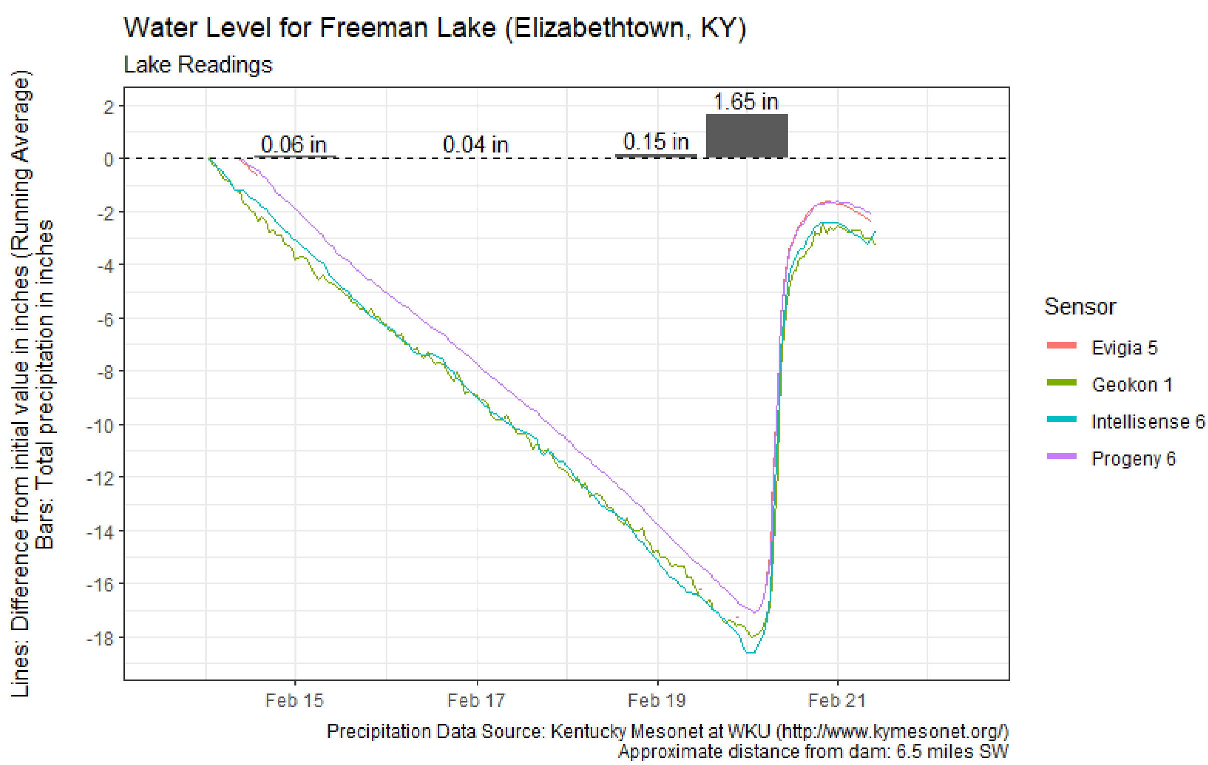
- Louisville/Jefferson County Metropolitan Sewer District (large)
- Elizabethtown (medium)
- Olive Hill (small)
- Barren County High School (very small)

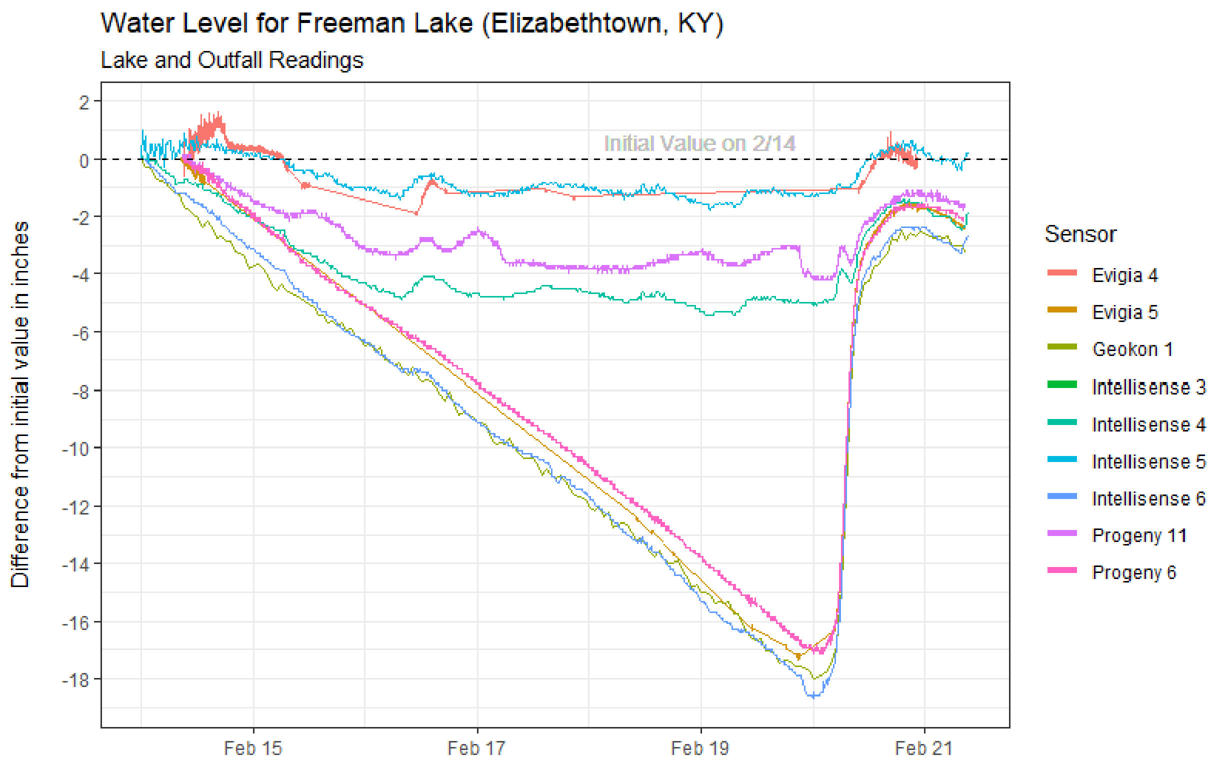
Appendix A – Sample Data Plots

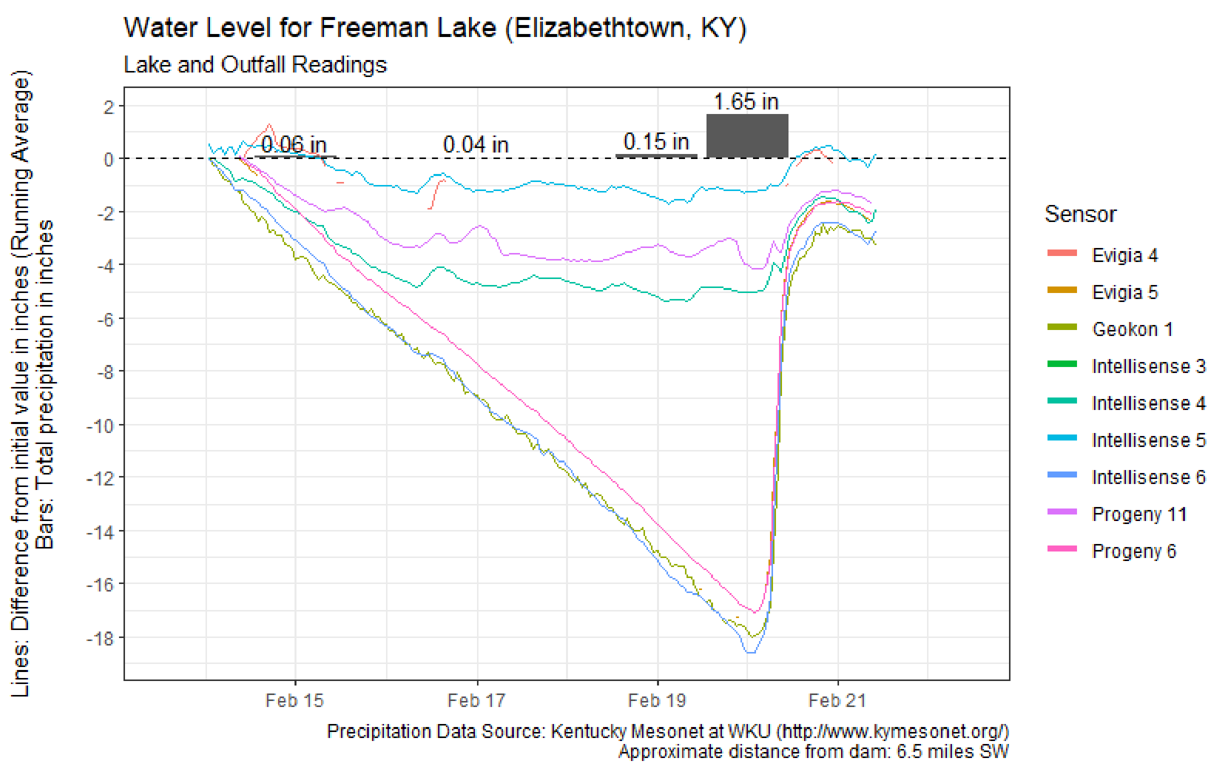


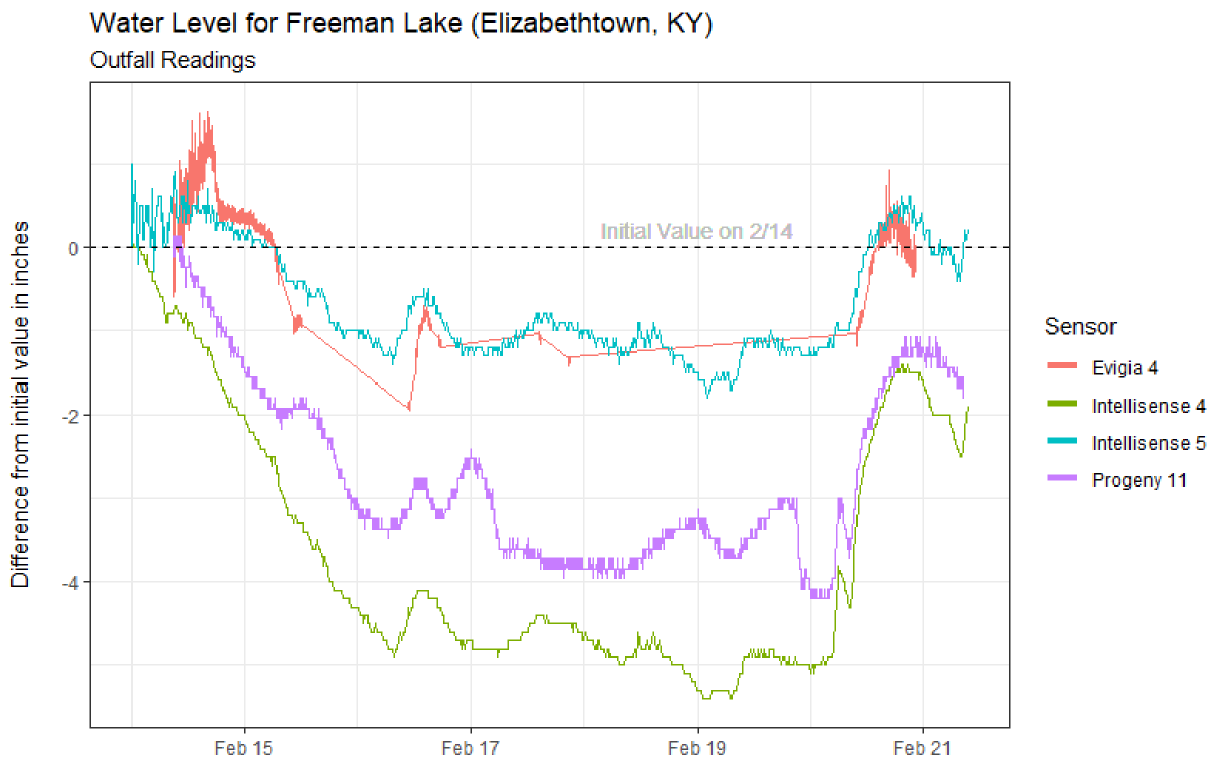



Water Level for Freeman Lake (Elizabethtown, KY)
Lake Readings
Initial Value on 2/14
Difference from initial value in inches
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 5
Geokon 1
Intellisense 6
Progeny 6

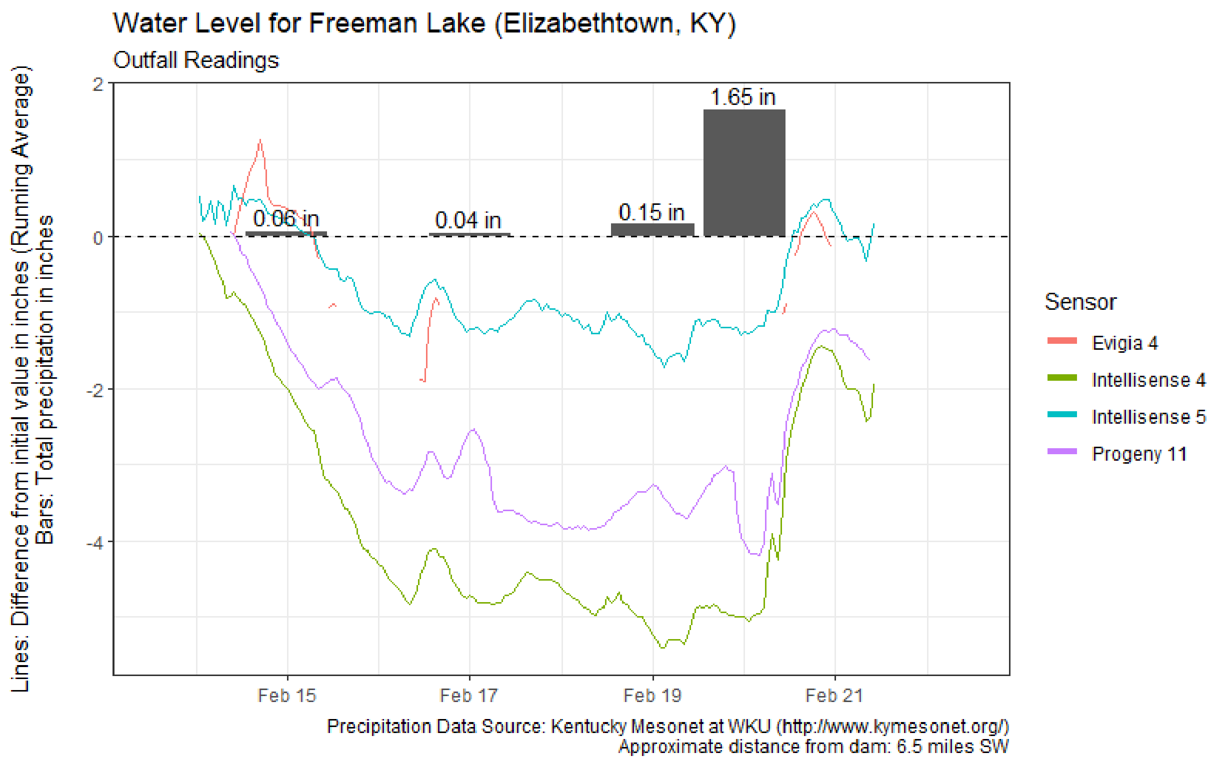

Water Level for Freeman Lake (Elizabethtown, KY)
Lake Readings
Lines: Difference from initial value in inches (Running Average)
Bars: Total precipitation in inches
0.06 in
0.04 in
0.15 in
1.65 in
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 5
Geokon 1
Intellisense 6
Progeny 6
Precipitation Data Source: Kentucky Mesonet at WKU (http://www.kymesonet.org/)
Approximate distance from dam: 6.5 miles SW


Water Level for Freeman Lake (Elizabethtown, KY)
Lake and Outfall Readings
Initial Value on 2/14
Difference from initial value in inches
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 4
Evigia 5
Geokon 1
Intellisense 3
Intellisense 4
Intellisense 5
Intellisense 6
Progeny 11
Progeny 6

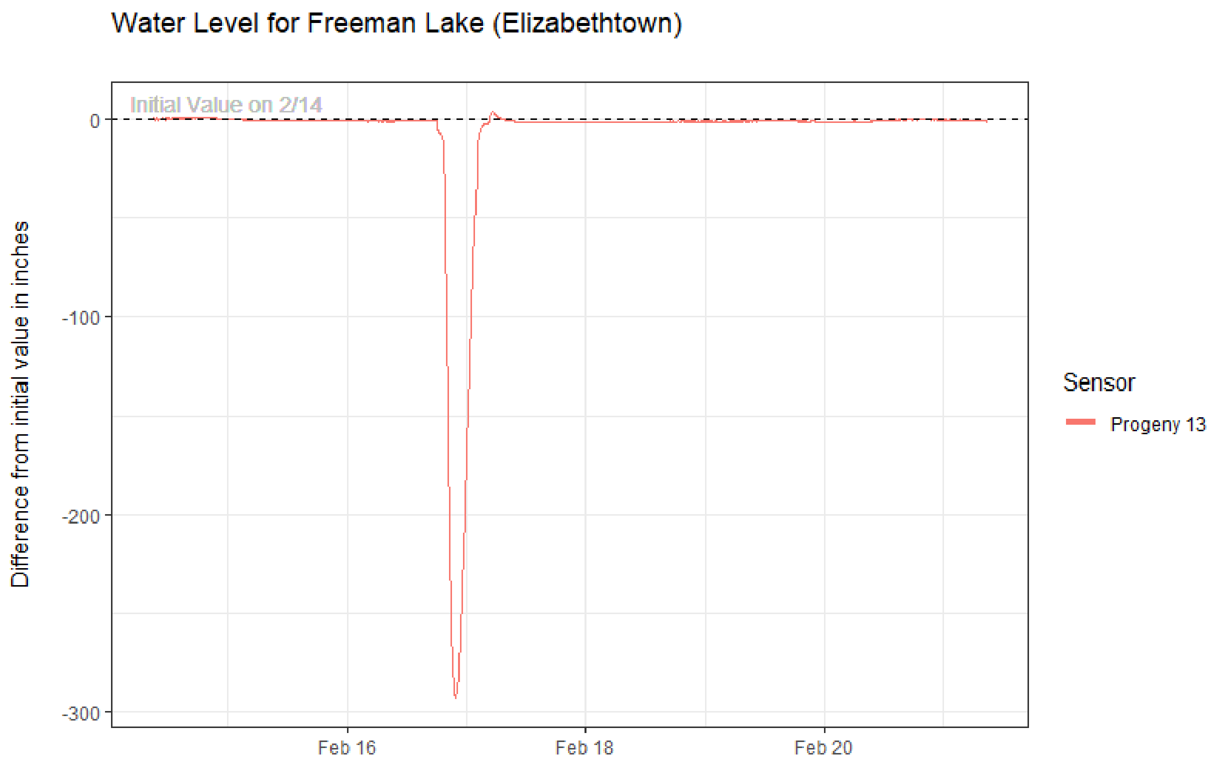

Water Level for Freeman Lake (Elizabethtown, KY)
Lake and Outfall Readings
Lines: Difference from initial value in inches (Running Average)
Bars: Total precipitation in inches
0.06 in
0.04 in
0.15 in
1.65 in
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 4
Evigia 5
Geokon 1
Intellisense 3
Intellisense 4
Intellisense 5
Intellisense 6
Progeny 11
Progeny 6
Precipitation Data Source: Kentucky Mesonet at WKU (http://www.kymesonet.org/)
Approximate distance from dam: 6.5 miles SW



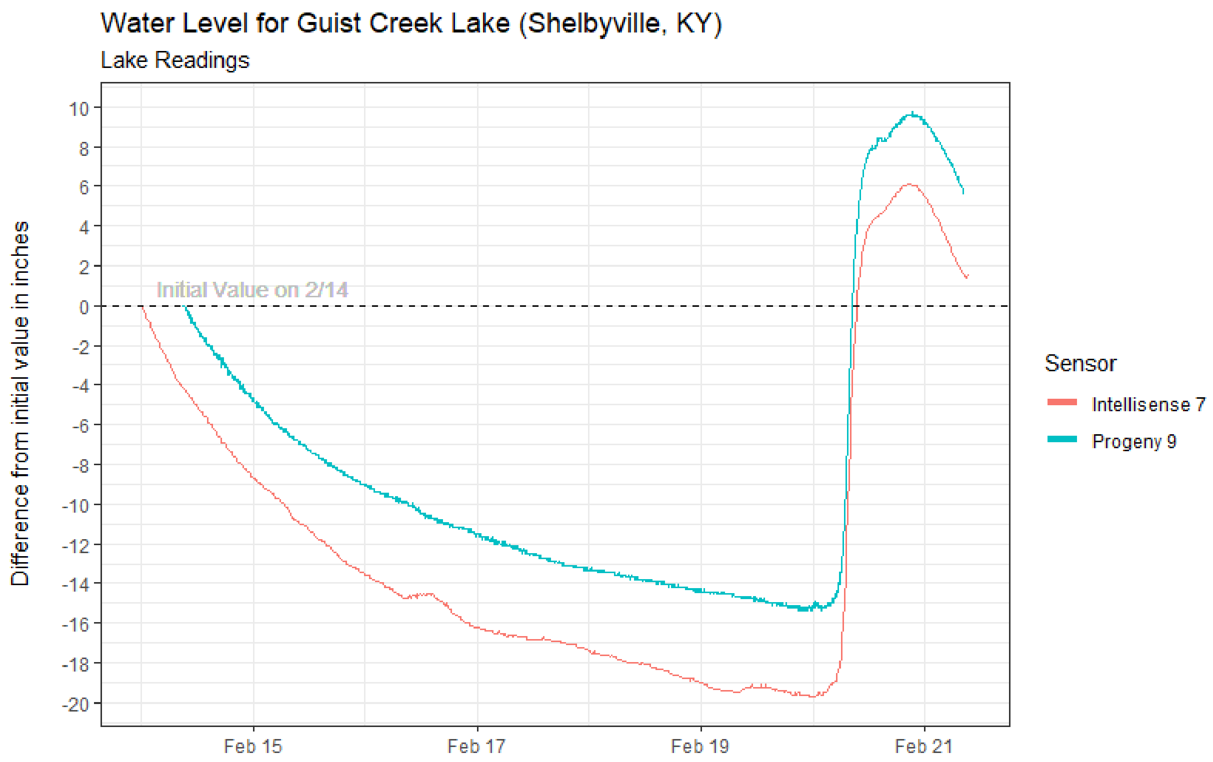
Water Level for Freeman Lake (Elizabethtown, KY)
Outfall Readings
Initial Value on 2/14
Difference from initial value in inches
0
-2
-4
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 4
Intellisense 4
Intellisense 5
Progeny 11



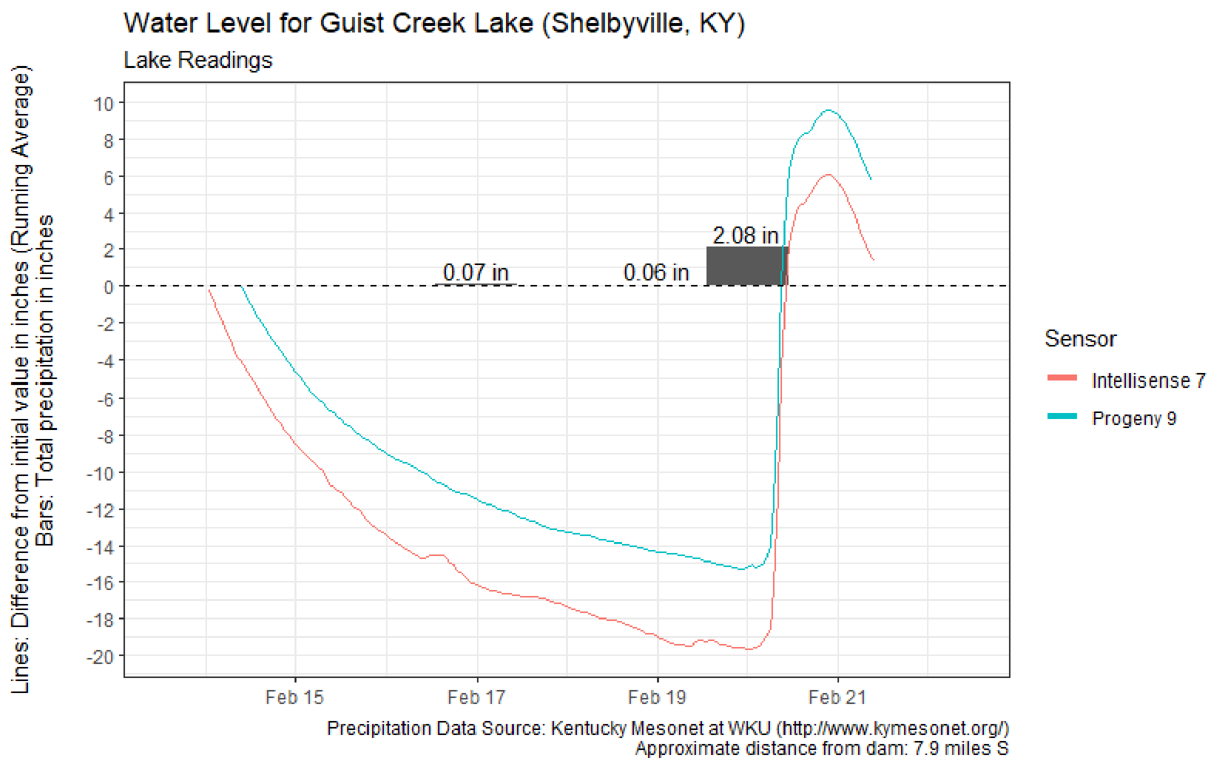
Water Level for Freeman Lake (Elizabethtown, KY)
Outfall Readings
Lines: Difference from initial value in inches (Running Average)
Bars: Total precipitation in inches
2
0
-2
-4
0.06 in
0.04 in
0.15 in
1.65 in
Feb 15
Feb 17
Feb 19
Feb 21
Precipitation Data Source: Kentucky Mesonet at WKU (http://www.kymesonet.org/)
Approximate distance from dam: 6.5 miles SW
Sensor
Evigia 4
Intellisense 4
Intellisense 5
Progeny 11

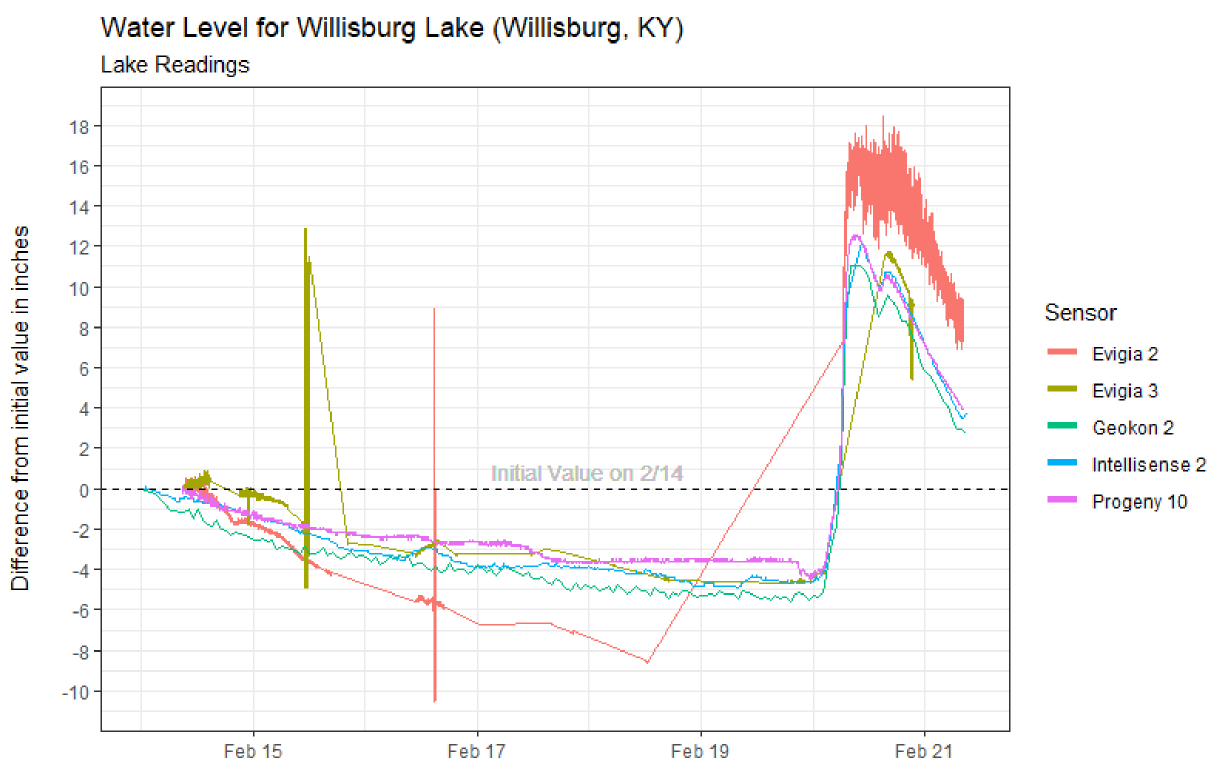


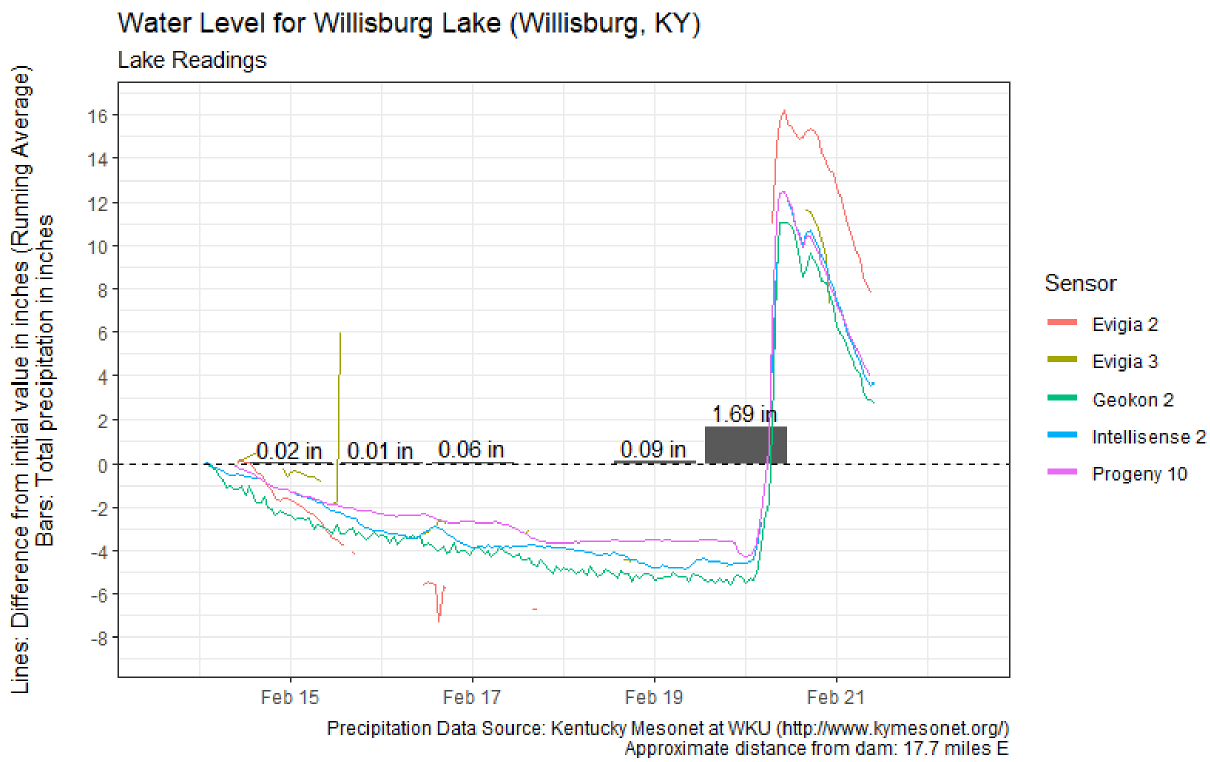
Water Level for Freeman Lake (Elizabethtown)
Initial Value on 2/14
0
-100
-200
-300
Difference from initial value in inches
Feb 16
Feb 18
Feb 20
Sensor
Progeny 13



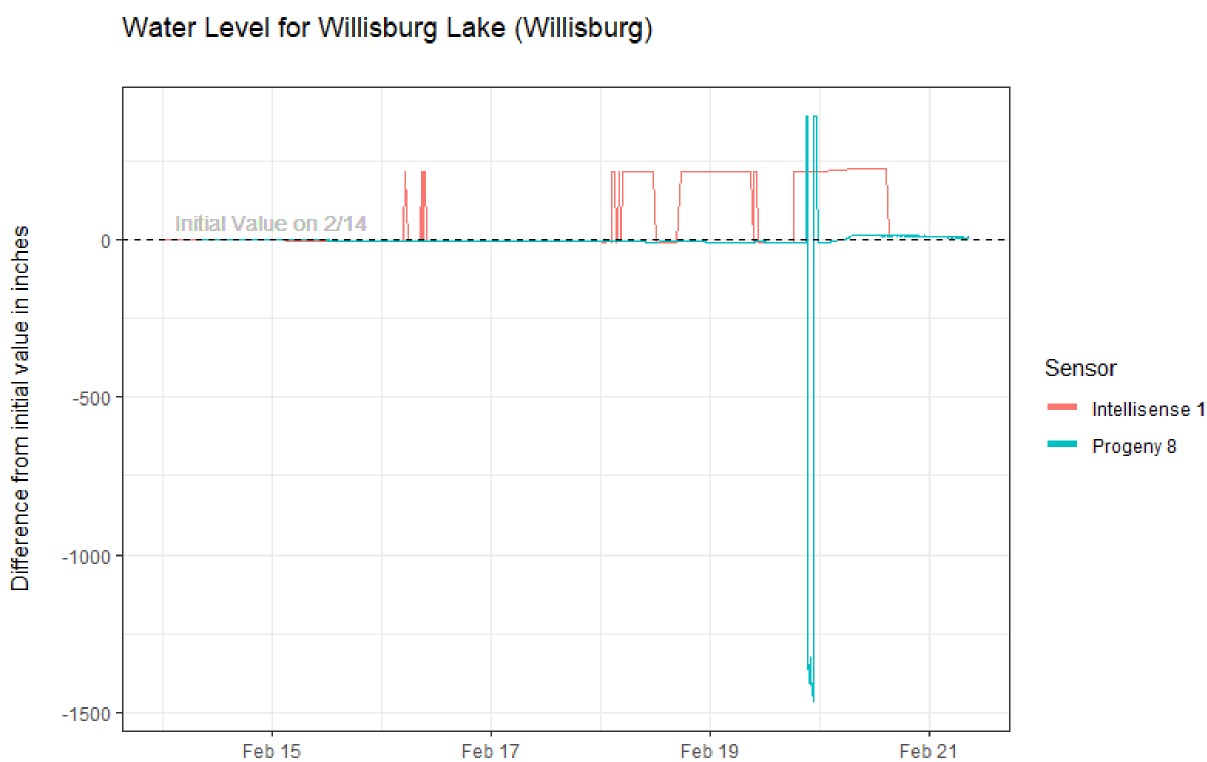
Water Level for Guist Creek Lake (Shelbyville, KY)
Lake Readings
Initial Value on 2/14
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Difference from initial value in inches
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Intellisense 7
Progeny 9


Water Level for Guist Creek Lake (Shelbyville, KY)
Lake Readings
Lines: Difference from initial value in inches (Running Average)
Bars: Total precipitation in inches
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0.07 in
0.06 in
2.08 in
Feb 15
Feb 17
Feb 19
Feb 21
Precipitation Data Source: Kentucky Mesonet at WKU (http://www.kymesonet.org/)
Approximate distance from dam: 7.9 miles S
Sensor
Intellisense 7
Progeny 9


Water Level for Willisburg Lake (Willisburg, KY)
Lake Readings
Difference from initial value in inches
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
Initial Value on 2/14
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 2
Evigia 3
Geokon 2
Intellisense 2
Progeny 10



Water Level for Willisburg Lake (Willisburg, KY)
Lake Readings
Lines: Difference from initial value in inches (Running Average)
Bars: Total precipitation in inches
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
0.02 in
0.01 in
0.06 in
0.09 in
1.69 in
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Evigia 2
Evigia 3
Geokon 2
Intellisense 2
Progeny 10
Precipitation Data Source: Kentucky Mesonet at WKU (http://www.kymesonet.org/)
Approximate distance from dam: 17.7 miles E



Water Level for Willisburg Lake (Willisburg)
Difference from initial value in inches
0
-500
-1000
-1500
Initial Value on 2/14
Feb 15
Feb 17
Feb 19
Feb 21
Sensor
Intellisense 1
Progeny 8

Appendix B – Sensor Installation Photos

Evigia Sensor at Willisburg Lake

Evigia Sensor at Feeman Lake

Intellisense Sensor at Willisburg Lake

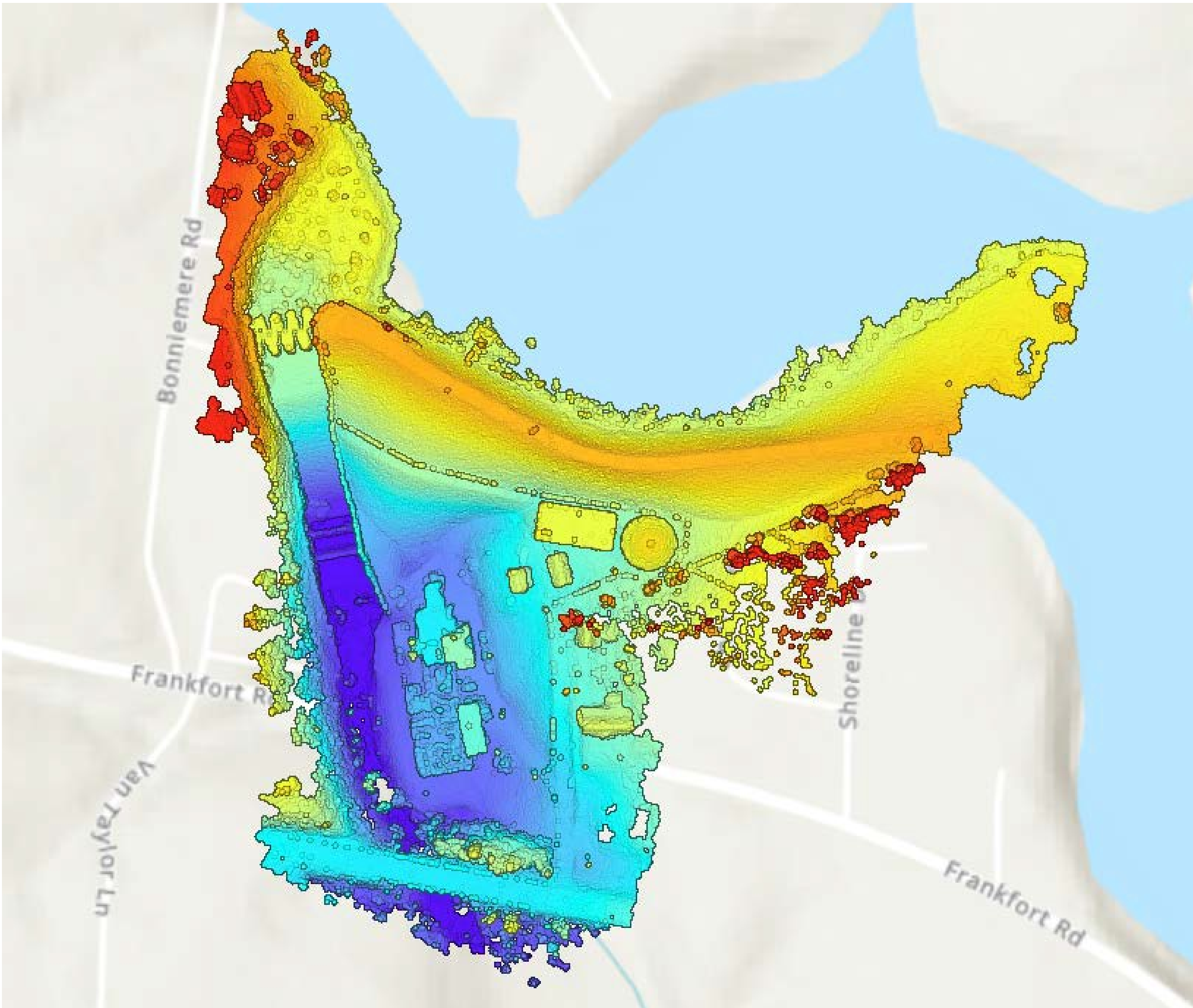
Intellisense Sensors at Freeman Lake

Progeny Sensor at Freeman Lake

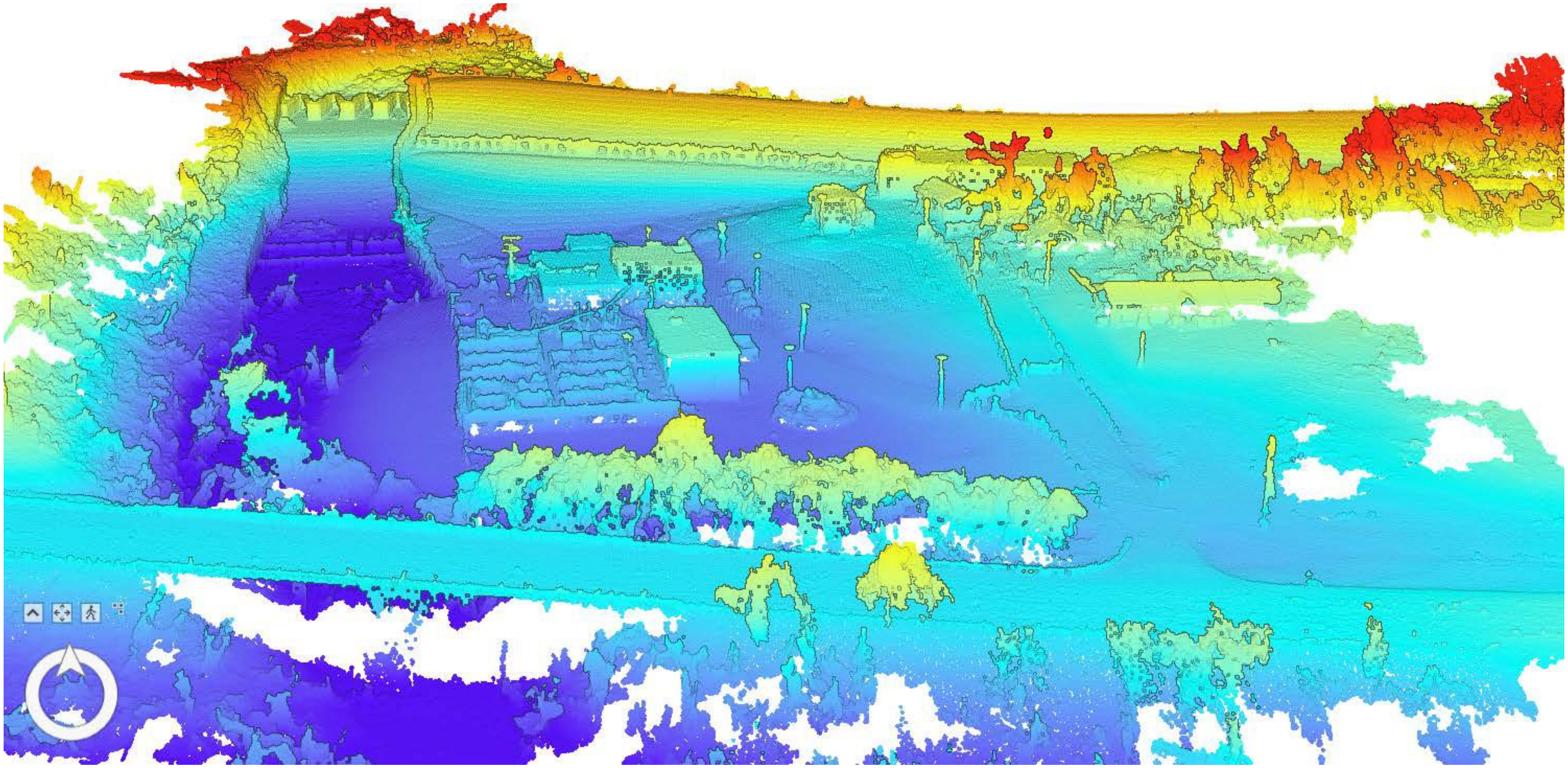
Progeny Sensor at Freeman Lake

Appendix C – Drone Data Samples

Triangulated Irregular Network (TIN) data developed from drone flight at Guist Creek Dam

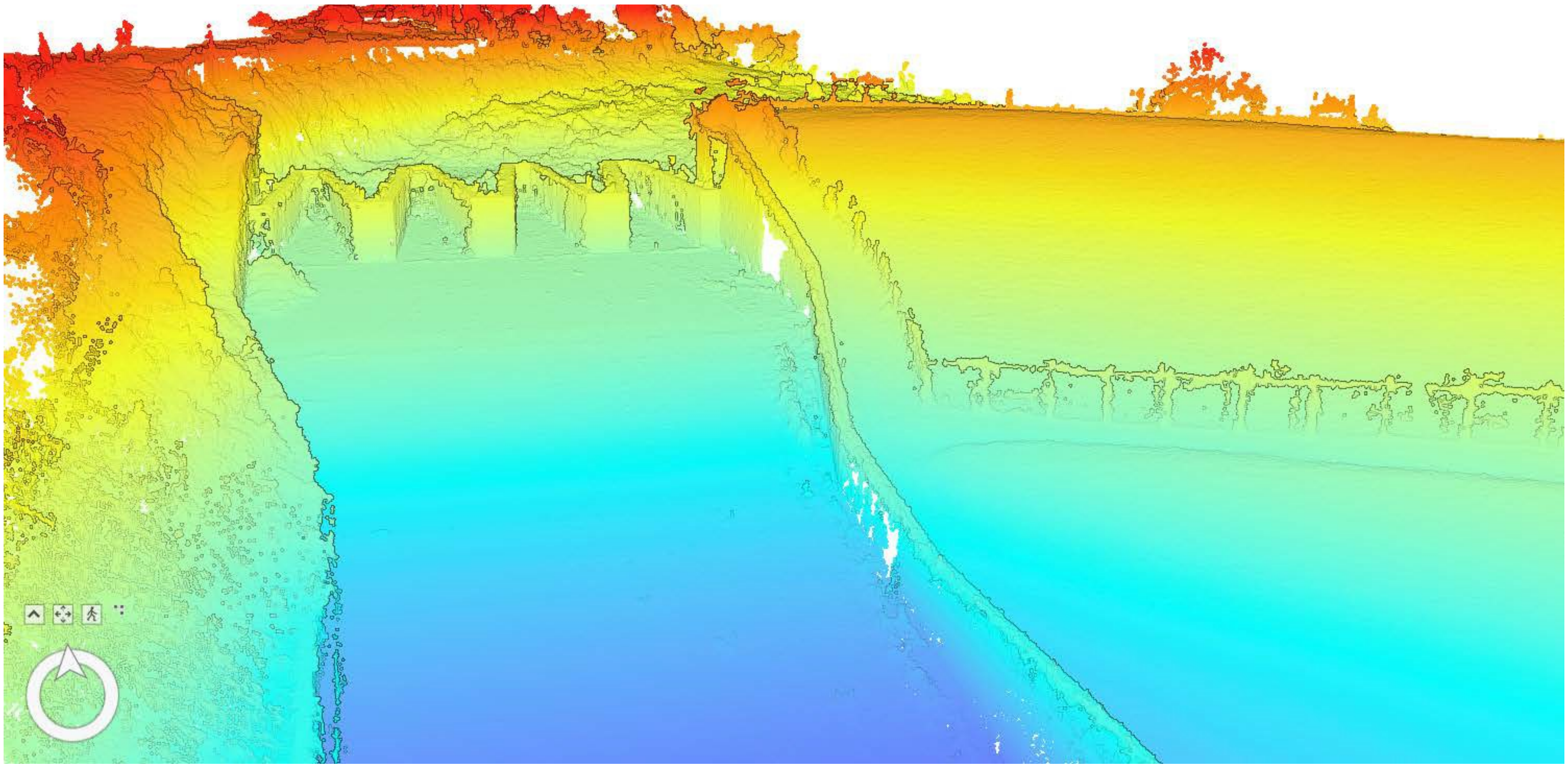


LIDAR data showing elevation from drone flight of Guist Creek Dam



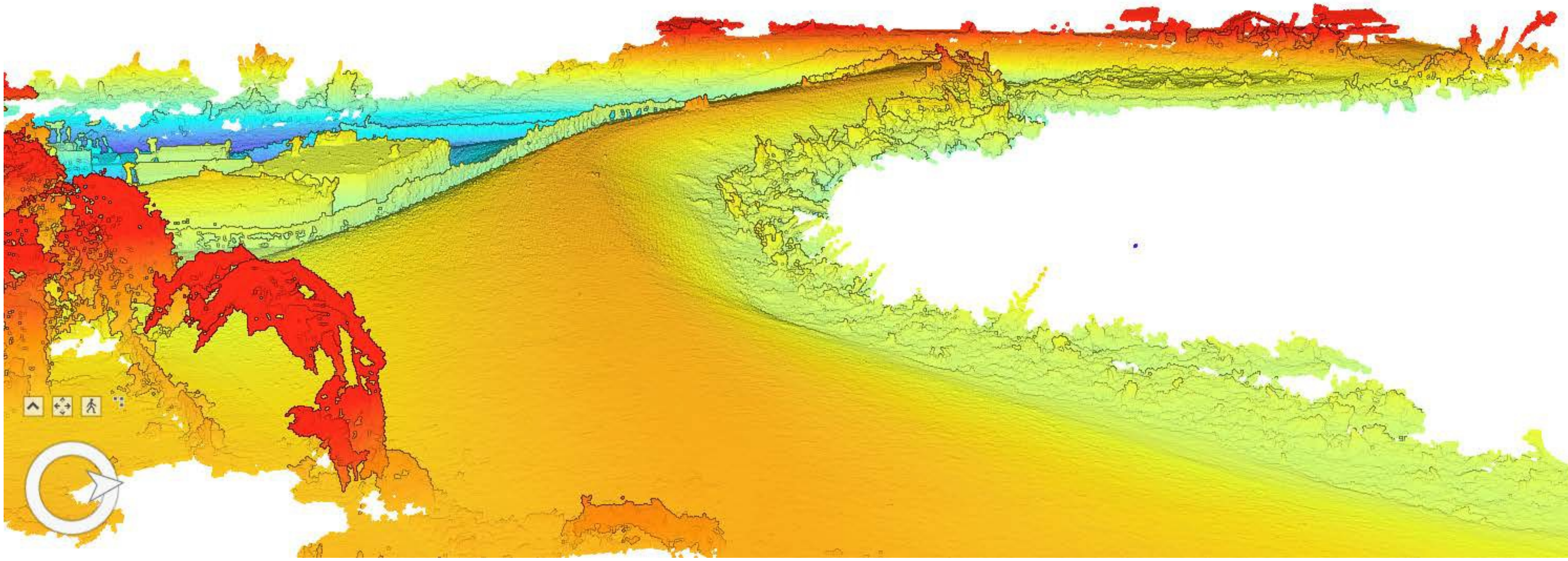
3-d representation of LIDAR data from drone flight of Guist Creek Dam

Representation of LIDAR data colorized from imagery from drone flight of Guist Creek Dam



3-d representation of LIDAR data from drone flight of Guist Creek Dam

Representation of LIDAR data colorized from imagery from drone flight of Guist Creek Dam



3-d representation of LIDAR data from drone flight of Guist Creek Dam

Representation of LIDAR data colorized from imagery from drone flight of Guist Creek Dam

Also see: Bathymetric Survey of Curtis Crum Lake - https://storymaps.arcgis.com/stories/f62f3a85ca2c468786be688bf7847c2e

Appendix D – Definitions for monitoring equipment

Seepage Weirs

Weirs can be used to monitor seepage from existing toe drains in dams. Two types of weirs were evaluated: (1) a box-type weir that can be placed downstream of a toe drain outlet pipe and (2) a weir that fits inside a pipe. Where there is not enough fall to install a box below an outlet pipe, a weir that fits inside a pipe would allow for flow measurement. Automation of either type of weir can be accomplished by installing a low-pressure transducer in the pool below the weir notch that can measure pressure and calculate depth of water. This can then be used to determine water height through the weir notch and corresponding flowrate. Monitored over time, this information coupled with pool level information will give useful trend information related to seepage rates. Data recorded that varied from this trend can then be cause for investigation.

Flow Monitors

Flow monitors can be used in lieu of weirs to measure flow from existing toe drains in dams. Automated flow monitors collect depth and velocity data to calculate flow through a pipe.

Soil Extensometers

Soil extensometers are installed in series to measure strain in earthen dams. Soil extensometers are manufactured with flanges on both ends which can be bolted together to form a string of sensors which can provide profiles of deformation. These can be installed in a shallow trench along the crest of the dam in locations where deformation can be likely, such as along the outlet conduit. If deformation is observed, it can be due to internal erosion along the conduit which can then be further investigated.

Vibrating Wire Piezometers

Vibrating wire piezometers can be installed in existing open standpipe piezometers at dams. Various diameters are manufactured to fit open standpipes with diameters as small as three-quarter inch. A cable transmits the signal from the vibrating wire piezometer to a readout box. For typical installations, cables from multiple piezometers are trenched to a single readout location. If action and/or threshold levels are established (e.g. Factor of Safety is less than 1.0 at a Piezometric Head of 10 feet), this gives a means to monitor for this condition in real-time as well as review trends over time, related to pool level. Data recorded that varied from this trend can then be cause for investigation.

In-Place Slope Inclinometers

In-place inclinometers can be installed to automate existing slope inclinometers at dams. A cable transmits the signal from the inclinometers to a readout box. The in-place inclinometers hang in the existing inclinometer casing with sensors typically spaced at five-foot intervals. The cables from the sensors can be trenched to the readout box. This can provide real-time information on slope movement and be used to evaluate trends over time. Data recorded that varied from this trend can then be cause for investigation.

Low-Pressure Transducers

Low pressure transducers can be used to monitor pool levels. These can be used to monitor the upstream pool, downstream pool, or to automate weir measurements. Notifications can be established for critical pool elevations such as emergency spillway elevation, top of crest, etc.

Notifications can also be set for changes in pool to alert rapid pool loss which can warrant an inspection. A cable transmits the signal to a readout box. The pressure transducers can be attached to a structure, installed in a sacrificial PVC pipe for protection.

IoT Flood Sensors

DHS S&T as the initiative sponsor, has established three (3) Small Business Innovative Research (SBIR) contracts to design, develop, deploy, test, evaluate and deliver operational Internet of Things (IoT) low-cost flood inundation sensors. DHS S&T intends to foster the successful commercialization of the flood sensor vendors (e.g. 3 SBIR companies) by working with stakeholders (e.g. State and local governments) to test and evaluate the sensors in operational field deployments over approximately six (6) months in 2018-2019.

Fiber Optic Sensing

Cleveland Electric Laboratories (CEL) reached out to DHS to discuss their instrumentation capabilities. Their technology was reviewed, and the information monitored by the instruments noted above can also be captured using sensors with fiber optic transmission. According to CEL, there are some benefits to fiber optic in that multiple sensors can transmit data on a single line, signal loss is less likely in fiber optic versus electric, and additional customization is available for data collection software.

One product that can monitor for deformation like soil extensometers is a geonet with fiber optic sensors embedded in the netting. This is manufactured by Tencate and is called GeoDetect. According to CEL, it has been used on tailings dams to monitor deformation under access roads. This product can be a viable option. It is installed under fill, so can be better suited for new dams but can be installed in a trench along the crest of existing dams.

Non-contact Water Level Sensors

Various methods exist for measuring water level without contact with the measured water. Two of the most common are via ultrasonic measurement and via radar measurement. These are reliable methods that have the added benefit of being mounted away from the water source. The units are mounted above the surface of the water and use ultrasonic or radar respectively to measure the distance from the sensor to the water. The ability to keep the sensors completely out of the water reduces maintenance issues that arise due to the harsh environment that moving water can cause. Sensors that are immersed in the water must have significant additional waterproofing and durability.

Drone

Drones (Unmanned aerial vehicles – UAVs) can serve multiple purposes for dam monitoring. Aerial images obtained from UAVs can be evaluated to identify green, lush areas which can indicate seepage in the area. A thermal camera can be used to identify seepage as well. Survey data obtained from a drone can be obtained as a baseline reading and then compared on a recurring interval to monitor for changes to the slopes and deformation indicating potential internal erosion or slope failures. Potential enhancements for “out of the box” drones include infrared and multispectral cameras.

Appendix E – Sensor Vendor Survey Results

Name of Stakeholder *	Kentucky Division of Water			
Organization *	Stantec			
Address *	3052 Beaumont Centre Circle, Lexington KY 40513			
Contact Name *	Katherine Osborne			
Contact Email *	katherine.osborne@stantec.com			
Contact Phone *	8594223047			
Vendor Evaluated *		**Intellisense**	**Evigia**	**Progeny**
Date of Survey *		02/11/2019	02/11/2019	02/11/2019
Shipping: See description to the right	Shipping: Stakeholder/Vendor engagement for shipping sensors to/from, the clear communication of shipping expectations, the arrival of contents and the effort needed			
2.1 Shipping: Vendor needed to ship additional sensor-related equipment post-initial site visit?	This is a Yes/No Question. For "No," select 1 For "Yes," select 4	4	1	1
2.2 Shipping: Vendor provided shipping info ahead of shipment (Tracking Number, # of expected pkgs, etc)	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	5	4	0
2.3 Shipping: Sensor Bill of Materials and all components were included?		4	3	0
2.4 Shipping: Shipment contents were damage-free?		5	5	0

2.5 Shipping: Stakeholder shipped sensors back to Vendor "x" times?	Zero" select 0 "Three times" select 1 "Twice" select 2 "Once" select 4	1	0	0
2.6 Shipping: Shipping sensors back to Vendor (coordination, boxing, securing, postage, etc) was straight-forward and required minimal effort.		4	0	0
Shipping: Pros				
Shipping: Cons				
Shipping: Comments		Bill of Materials not include in box but email communication alerted us of what to expect, all components included; Additional shipments - Freeman replacement sensors, Guist replacement sensor, and SDS concrete bit sent	Bill of Materials not include in box but email communication alerted us of what to expect, all components included	nothing shipped to us,
Shipping: Recommendations				
Documentation & Support: See description to the right	Documentation & Support: Vendor's documentation or instructions (user guides, videos, etc.) to provide stakeholder with clear/concise path forward (similar to receiving a commercial product via on-line provider). Support includes responsiveness via phone or email and resolution to the issues presented.	4	4	1
2.7 Doc. & Support: Vendor provided detailed, step-by-step	EVALUATION SCORING: (1) Strongly Disagree;	4	4	1

(written) instructions for installation, mounting, calibration, operational use and monitoring of sensors?	(2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A			
2.8 Doc. & Support: Vendor provided detailed, step-by-step (on-line, video, YouTube, etc.) instructions for installation, mounting, calibration, operational use and monitoring of sensors?		5	4	1
2.9 Doc. & Support: User Guide provided sufficient direction for an assured repeatable process?		5	5	1
2.10 Doc. & Support: If stakeholder performed field installation (or re-installation), sensor start-up sequence easily followed User Guide Documentation as described?		5	5	1
2.11 Doc. & Support: User Guide directions for all sensor functional operations were clear and concise?		5	5	1
2.12 Doc. & Support: Vendor provided adequate telephone support to remedy sensor questions/issues?		5	5	1
2.13 Doc. & Support: Data format documentation was provided in sufficient detail?		5	5	1
2.14 Documentation & Support: What additional Documentation (tools/support) does the		No written website user guide provided however, provider	None	

stakeholder need?		demoed website in person		
Documentation & Support: Pros		ppt, you tube video, and email/verbal communications		no documentation provided
Documentation & Support: Cons				
Documentation & Support: Comments			Installation guide provided	
Documentation & Support: Recommendations				
Vendor Website: See description to the right				
2.15 Website: Vendor provided website user account and detailed, step-by-step instructions for website access, use, Graphical User Interface (GUI), interpretation and data download.	Vendor Website: (Post installation) Stakeholder interaction with the sensors/sensor-data are likely via the Vendor-provided website. This section addresses the Vendor website's ease of use, information provided, data accessibility and ability to review the data in the stakeholder's software solution.	4	4	1
2.16 Website: Cloud/Website access was clear, concise, and easily implemented?		4	2	5
2.17 Website: Vendor website GUI was intuitive/easy to use?		4	2	5
2.18 Website: Website GUI allowed for easy identification and op status at all deployed sensor locations (e.g. map, working/not-working or power/no power)?		4	2	5
2.19 Website: The web GUI provides intuitive use of mapping software for navigating and		5	2	5

displaying of sensor data?				
2.20 Website: Sensor power strength (battery voltage, battery percentage, charging/not-charging status and interpretation of these data) was intuitive?		4	2	4
2.21 Website: Navigating website to data from multiple sensors was intuitive and easy to use?		4	2	5
2.22 Website: Comparison of sensor data (current/historical) was easily determined?		4	4	4
2.23 Website: Vendor website allowed data download and access to (current and historical) raw data?		4	4	4
2.24 Website: Vendor's GUI was intuitive and provided the data/information anticipated?		4	2	5
2.25 Website: Cloud/Website access to raw data was easily accessible?		5	2	2
2.26 Website: Raw data from Vendor's Sensor/Cloud/Website was displayed in stakeholder's software solution for viewing sensor data (i.e., Contrail)?		4	2	2
Vendor Website: Pros		map with labels, alerts visible, separate access to raw data provided, can change time	change the time, can download via excel; easily collect values from graph	map of location, clearly see those not functioning; short numbering; clickable to get

				to data; can change time;
Vendor Website: Cons		naming convention too long;	no map with labels or color coding, had to request key of sensor names, appears to be a data lag in reporting; appears to have false reporting (large spikes); times out often; no access to real time data	historical limited to a week
Vendor Website: Comments			ppt slides sent for instructions on using website, will allow access to change and set up alerts in future	
Vendor Website: Recommendations		Sensor selection to view graph in one click would be nice	interface could be more user friendly	a description with sensor name would be helpful
Field Installation: See description to the right	Field Installation: Stakeholder experience (effort, materials, etc) with installing, re-installing or taking			

	corrective actions with vendor's sensors. Field installation also refers to the grouping or bundle of sensors (e.g. Gateways and nodes making up the mesh network). Questions refer to all site locations (in general) as opposed to reporting on each individual sensor unit at each site location. Please use Pro/Con/Comment/Recommendations text box to highlight specific comments on sensor bundles.			
2.27 Field Installation: Specialized tools/materials required for installation?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	2	2	2
2.28 Field Installation: Vendor's website was accessible in the field?		4	4	4
2.29 Field Installation: Sensor security materials/measures were adequate for stakeholder-identified locations?		4	4	4
2.30 Field Installation: Sensor cameras were easy to install/align to desired direction and suitable for stakeholder's needs (Camera installs provided suitable/appropriate imagery)?		4	0	4
2.31 Field Installation: Sensor element (e.g., pressure		2	4	2, damage to sensor at guist

transducer) remained secured/stable between original installation and operational evaluation period?				
2.32 Field Installation: Sensor components (e.g. cable, antennas, pressure transducer, camera, etc.) were durable/flexible/functioning post-installation?		4	4	4
2.33 Field Installation: Vendor's return visit(s) resolved sensor functionality problems?		0	4	0
2.34 Field Installation: After sensors "fixes", sensors worked at what % / performance level?	0% select 1 25% select 2 50% select 3 75% select 4 100% select 5	5	5	N/A
2.35 Field Installation: Stakeholder performed sensor installations (without Vendors) and was able to install/operate successfully?		5	0	0
2.36 Field Installation: If stakeholder performed sensor installs or corrective actions, select the minimum number of stakeholder persons required to install one sensor.	"five people" select 1 "four people" select 2 "three people" select 3 "two people" select 4 "one person" select 5	4	4	4
2.37 Field Installation: If stakeholder performed installs/re-installs of sensors, select the Total number of stakeholder's person-hours required to install/re-install one sensor.	"more than four hours" select 1 "three-four hours" select 2 "two-three hours" select 3 "one-two hours" select 4 "less than one hour" select 5	5	5	0
2.38 Field Installation: What				

additional Field Installation tools/support/resources does the stakeholder need?				
Field Installation: Pros				
Field Installation: Cons		Guist sensor broke away from brick due to high velocity flow;		
Field Installation: Comments		No return visits made, new equipment mailed to stakeholder for install, 1 person could perform install but 2 needed for safety reasons, less than 1 hour install time not including travel time	Experiencing data gap issues, no installation performed without vendor,	Damage to sensor at Guist, reinstalls upcoming, no installation performed without the vendor,
Field Installation: Recommendations				
Power: See description to the right	Power: Sensor power is a key driver for the success of this project. Did the sensors maintain power to continue sending data to the Vendor's aggregation site?			
2.39 Power: Stakeholder noticed negatively impacted performance fluctuations during day/night and weather condition variations (cloudiness, hot/cold temps)?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	2	2	2
2.40 Power: For sensors whose batteries discharged, the batteries recharged during improved conditions and re-initiated on		0	0	0

their own to provide full sensor functionality?				
2.41 Power: Sensors maintained adequate power strength for sensor functionality, imagery capture/transmission and continuous reporting during the operational evaluation period?		4	0	
Power: Pros				
Power: Cons				
Power: Comments			No battery issues noted	No battery issues noted
Power: Recommendations				
Calibration: See description to the right	Calibration: There is a default calibration for Vendor sensors at installation. This section addresses the adequacy of those default calibration settings and the ability for the stakeholder to modify them.			
2.42 Calibration: Sensor default parameters were adequate for stakeholder needs?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	4	4	4
2.43 Calibration: Vendor documentation provided calibration procedures and/or future calibration instructions.		4	2	2
2.44 Calibration: Sensor 'triggers'		2	2	2

(sampling and reporting frequency) were tested and easily adjustable via the website?				
2.45 Calibration: If in-stream sensors were replaced/altered after the original installation, these sensors were installed with the same calibration values as those originally installed?		4	4	4
2.46 Calibration: Sensor accuracy was compared to higher order ("truth") sensor readings (e.g. USGS gage station or similar stakeholder-provided sensor)?		3	3	3
2.47 Calibration: If compared to higher order sensors, these sensors met stakeholder needs (accuracy, reporting freq., operational 'up-time', etc.) for a 'commercial-grade' sensor?		3	3	3
2.48 Calibration: Comments on sensor comparison to higher order sensors.		Unsure if this was performed	Unsure if this was performed	
Calibration: Pros		recalibration not required unless moved, triggers were set and tested successfully but unable to adjust on website		
Calibration: Cons				
Calibration: Comments			Triggers not yet	Triggers not yet

			implemented, planned after reinstall complete, Unsure if calibration with higher order was performed	implemented, planned after reinstall complete, Unsure if calibration with higher order was performed
Calibration: Recommendations				
Communications: See description to the right	Communications: Sensor communications across sensor nodes using radio/cellular frequency capabilities during the operational evaluation.			
2.49 Communications: Sensor antenna (default) proved sufficient between Gateway & Nodes for connectivity?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	3	4	4
2.50 Communications: Radio or cellular strength could be tested in the field in real-time during the evaluation period?		4	3	4
2.51 Communications: Cellular network across stakeholder sites demonstrated suitable signal strength during the evaluation period?		4	4	4
2.52 Communications: Radio network across stakeholder sites demonstrated suitable signal		0	0	0

strength during the operational evaluation period?				
2.53 Communications: Sensor network connectivity failover was tested during the operational evaluation period and results were adequate?		4	4	4
2.54 Communications: Sensor-to-sensor linear connectivity was proven adequate during operational period without need to add or replace radio nodes with cellular nodes?		0	4	4
2.55 Communications: In general, the sensor communications were operational approximately?	"0%" select 1 "25%" select 2 "50%" select 3 "75%" select 4 "100%" select 5	4	3	3
2.56 Communications: Stakeholder attempted a "swap" of deployed sensor comms in the field (radio node for cellular node or cellular node for radio node) during the op. eval period?		0	0	0
2.57 Communications: What additional Communications functionality/capabilities are needed by stakeholder?				
Communications: Pros				

Communications: Cons				
Communications: Comments		unsure if nodes are used,	were unable to test connectivity in real time,	
Communications: Recommendations				
Data & Transmission: See description to the right	Data & Transmission: Transmission of data from sensors and viewable by the Vendor's website (or by 3rd party website).			
2.58 Data & Transmission: Data default sampling/transfer rate was sufficient?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	4	3	4
2.59 Data & Transmission: Data sampling contained the format/elements needed by stakeholder?		4	4	4
2.60 Data & Transmission: Time period for historical data was adequate for stakeholder needs?		3	4	2
2.61 Data & Transmission: The data provided for each sensor was easily readable (units/displays) and provided what the stakeholder needed?		4	2	4
2.62 Data & Transmission: Data sampling/transfer rate was easily		2	4	2

modified remotely?				
2.63 Data & Transmission: Historical data for sensor was easily obtained (GUI/printout/export)?		4	4	4
2.64 Data & Transmission: Data viewing for historical data was adequate for stakeholder needs?		4	4	4
2.65 Data & Transmission: Data transmission was continuous (given sampling schedule) without any apparent data loss?		4	2	4
2.66 Data & Transmission: Data ingest to the stakeholder's sw solution (i.e., Contrail) from vendor's/sensor's environment was straightforward, timely and adequate for stakeholder's needs?		4	2	2
2.67 Data & Transmission: All needed data elements were displayed in the stakeholder's software solution (i.e., Contrail) from vendor/sensor environment?		4	2	2
2.68 Data & Transmission: What additional data format/elements are needed by stakeholder?			access to real-time data	access to real-time data
Data & Transmission: Pros				
Data & Transmission: Cons			readability difficult	

			because sensors are plotted on same graph, require manual selection, no access to real-time data,	
Data & Transmission: Comments		time period limited to a week,	appear to be delays or lags in data collection,	
Data & Transmission: Recommendations				
Capabilities: See description to the right	Capabilities: Sensors camera/imagery and GPS capabilities proved adequate for stakeholder needs.			
2.69 Capabilities: Camera provided image capture (frame/video) from remote location?	EVALUATION SCORING: (1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree; (0) N/A	4	2	5
2.70 Capabilities: Camera provided image capture (frame/video) "on demand"?		4	2	5
2.71 Capabilities: Camera resolution and field-of-view were acceptable?		4	2	5
2.72 Capabilities: Camera provided suitable quality for both day/night		4	2	4

image capture (frame/video)?				
2.73 Capabilities: Camera imagery (current and historic) was easily accessed and retrievable from the vendor's GUI and/or stakeholder's software solution?		4	2	4
2.74 Capabilities: GPS locational accuracy met stakeholder needs for locating sensor (via GUI and for field location)?		4	4	4
Capabilities: Pro				
Capabilities: Cons		no access to historic camera records		
Capabilities: Comments				
Capabilities: Recommendations			cameras have not been installed yet,	
Conclusions: See description to the right	CONCLUSIONS: Stakeholder candid assessment of Vendor sensor operational performance and interest in acquiring additional enhanced sensors.			
2.75 Conclusion: Overall (without having received Beta sensors yet), would you purchase sensors from this Vendor?		yes	no	no
2.76 Conclusion: Would the stakeholder be willing to receive Beta Sensors without any funding for Vendor installation, communications or technical support?	This is a Yes/No question. For "No" select 1 For "Yes" select 4	4	4	4

2.77 Conclusion: Would the stakeholder be willing to and perform another review/survey for the Beta sensors such as this initial effort?	This is a Yes/No question. For "No" select 1 For "Yes" select 4	4	4	4
2.78 Conclusion: What additional Survey Questions should DHS S&T ask for future evaluations?				
2.79 Conclusion: What should DHS S&T do to improve the Flood Sensor initiative?				
2.80 Conclusion: What would you state as the potential benefit of the Flood Sensors to your community (quote for use in DHS S&T press release)?	Flood Sensors provide DOW a cost effective, replicable solution to provide dam monitoring services to areas with little to no existing instrumentation.			
Final Remarks: Please provide final remarks and commentary on any topic that may or may not have been included in the survey questions above:				