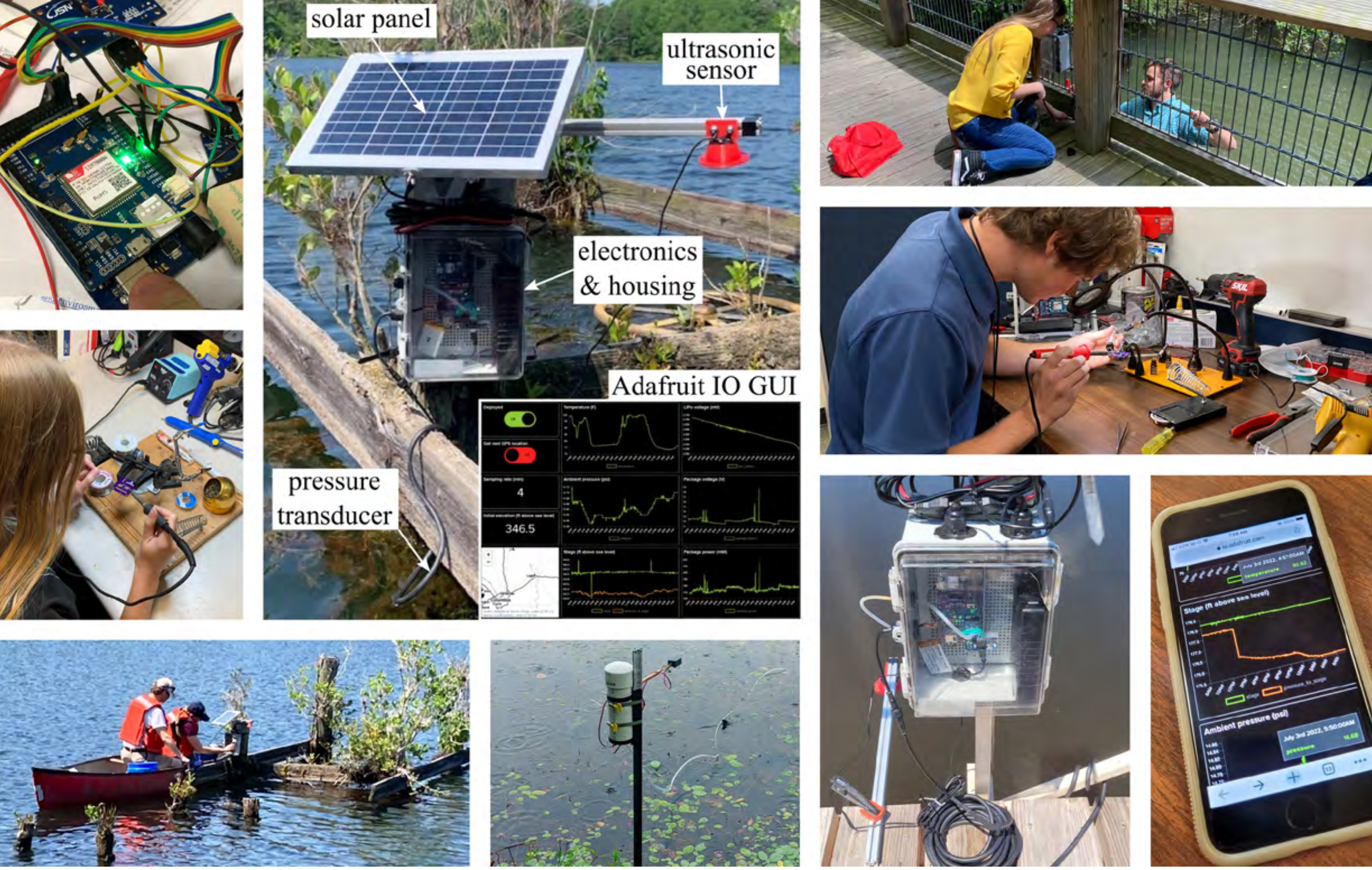


An Inexpensive, Open-Source, Remote Water Level Monitoring Solution for Dam Safety

Corinne Smith | Austin R.J. Downey, Ph.D. | John McCain, P.E.

ABSTRACT

Water level is an essential parameter in monitoring the performance and condition of dams, and sudden changes in water level can indicate a potentially hazardous situation. Traditional gaging technology poses financial obstacles to organizations attempting to monitor multiple dams that may not have the infrastructure for large systems. Open-source electronics and the Internet of Things (IoT) offer a more-economical and flexible platform to develop monitoring systems tailored to dam safety needs. The South Carolina Department of Health and Environmental Control's Dam Safety Program ("Program") has developed a remote water level monitoring system prototype using the Arduino open-source electronics platform and Adafruit IO cloud service. Ultrasonic and pressure-based methods are used to measure water level, and data are sent via a cellular network to a graphical user interface to provide real-time monitoring accessible through any internet-connected device. The entire system costs less than $500 USD plus an estimated $30 USD per month for telemetry. All electronics, software, and hardware designs are completely open-source and available in a GitHub repository. When tested against traditional technology, the system proved capable of capturing and displaying accurate readings in real time. The system was also deployed on a dam and effectively displayed water level data for a 14-day deployment.

INTRODUCTION

Identification of the Need

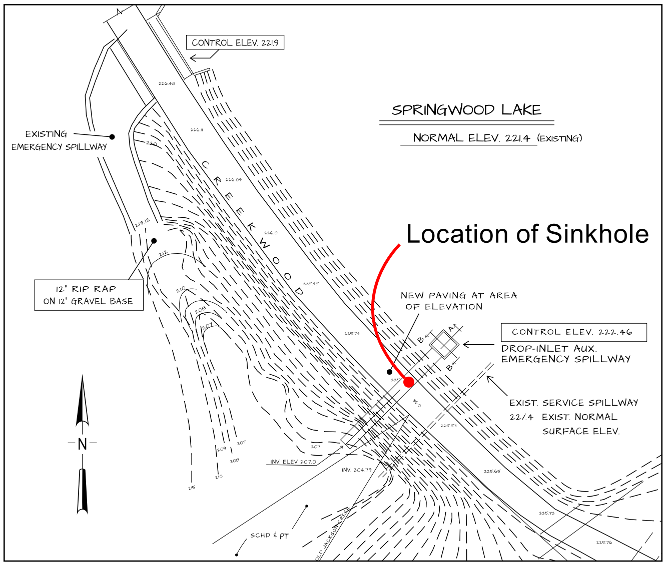
South Carolina endured a thousand-year flood[1] in 2015, Hurricane Matthew in 2016, and Hurricane Irma in 2017. All told, over this period, 70 state-regulated dams failed, and hundreds of others experienced extreme hydraulic loadings that caused various damages. Consequently, the South Carolina legislature boosted dam safety funding, resulting in increased program staffing, training, tools, and other resources. Additionally, for the first time, contracts were put in place for engineering and construction support to improve and grow the Dam Safety Program and provide a capacity for responding to emergencies at dams and reservoirs.

While the Program's growth saw an expansion in the use of new tools and technologies, the Program mostly remained unaware of water-level monitoring instrumentation and technologies. However, the Program's experience with a particular dam would soon change that.

Springwood Lake Dam, Part I

On March 20, 2018, a community resident notified Program staff that a sinkhole had been observed in the pavement of Creekwood Drive, a two-lane, state-maintained road on the crest of Springwood Lake Dam in Columbia, SC. Upon staff arrival, it was immediately apparent that the sinkhole was significant, creating a void under the pavement and depression in the surrounding road, which was gradually collapsing (Figure 1). This sinkhole was located directly above the 10-foot-diameter corrugated metal pipe, which serves as the auxiliary spillway discharge conduit (Figure 2). Inside the pipe, jets of water were observed at several positions around the pipe circumference, along with inflow at pipe joints, as shown in Figure 3.

Figure 1 Springwood Lake Dam in Columbia, SC – March 22, 2018



Elevations in NGVD29; Subtract 0.80-ft to Convert to NAVD88

Figure 2 Plan View from 1984 Modification to Add 14x14 Concrete Drop Inlet as Second Auxiliary Spillway

Figure 3 Upstream View of Springwood Lake Dam Auxiliary Spillway Discharge Conduit – March 21, 2018

On March 22, 2018, the Program issued an Emergency Order to the dam owner, the Springwood Lake Homeowners Association (HOA), requiring it to immediately lower the water level in the lake under the supervision of a licensed engineer. Upon hand-delivery of the Emergency Order to the HOA President, the

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[1] **"Thousand-Year Flood" was the name given to the weather phenomenon that struck South Carolina between October 1-5, 2015, by the media and the public. While parts of the state are believed to have exceeded a 1,000-year flood event, this was mostly confined to the coastal and eastern parts of the state. More can be read about this event at the following website: https://dnr.sc.gov/flood2015**

Program learned the HOA did not have the resources to take the necessary actions to mitigate the threat. The HOA President requested the Program's assistance to take whatever actions the Program staff deemed necessary. At this point, the Program instituted 24-hour-a-day monitoring of the dam by teams of two staff members. The Program also activated its emergency contracts to get crews to the dam to deploy pumps and install a siphon system. The first pump was deployed early on March 23, and the siphons were installed and flowing by the end of the day. As the level dropped, boards were removed from the 48-inch diameter, half-round drop inlet spillway.

On March 25, the 24-hour-a-day monitoring was reduced to twice a day. The Program used dam breach modeling software[2] to establish that a water surface elevation of 216-ft MSL (NAVD88) posed minimal risk in the event of dam failure, and this was established as the safe water level for reservoir maintenance (Figure 4). For context, the historical average pool elevation is 220.6-ft, the auxiliary spillway control elevation is 221.66-ft, and the upstream invert of the 10-ft-diameter pipe is 208.2-ft (all elevations in NAVD88).

On March 30, 2018, the Program provided notice to the HOA President that the Program would stop monitoring the dam and that responsibility for managing the water level (i.e., operating the siphon system) and observing the condition of the dam was being returned to the HOA and their consulting engineer.

Figure 4 Springwood Lake Dam Auxiliary Spillway Marked With the "Safe" Water Level Elevation of 216.0-ft MSL (NAVD88)

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[2] Decision Support System for Water Infrastructural Security (DSS-WISETM) Lite, https://dsswiseweb.ncche.olemiss.edu/userpages/about.php

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Springwood Lake Dam, Part II – Déjà vu all over again

By September 4, the sinkhole had turned into three sinkholes, and the original sinkhole had grown in size, as depicted in Figure 5. The Program was also closely monitoring the development of Hurricane Florence (at the time a Category 2 hurricane on the Saffir-Simpson scale), located approximately 1,100 miles east-southeast of Bermuda and forecast to make landfall along the south Atlantic coast. The Program's rain gauge at the dam measured 4.7-inches of rainfall on the morning of September 17 due to Hurricane Florence, which caused the water level to rise faster than the two six-inch siphons could accommodate. The water level elevation reached 220.0-ft, which caused the jets and inflow into the 10-foot-diameter spillway conduit to resume, just as was observed back in March. The Department reinstituted 24-hour-a-day monitoring, ending September 20 with the water level elevation at 214.7-ft.

Figure 5 Springwood Lake Dam – September 4, 2018

Note: As the picture shows, the disassembly of one of the siphons was a common occurrence, as neighborhood residents continued to use the dam for bicycling, walking, etc., and the presence of this siphon was an inconvenience.

Springwood Lake Dam, Part III – This is getting ridiculous

Potential Tropical Cyclone 14 (later Hurricane Michael) formed in the northwestern Caribbean Sea near Belize on October 6, 2018, and again South Carolina was in the sights of a tropical system. The 3.25-inches of rainfall at Springwood Lake received October 11-12 caused the water level in the lake to rise to 221.2-ft. For a third time, the Program initiated 24-hour-a-day monitoring by teams of two, starting on October 11 and ending on October 15.

Springwood Lake Dam, Part IV – We are way past ridiculous now

Between November 13 and November 16, 2018, another 3.25-inches of rainfall resulted in a return to high water levels (221.8-ft MSL on November 15). Again, observers noted the jets and inflow inside the pipe, and the Department reinstated 24-hour-a-day monitoring on November 13, continuing through November 20.

Defining the Need

The Springwood Lake HOA finally undertook stabilization measures at the end of 2018 and completed them in January 2019, such that the Department's concerns about the safety of the dam were finally addressed. All told, over four periods of 24-hour-a-day monitoring of Springwood Lake Dam by teams of two staff members, the Program spent 828 staff hours on the Springwood Lake Dam. As a result of the Program's experiences with Springwood Lake Dam and a clear need for a monitoring capability that does not involve the use of staff to serve as babysitters, the Program began to investigate monitoring and instrumentation technologies. The Program's engineering contractor, CDM Smith, researched commercially available solutions and, in February 2019, provided a summary of their findings. The Program generally found that the commercial products and services that offered out-of-the-box solutions had high upfront costs or maintenance and service fees that priced those options out of contention for a state agency with a limited budget.

While commercial options provide outstanding features, capabilities, and reliability, the Dam Safety Program was looking for a product that didn't seem to be available at the time. The Program searched for a solution meeting the following minimum requirements:

- A low-enough cost that if units were stolen, vandalized, or irreparably damaged, it would not represent a significant loss to the state (goal: less than $1,000 per unit)
- Allow for rapid deployment and retrieval in a wide range of conditions and circumstances without a robust or time-consuming installation and set-up process
- Allow for staff to assemble and repair units either in the office or in the field (i.e., to not be reliant on proprietary hardware and software)
- Provide real-time (or near real-time) monitoring from remote locations and be able to send alerts via text message or email (i.e., have cellular connectivity) to IoT devices

- Have redundant water level sensors (i.e., at least two sensors monitoring water level by independent methods)

An Opportunity Presents Itself

A fortuitous event led the Program to find a partner to develop an in-house water level monitoring solution. One of the Program's interns at the time was a senior mechanical engineering student at the University of South Carolina (UofSC) and overheard a conversation between staff members about the need for a means to monitor conditions at a dam remotely. The intern had recently completed a semester of senior design and suggested that his professor might be interested in a water level monitoring system as a future senior design project. A few emails and phone calls later, the Dam Safety Program partnered with the Department of Mechanical Engineering at the UofSC to develop a remotely monitored, do-it-yourself, internet-connected water level monitoring system.

The Program proposed this idea for a senior design project in December of 2019, and a team of five students accepted it in January 2020. The Dam Safety Program was the customer in this arrangement, and the senior design team was tasked with developing a product to fit its needs. The team performed a customer needs analysis and identified critical technical challenges. They investigated existing products and the associated proprietary technologies compared with open-source solutions. They built a working prototype and even managed to collect some data. Ultimately, several senior design teams would work on this project; however, they could not deliver a final prototype that met all the customer's needs, due in large part to the complexity of the project and, specifically, to the cellular connectivity requirement. While a final working prototype was not delivered, the contributions of these senior design teams laid much of the groundwork for eventual success.

Following efforts utilizing the senior design class, the Program began a direct collaboration with Professor Austin Downey in the Mechanical Engineering Department at UofSC and a research assistant in his lab, Corinne Smith. Professor Downey's area of research and the activities in his lab aligned very closely with the Program's goals for this project. Ms. Smith accepted an internship with the Dam Safety Program in January 2022 and has been dedicated to this project since then.

As a result of Ms. Smith's efforts in building on the groundwork laid by the senior design teams, the Program is currently working with a prototype that consists of a common, open-platform microcontroller, off-the-shelf parts, and a low-cost cellular service catering to IoT devices.

A VISIT WITH THE USGS

On May 12, 2022, several Dam Safety Program members visited the United States Geological Survey (USGS) offices in Columbia, South Carolina, to learn about their methods and instruments for stream-level gaging. Although the USGS' mission is stream gaging and not dam and reservoir level monitoring, the visit proved insightful for developing a water level sensor system. Two common USGS streamgage installations are stilling wells and bubble gages (Sauer & Turnipseed, 2010). Both capture accurate water level data but are often expensive, large, and require a robust permanent installation. A typical bubbler installation requires a concrete footing for an antenna tower and equipment mounting, trenching for the bubbler pipe, and additional concrete to secure the end of the bubbler beneath the surface of the water body (see Gopenko and Zhang, 2022, for an example of a bubbler station installation). Stilling wells have even greater installation requirements. Figure 6 shows one example of a stilling well installation with a float-driven sensor, which requires a structure to house the stilling well and instrumentation and must be robust enough to withstand flood flows in the monitored stream.

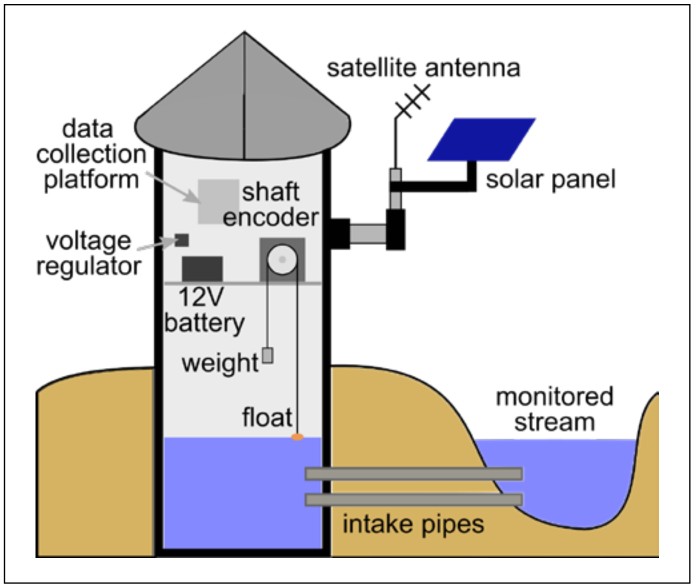

Figure 6 Stilling Well Schematic

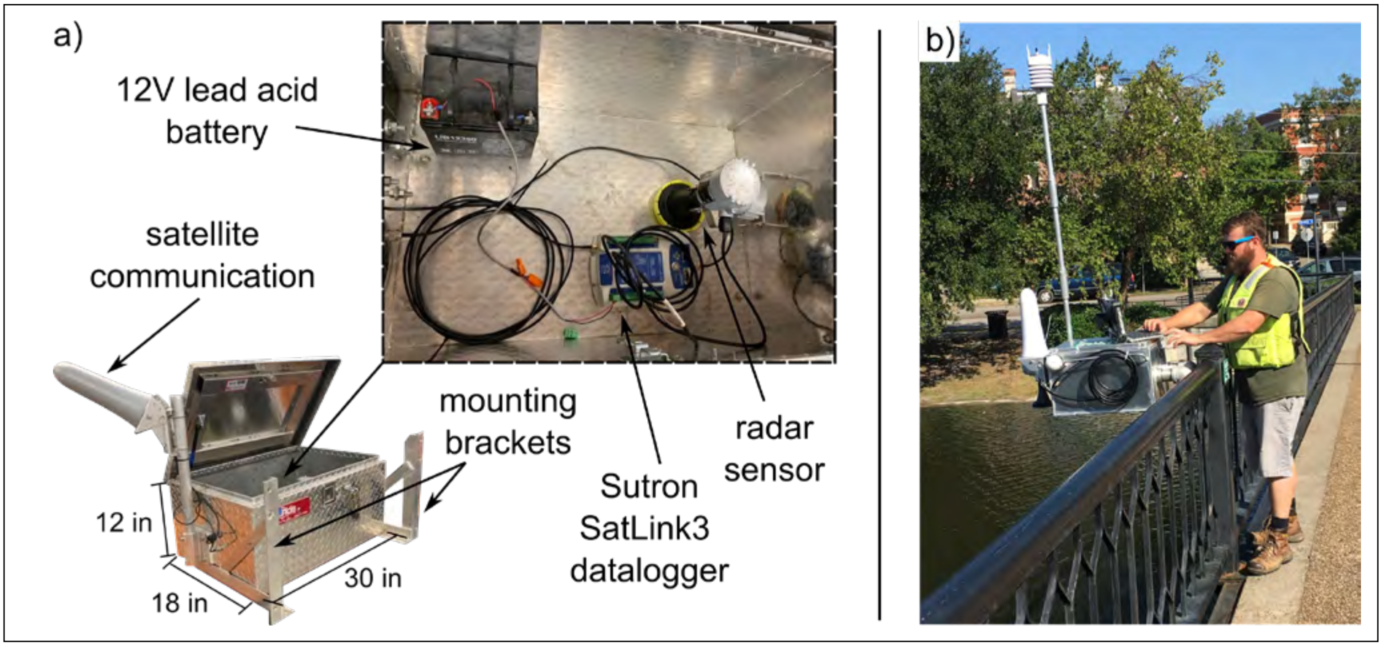

Photo by Howard Ross, USGS

Figure 7 USGS Rapid-Deployment Gage (RDG) Including Components (a) and Deployment (b)

The value of this technology is unquestionable in terms of providing vital data on the nation's surface waters. However, many in the dam safety community will agree these types of installations are not a practical or economical solution for a large number of the nation's 90,000+ regulated dams (National Inventory of Dams, 2022), many of which are small, privately-owned, and lack sufficient funds even for basic maintenance.

In addition to permanent installations, the USGS also has a non-permanent stream gaging capability in the form of its Rapid-Deployment Gages (RDGs), shown in Figure 7, which are smaller and portable for temporary deployments. RDGs measure water level using a radar sensor and transmit data hourly via satellite. But, they are still prohibitively expensive for widespread use by a state dam safety program, with a per unit price of approximately $13,000 USD (J. Shelton, personal communication, May 12, 2022).

When real-time monitoring isn't required, the USGS uses water level dataloggers, such as the HOBO® self-contained water level logger shown in Figure 8. For accurate results, two loggers are required: one deployed in the water body to measure hydrostatic pressure and a second deployed above the water to measure the ambient barometric pressure. The data from the two loggers are post-processed in the HOBOware® Pro software, where barometric pressure and temperature corrections are applied, and the resulting output is the water level reading. It is important to emphasize that these dataloggers do not transmit data in real time; they continuously collect and store data in onboard memory during deployment, and results are available after the sensors are retrieved and the data downloaded and post-processed in the HOBOware® Pro software. These loggers are highly portable and easy to deploy but are still expensive for a state dam safety program at around $1,330 USD per unit (HOBO Water Level Data Logger Deluxe Kit (30'), 2022).

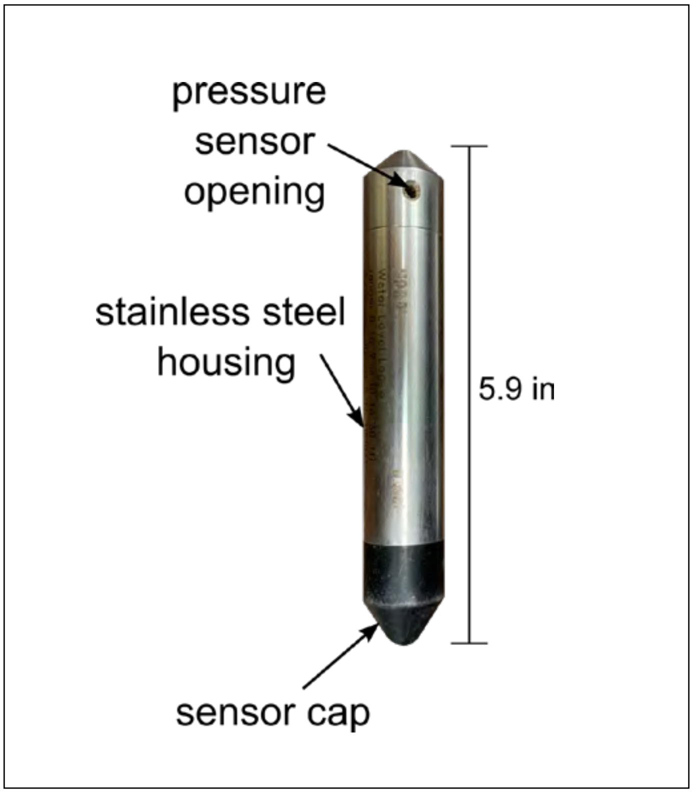

Figure 8 HOBO® Self-Contained Water Level Logger

THE DIY APPROACH

As already mentioned, a solution that addressed all the South Carolina Dam Safety Program's requirements did not appear to exist on the commercial market, so the Program turned to open-source solutions within the IoT framework. The IoT is a network of devices that allow data to be collected from sensors on the device and connect to the internet via a common protocol, including Wi-Fi, Bluetooth, and cellular (Clark, 2016). This allows a user to view sensor data simply through an Internet-connected device, like a laptop or mobile phone. Open-source electronics are economical due to manufacturing flexibility (i.e., no expensive licensing), and many are IoT compatible. This prompted the Program to explore a low-cost, open-source, IoT remote water level monitoring alternative to traditional gaging technology.

The Program has designed a cellular network-based remote water level monitoring system with a custom graphical user interface (GUI) to meet size, portability, cost, power, and serviceability requirements. The end user can customize the electronics and housing designs to adapt to each site's specific needs and challenges, offering great flexibility during deployments. Open-source software platforms have a wealth of documentation and tutorials to aid the user in modifying existing code to fit different sensor applications. The sensor system is entirely open-source, and all design files and specifications, the Arduino operating code, documentation (both by DHEC and by the individual component manufacturers), and test data can be found and cloned from a public GitHub repository (Smith et al, 2022). The Program hopes this will lead to free and open sharing of this technology among other state dam safety programs and dam owners and that refinements, improvements, and new applications will follow in time.

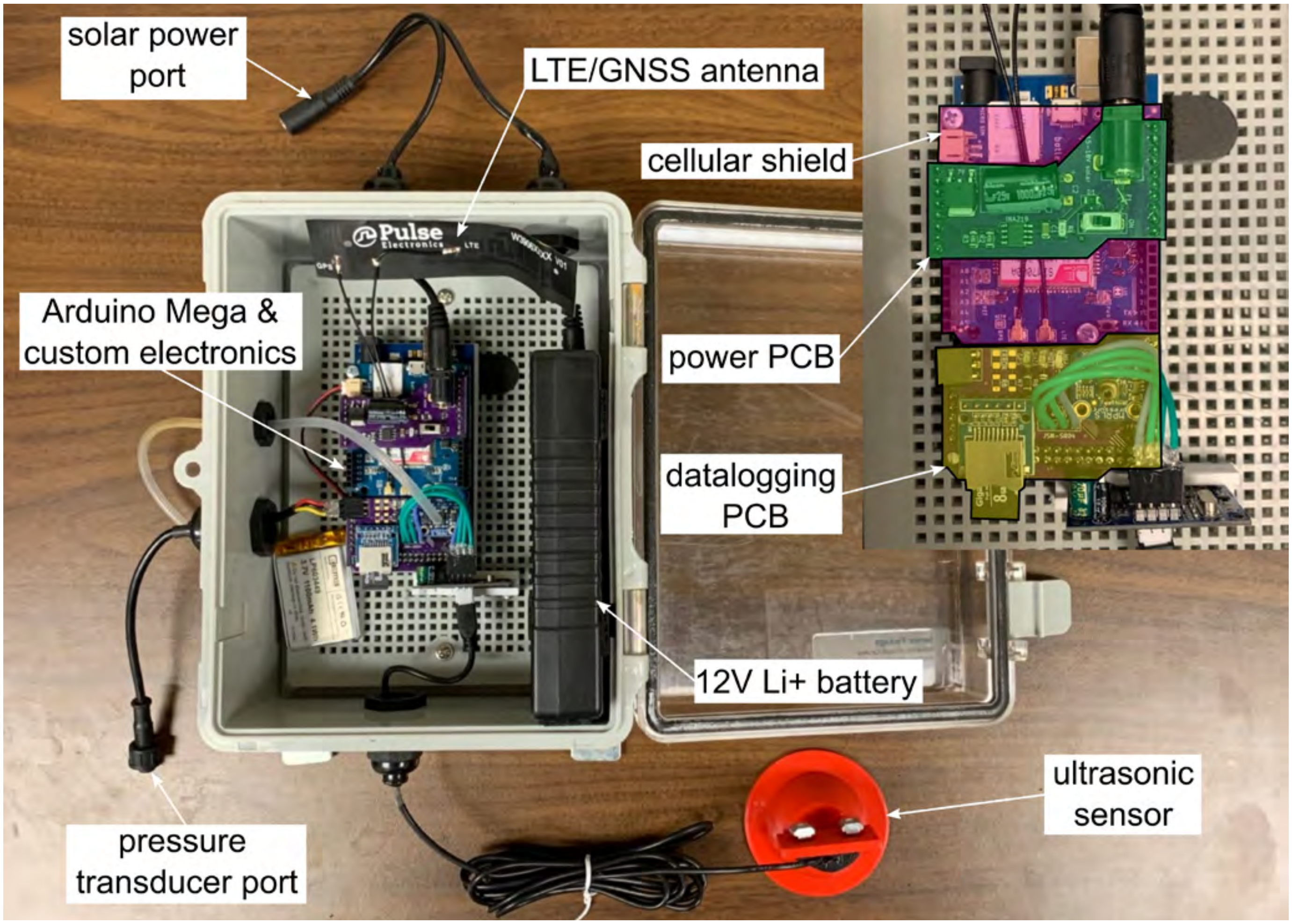

Figure 9 Individual Components of the SC Dam Safety Program's Remote Water Level Monitoring System

Note: The inset shows the power and datalogging PCBs along with the cellular shield on the Arduino Mega as the system's electronics.

REMOTE MONITORING SYSTEM DESIGN

Hardware

The remote monitoring system created by the Program is based on the ATMega2560 microcontroller using the Arduino Mega development board. Arduino is an electronics company that develops and shares IoT-compatible hardware and software designs. The Program's design uses three sensors to measure water level: an ultrasonic sensor (JSN-SR04T), a pressure transducer (G1/4 pressure transducer sensor), and a ported barometric pressure sensor (MPLRS).

In addition to the water level measurement sensors, the system incorporates sensors to monitor the health and performance of the sensor package, measuring battery voltage and power consumption (INA219) and the internal temperature of the electronics housing (MCP9808). A microSD card and an external clock (DS3231) keep track of time intervals between data collection, record time stamps of when data is collected, and as backup on-device data storage. Custom printed circuit boards (PCBs) create a compact design to house all the sensors. The power PCB contains the battery barrel jack, voltage and power sensor, and power switch. The datalogging PCB contains the ultrasonic, pressure, and barometric pressure sensors along with a real-time clock and microSD card. A 12 V lithium-ion battery (TalentCell Li+ battery) powers the system and can be used in tandem with a 12-18 V solar panel to both recharge the battery and partially power the system during the day to facilitate extended deployments. All electronic components are housed in a weatherproof ABS junction box with cable glands to protect the hardware. Figure 9 displays the system's individual components, and Table 1 breaks down the specific part numbers and prices.

The system is connected to the IoT using the Botletics SIM7000A cellular shield (modem) and a Hologram Global SIM card. Hologram is a cellular platform built for the IoT that features a Global IoT SIM card for cellular projects. The SIM card allows the IoT device automatically to switch between nearby participating carriers with the best signal. (In our experience in the Columbia, SC, area, this has alternated between AT&T and T-Mobile.) The device communicates using the LTE CAT-M1 standard, which was designed for IoT devices and is ideal for systems with low data transfer rates (Wolbert, 2022). Over 14 days of test deployments with a fixed sampling and transmission rate of four minutes, the system transmitted on average 0.53 MB of data per 24-hour period using the Message Queueing Telemetry Transport (MQTT) protocol. Data are transmitted using MQTT to Adafruit IO, an IoT service that acts as the MQTT broker by interpreting data sent to the device. Adafruit IO hosts the custom GUI and displays the system's data.

TABLE 1 REMOTE MONITORING SYSTEM PRICE BREAKDOWN

COMPONENT NAME	PRICE (USD)
ELEGOO Mega R3 ATmega2650 board	$20.99
Botletics SIM7000A cellular shield	$65.00
Datalogging PCB & electronic components*	$33.89
Power PCB & electronic components*	$11.68
12V package battery (TalentCell Li+ 12V/6000 mAh battery pack)	$39.99
3.7V shield battery (EEMB LP603449 3.7V/1100 mAh LiPo battery)	$13.89
Weatherproof housing (Zulkit IP65 ABS junction box 8.7 x 6.7 x 4.3 inch)	$27.99
Waterproofing glands	$8.99
10W solar panel (SUNERPOWER 12V waterproof solar panel battery trickle charger)	$59.95
Ultrasonic sensor (Stemedu JSN-SR04T waterproof ultrasonic sensor)	$13.99
Pressure transducer (G1/4 pressure transducer sensor)	$18.87
Barometric pressure sensor (Adafruit MPRLS ported pressure sensor)	$19.99
Cable for pressure transducer (25 feet, AWG 18/3)	$8.18
Hologram Global IoT SIM card and plan	$1.05/month + $0.40/MB
Adafruit IO+ subscription	$10/month
TOTAL	**$343.40 + $11.05/month + $0.40/MB** (estimated $16.43/month in data use)

Note: Detailed lists of electrical components and links to products are located in the GitHub repository (Smith et al, 2022).

The three sensors (ultrasonic sensor, submersible pressure transducer, and barometric pressure sensor) provide two types of water level sensing. The ultrasonic sensor is a range finder positioned above the water surface and returns the distance from the sensor to the top of the water. The ultrasonic sensor emits a 40 kHz burst of ultrasound reflected off the water surface back up to the sensor, and the ATMega2560 converts the time between emission and reflection to a distance measurement. It is important to place the ultrasonic sensor well clear of any obstructions between it and the water surface, as the ultrasound burst expands outward from the sensor in a 75-degree cone and any interference, such as the support beams of a bridge or a spillway riser, could result in false readings. This usually requires attaching the ultrasonic sensor to a pole or rod to extend it beyond its mounting location. With the ultrasonic sensor mounted 5 ft above the water surface, the diameter of the ultrasonic cone is about 7.7-ft. The cone's diameter, and thus the requirement for clearance, increases by 1.5 feet for every 1-ft drop in water level.

The pressure transducer measures the hydrostatic pressure from below the water surface while barometric pressure is measured using a ported pressure sensor (MPRLS) to correct the pressure transducer's hydrostatic pressure measurement for changes in atmospheric pressure. The barometric pressure sensor is contained in the electronics housing and ported to the ambient atmosphere. The pressure transducer works by producing a voltage from pressure exerted on a piezoelectric diaphragm within the sensor. A15-foot-tall water column testing apparatus was used to establish a pressure-voltage relationship. The ATMega2560 compares the measured voltage/pressure to the initial voltage/pressure value to calculate the change in water surface elevation and outputs the current water surface elevation. Barometric pressure is accounted for in post-processing, but the Program is working to implement the calculations in the code before transmission. It is important that the pressure transducer does not move during the deployment and thus should be secured to a solid structure or anchored to the pond bottom, ideally in an area with a low flow velocity. Lastly, the cable from the pressure transducer should be secured to prevent damage to the electronics package.

The initial water surface elevation at the time of deployment is measured by Program staff using RTK-corrected GPS and input into the GUI at initiation. The ultrasonic sensor and pressure transducer compare the change in measured values between the current measurement and the measurement at initiation to get the value to add or subtract, depending on the direction of change, from the initial water surface elevation. The result is the current water surface elevation in feet above mean sea level.

The three sensors provide two independent measurements for water surface elevation that the user can compare to validate if the sensors are operating correctly and provide increased confidence in the data. This increased confidence level is especially valuable if the data signal a hazardous water level that could lead to issues at the dam, such as overtopping.

Software & Graphical User Interface

The remote monitoring system runs on custom code Ms. Smith wrote in the Arduino language and is executed by the ATMega2560. Code libraries are needed for many of the hardware components, and the manufacturers typically provide these. The custom code calls on these libraries to communicate with the sensors and other hardware and facilitates cellular communication with the MQTT broker. The Arduino platform is versatile, so an end user only needs to plug the Arduino Mega into a common PC and upload the code freely available on the Program's GitHub.

A custom GUI hosted on the Adafruit IO website displays data from the remote monitoring system. The MQTT protocol allows for two-way data transfer. Sensor data get published, which means they are sent from the device to the GUI. Similary, data sent from the GUI to the device via commands are subscribed. Adafruit IO acts as the intermediary between the GUI and the device and is thus the MQTT broker. The GUI publishes data as the following line graphs: ultrasonic sensor stage, pressure transducer stage, internal electronics temperature, barometric pressure, cellular shield battery voltage, system battery voltage, and system battery power. A simple map also displays the device's location from GPS. Controls on the GUI handle subscribed data. For example, to set or change the sampling rate, the user enters a value in a text box on the GUI and that value is sent from the GUI to the broker then to the device. GUI controls include a deployment toggle switch, a GPS location query switch, a sampling rate value, and an initial elevation value. Elevation thresholds can also be set in the GUI as Actions, which are conditional statements that compare feed data to user-input values. If the data point is not within the user-defined threshold, an email alert is sent to the user with the feed name and value. Figure 10 shows the GUI during deployment on Spring Lake Dam.


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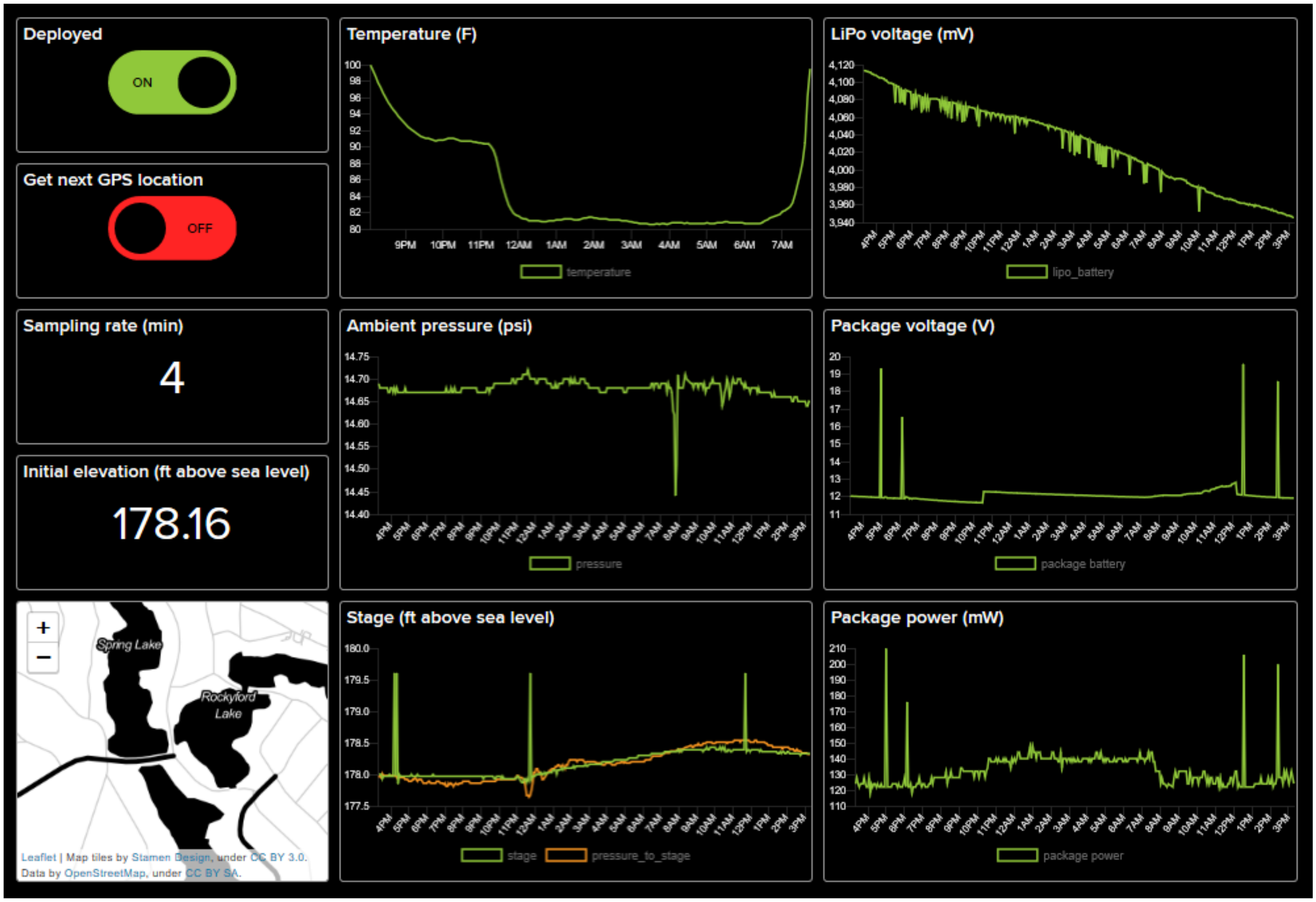

Deployed: ON

Get next GPS location: OFF

Sampling rate (min): 4

Initial elevation (ft above sea level): 178.16

Figure 10 GUI During a 24-Hour Deployment from July 7 – 8, 2022

Note: Shows deployment state, GPS query state, sampling rate in minutes, initial elevation, location of deployment, internal package temperature, barometric pressure, ultrasonic (green) and pressure-based (orange) water levels, cellular shield battery voltage, system battery voltage, and system power use.

DEPLOYMENT PROCESS

There are three steps to deploying the system: 1) sensor assembly, 2) housing setup, and 3) software initialization.

Step 1 – Sensor Assembly: The first step involves building the electronics and housing, which entails soldering electronic components, assembling the microcontroller base, waterproofing the pressure transducer, 3D printing the ultrasonic sensor housing, and building the system housing. The custom PCBs, cellular shield, and Arduino Mega must all be assembled (Figure 9) then the electronics and battery are fastened into the housing.

Step 2 – Housing Setup: The housing is deployed at the desired gaging location after the sensor assembly. The best sites provide an existing robust structure to mount the housing and solar panel, provide plenty of clearance above the water surface, and provide exposure to direct sunlight to optimize solar charging. Clearance above the water surface is necessary for accurate ultrasonic readings because any obstructions can cause false readings. Consideration should be given to the potential drop in water level in evaluating this clearance requirement. Past deployments have mounted the system to bridges, spillways, and decks, as shown in Figure 11.

Step 3 – Software Initialization: Once the housing is set up, the system must be initialized. Before powering on the system, email alerts can be configured in Adafruit IO by adding an Action. When powered on, the system will automatically connect to the network and MQTT broker, with the status of these connections indicated by LEDs on the datalogging board. Once connected, the user sets the desired sampling rate and initial elevation of the system using the GUI. These parameters may be modified until the deployment switch is toggled, which initializes the system and begins data collection. The data collection LED will then light up, and data will be collected and published to the GUI. During deployment, the user may change the sampling rate and query the GPS location. Figure 12 outlines the deployment control and data collection process using MQTT protocol.

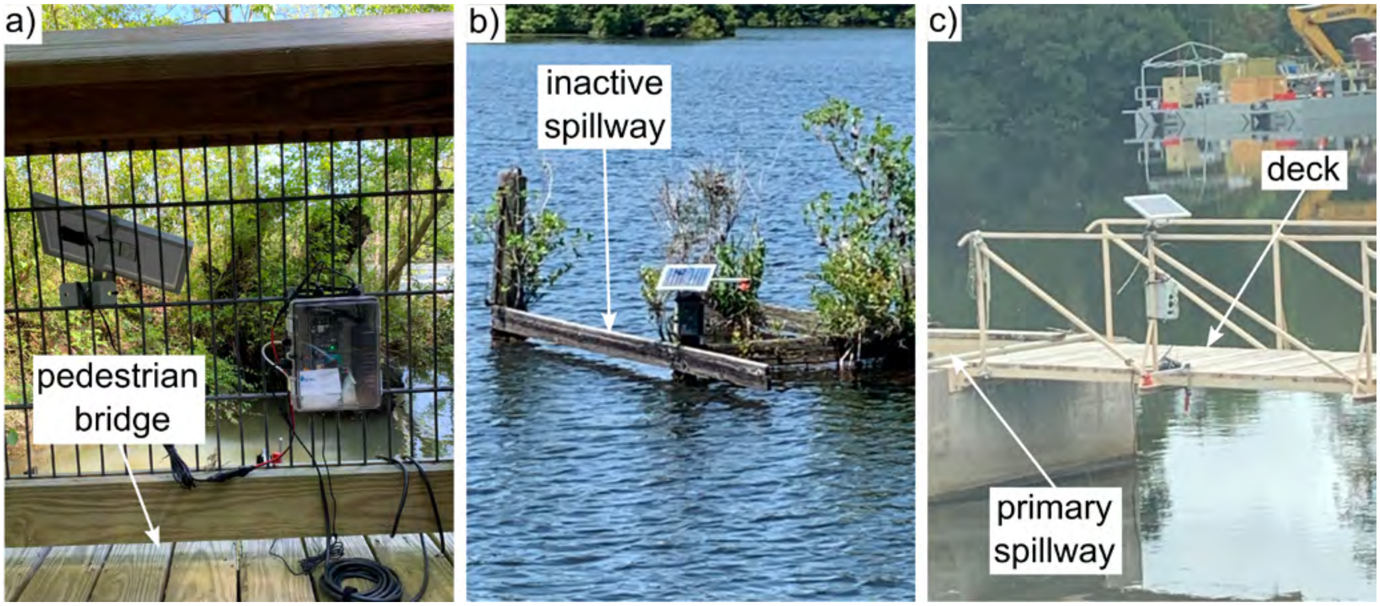

Figure 11 SC Dam Safety Program's Remote Monitoring System Deployed

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Note: a) a pedestrian bridge at the Saluda Riverwalk; b) an old spillway at Clemson Sandhills REC Pond Dam; and c) a walkway next to the primary spillway at Spring Lake Dam.

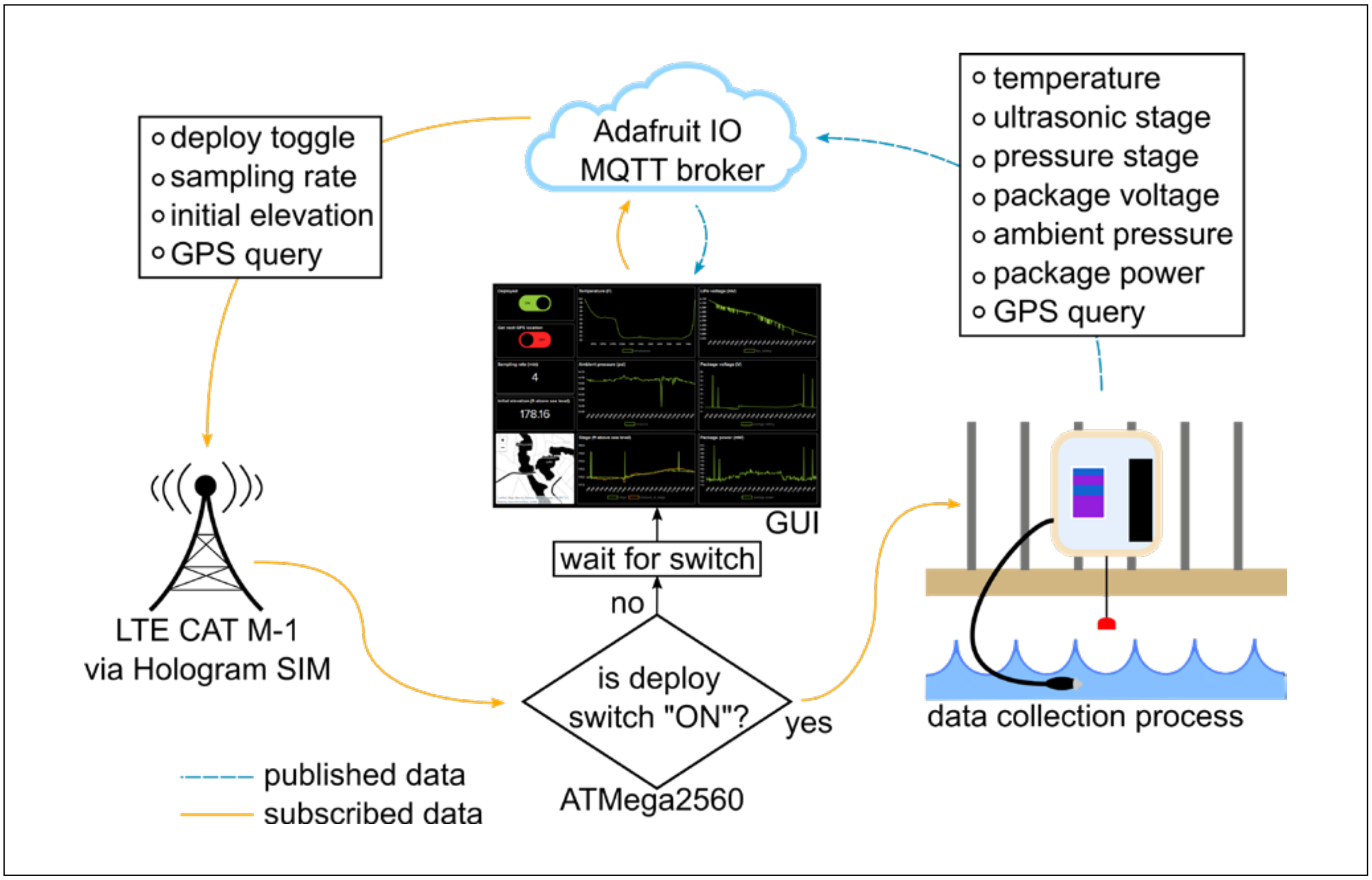


Figure 12 Data Collection Process and Deployment Switch Control of the System

VALIDATION AND FIELD WORK

Saluda Riverwalk, Columbia, South Carolina

A field test was conducted to assess the system's suitability for accurate water level measurement and transmission at the Saluda Riverwalk in Columbia, South Carolina. The system was deployed on a pedestrian bridge spanning a tributary whose water elevation fluctuates with the Saluda River, providing a test area with a lower flow velocity than the River. USGS gage 02169000, a stilling well installation, is located 250 feet upstream from the deployment area and was used as validation against the ultrasonic and pressure transducer readings. Additionally, two HOBO® water level loggers (HOBO® U20 001-01) were deployed with the system, one submerged next to the pressure transducer and one inside the housing with the barometric pressure sensor. These two methods are reliable water level monitoring tools used by the USGS. They are ideal for validating the performance of the Dam Safety Program's remote water level monitoring system. Upstream from this deployment site is the Saluda Dam, which frequently releases water and causes the Saluda River's water level to fluctuate, testing the 'sensors' ability to capture changing water level data. The gaging location, set up, and data collection are shown in Figure 13.

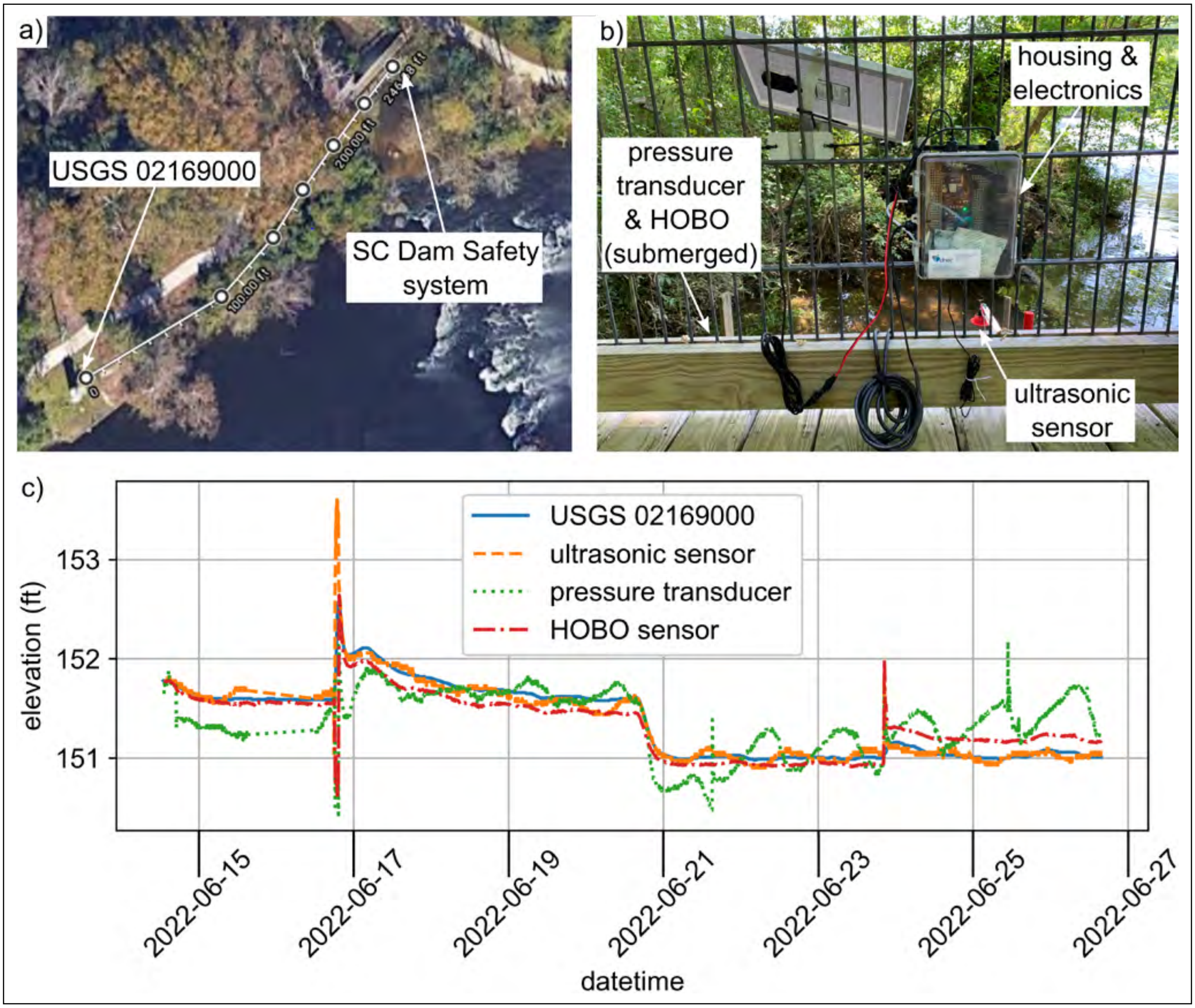


Figure 13 Field Test Conducted at the Saluda Riverwalk

Note: Shown is a) the deployment site relative to USGS 02169000 (Google); b) the system deployed on a pedestrian bridge spanning a creek level with the Saluda River; and c) the water level data captured by the system, USGS 02169000, and HOBO® water level loggers.

The data show that the ultrasonic and pressure transducer data were consistent with the USGS gage and HOBO® data throughout the field test's duration. It is important to note that the ultrasonic and pressure data shown was downloaded directly from the GUI rather than retrieved from onboard memory, demonstrating the system's ability to send data to the MQTT broker reliably. The data for USGS 02169000 were downloaded from the national USGS dashboard (USGS, 2022). The data for the HOBO® sensors were retrieved from the 'loggers' onboard storage and processed in the HOBOware® Pro software. The largest deviation between the ultrasonic sensor and USGS 02169000 occurs 06/16 18:30 at a +1.45 ft difference. Due to noise from the ultrasonic sensor, a median filter had been applied to the data to filter out error spikes, which were classified as data points with a difference of ±3 ft from the previous data point. The dynamic nature of water levels in the Saluda River requires this threshold to be relatively high to prevent data loss, which likely caused the extreme spike during the initial increase in water level. The other three sensing methods show a spike in water level at the same time as the ultrasonic sensor, but none as extreme. The most significant deviation between the pressure transducer and USGS 02169000 occurs at 6/16 19:15 at a -2.14 ft difference. This occurs during the same water level spike that the largest ultrasonic sensor error occurs, except the pressure sensor undershoots the USGS 02169000 reading instead of overshooting like the ultrasonic sensor. It is important to note that the HOBO® sensor, which also uses hydrostatic pressure, likewise experiences this undershoot error and does not agree with the USGS 02169000 data. Due to the USGS stilling well and the HOBO® sensor being in different locations, the HOBO® sensor data likely more accurately reflects the water level at the site of the test deployment. Also, the similarity in sensing methods between the HOBO® sensors and the Program's sensor system (and similar post-processing of the data) makes the HOBO® sensor data a better reference for the true water level in this test. Although this was the largest single error for the pressure transducer, the data show that the recorded water level oscillates daily around the other three methods. Ambient pressure recorded by the MPRLS sensor was used to compensate for the absolute pressure readings using the same post-processing formula as the pair of HOBO® sensors, but this phenomenon continues. One possible reason for this could be the tradeoff for a less expensive pressure sensor used by the Program resulting in a high hysteresis as the water level fluctuates.

Spring Lake Dam, Richland County, South Carolina

A second validation test was performed at Spring Lake Dam in Richland County, South Carolina (not to be confused with the previously mentioned Springwood Lake Dam that experienced the sinkholes). This test aimed to determine the system's suitability for dam safety applications where water level fluctuations are not as dynamic as in locations such as the Saluda Riverwalk. The system was deployed near the primary spillway of Spring Lake Dam. Unlike the Saluda Riverwalk, the deployment site was in full sun, allowing the solar panel to fully charge the battery each day and indicating that the system could be deployed long-term without swapping out the 12 V battery. The smaller cellular shield battery had to be swapped out every 3-4 days. A new design is being tested to eliminate the need for the shield battery and power the entire system from the rechargeable 12 V battery. Adafruit IO Action were configured for when the water elevation reached the emergency spillway (177.62-ft MSL) and the dam crest (181.5-ft MSL). Both the pressure transducer and ultrasonic sensor data were recorded. There were no established water level gages nearby to validate the system's readings, but data from a rain gauge located 1,000 feet downstream are used to correlate the change in water level with rainfall. The rain gauge is part of the Community Collaborative Rain, Hail, and Snow network, and data shown are retrieved from station SC-RC-139 (CoCoRaHS, 2022). Figure 14 shows the remote monitoring system deployed on Spring Lake Dam and the data captured during the 339-hour deployment lasting from July 1 to July 15, 2022.

The data show relative agreement between the ultrasonic and pressure transducer readings. Like in the Saluda Riverwalk validation test, data are downloaded directly from the GUI, and a median filter processes the ultrasonic sensor data while ambient pressure is accounted for in the pressure transducer data. On July 2, at 12:36 p.m., the pressure transducer reading suddenly drops -1.18 feet while the ultrasonic sensor remains constant. The pressure transducer reading continues to drift until recalibrated by staff via the GUI at 2:24 p.m. However, both the ultrasonic and pressure transducer capture the rainfall event occurring around July 3 at 11:00 p.m. It is hypothesized that the sudden drop was caused by a human disturbance to the system (likely a curious resident of the neighborhood), as the access gate on the walkway accidentally was left unlocked, and the pressure transducer was found in a slightly different position than where it was placed originally. Spikes in the pressure-based water level readings occur at July 7, 07:47-07:49 a.m., and July 8 08:26-08:42 a.m. These spikes are attributed to sudden fluctuations in ambient pressure readings and appear after the pressure transducer data is processed and do not originate from the submerged transducer. These findings highlight the need to deter people from tampering with the system, the requirement of securely anchoring the hydrostatic pressure transducer, and the importance of having two methods of measuring water level for self-validation.

The rising and falling water level aligns with periods of rainfall. The days with the greatest change in ultrasonic water level are: July 4 with a +0.36 ft increase and 0.33 in of rainfall; July 6 with a +0.52 ft increase and 0.87 in of rainfall; and July 9 with a +0.4 ft increase and 0.68 in of rainfall. The remaining days with little to no rainfall show relatively constant water levels. It is important to note that SC-RC-139 rainfall data were inconclusive on July 13.

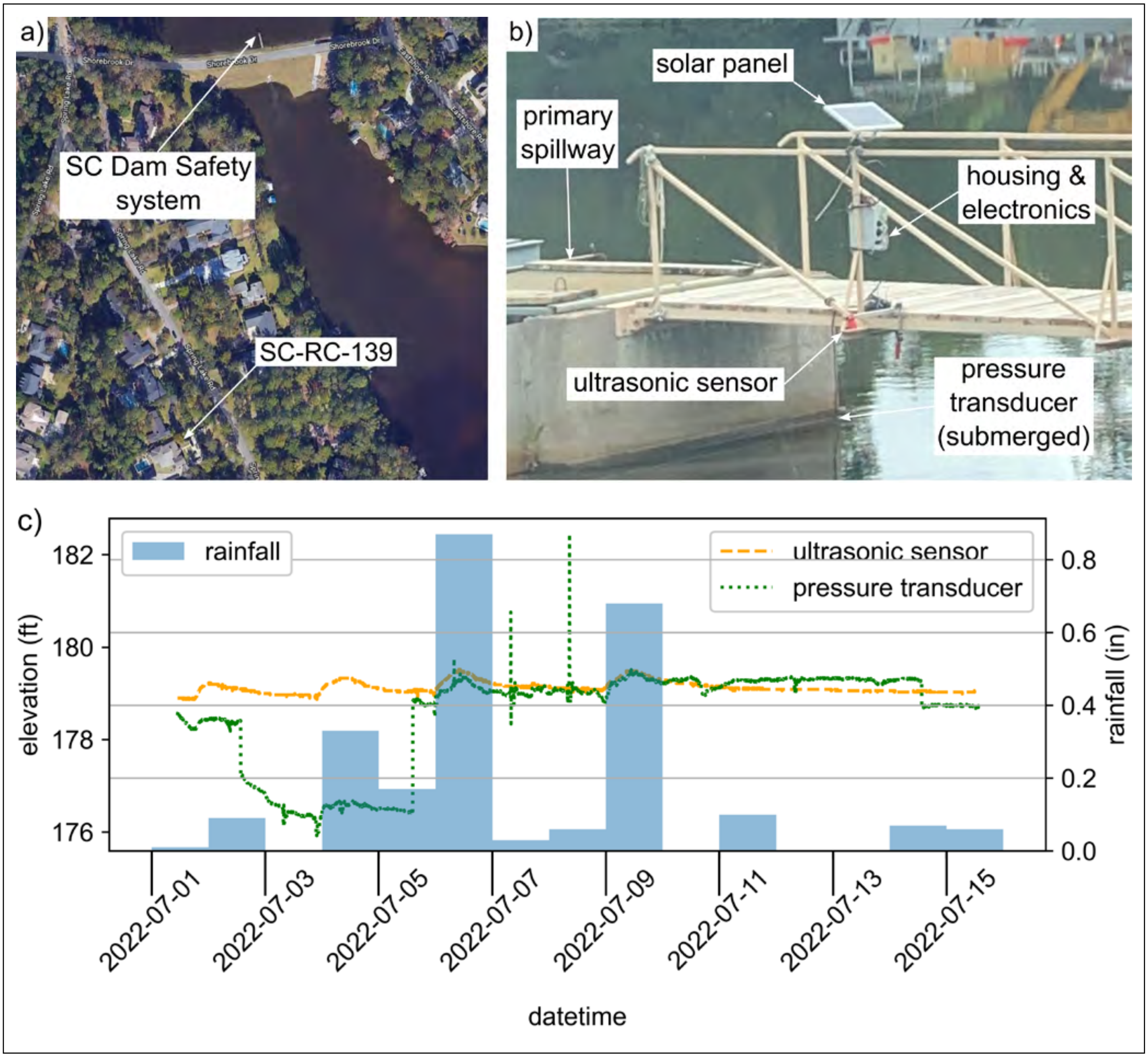


Figure 14 Field Test Conducted at Spring Lake Dam

Note: Shown is a) the deployment location and proximity to SC-RC-139 rain gauge (Google); b) the remote monitoring system set up on an access walkway for the dam's primary spillway; and c) the data from the remote monitoring system and SC-RC-139 over 14 days.

CHALLENGES AND LIMITATIONS

Despite the promise the remote monitoring system has shown so far for a state dam safety program application, the system comes with limitations. One major issue is the drift of the pressure transducer reading, whose cause the Program is investigating. The pressure transducer can deviate significantly over time from the ultrasonic sensor even when ambient pressure is accounted for, which requires recalibration (i.e., measuring the water level elevation) and reinitialization of the ATmega2560. The Program uses a very low-cost pressure transducer not intended for this purpose, and the challenges with data spikes and drift are likely partly attributable to this. This may be addressed by using a higher quality pressure sensor that is on par with commercial systems, but that will increase the system's cost if instruments like the $1,330 USD HOBO® water level loggers are used. Utilizing redundant sensors to monitor water levels by independent methods is one way the Program is addressing this challenge. Temperature compensation is another strategy by commercial systems to increase the accuracy of pressure transducer readings, so a submersible temperature sensor is being considered. Another limitation is the power consumption of the system. In areas with ample sunlight, the solar panel can easily recharge the 12V battery daily, but in shadier areas, it will have to be replaced regularly.

Additionally, the small cellular shield battery must be replaced often to maintain connectivity, but this is being addressed by a new design that will eliminate the need for the cellular shield battery. Yet another limitation is that the MQTT broker can only process data for one system at a time, so networking multiple systems will have to be done intentionally to prevent data transmission overlap. This can be facilitated by increasing the sampling and transmission interval of the packages to allow more downtime for the broker.

One of the biggest challenges the Program sees for the widespread adoption of this system is that it requires technical skill to fabricate and maintain. Unlike commercial options, the tradeoff of the system being wholly open-source and self-serviceable is that technical knowledge of electronics, skill in soldering, and troubleshooting are necessary. Documentation is provided to facilitate this learning curve, but the system will not be as user-friendly as

its commercial alternatives. Additionally, the Program will have to provide some level of technical support indefinitely, as the individual components are sure to change with manufacturers updating or discontinuing products and the Arduino libraries being updated. The Program has already experienced a library update causing unexpected behavior from the system.

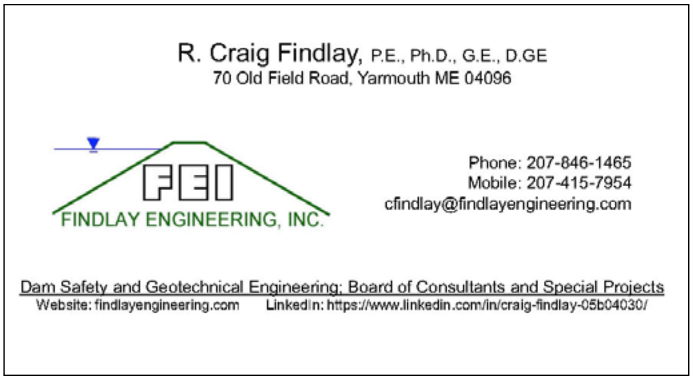
IN THE FUTURE

Looking forward into the short-term, the Program is excited to begin deploying these sensors on dams of concern all over South Carolina. The Program continues to make minor adjustments and refinements, and does not see this ever really stopping. Still, the Program has a water level monitoring system that meets most of its basic requirements. The full impact of this new capability is yet to be fully realized. The Program will soon have the ability to set these relatively cheap sensor packages at multiple dams across the state and establish alert thresholds for water surface elevations so that the Program will receive real-time notifications, day or night, of what's happening at a dam (for example, when flow initiates in a dam's emergency spillway). Dams under enforcement action with requirements for a reduced (or drained) reservoir can be monitored in real-time. These sensors can be used to calibrate or validate hydrologic and hydraulic models. The technology will be shared with dam owners as well. While the learning curve may be steep now, the Program envisions some of the state's dam owners will be interested, and as a result, will gain an understanding of how their dam and reservoir function and respond to rainfall events. Use in emergency planning and EAPs is also a logical application, but whether these sensor systems will be robust and reliable enough to utilize in emergency decision-making will not be known until much more data are collected under a wide range of locations and conditions. Regardless, the experience of babysitting Springwood Lake Dam should not be something the Program has to repeat with this new tool.

The Program is also developing other sensors that utilize the same base electronics package. A system for monitoring siphons is the next area of focus. This would be a pair of sensors (again using different sensing techniques for redundancy and confidence) mounted on a siphon and used to inform the user whether the siphon is flowing. The Department frequently relies on siphons to safely dewater a reservoir during an emergency. Since siphons may need to run for days (or even weeks) to fully dewater a reservoir, knowing if a siphon loses prime or stops flowing is extremely valuable. A second Program intern, Parker Lovett, a student in the Electrical Engineering Department at Clemson University, has been working on this sensor package, and our first test deployment is expected by the end of the summer. A camera would also be an extremely valuable addition to any sensor system, as video or still images can provide further confirmation of what the data are signaling and can also give information on the condition of the embankment that water level alone cannot convey.

In the mid-term, the Program plans to focus on simplifying the set up and deployment demands and reducing the learning curve for the layperson to make this sensor system more accessible to dam owners and other groups with little to no technical background. Also, the Program intends to look into incorporating the data feeds from these sensors into a Geographic Information System. Then the water level data from a network of sensors can be combined with a wealth of other useful data (e.g., quantitative precipitation estimates from the National Weather Service, or stream gage and earthquake data from the USGS) to improve the Program's overall situational awareness and aid in decision making.

Long-term, the Program envisions this low-cost, DIY technology developing a community of both hobbyists and professionals working together to keep the technology current and provide innovations one cannot foresee. This could also force the commercial market to pay more attention to the lower-cost end of the market and begin to develop sub-$1,000 USD monitoring solutions appropriate for this identified need.



CONCLUSION

In summary, we have demonstrated that it is within the ability of a small state dam safety program to develop in-house instrumentation and monitoring capability and for that capability to be as scalable as needed, based on budget, staff size, technical expertise, number of dams requiring monitoring, etc. An inexpensive option has been identified, but with limitations and challenges that must be understood. More robust, reliable, and expensive commercial options exist and have their place. Still, state dam safety programs typically operate under limited budgets, making these commercial options impractical for large-scale deployment. We have also shown that there are better, more efficient ways to utilize staff in times of emergency than sitting on a dam waiting for something to change. Even with a basic monitoring and instrumentation capability, one staff member can monitor multiple dams, and be instantly alerted to any change that requires immediate on-site investigation.

By no means should the complexity of this undertaking be neglected, as the Program's partnering with the state's public universities was essential for this project to even get off the ground, much less result in a working prototype. No small amount of luck allowed us to make the partnerships that allowed this effort to succeed, and by no means is this work done. The technical hurdles remain steep for widespread adoption of this technology to occur, but middle schools and high schools are incorporating Arduino and Raspberry Pi programming into STEM curriculums nationwide, and engineering schools are offering semester-long courses in mechatronics, PLCs, and 3D design. We believe the timing is right for an inexpensive water level monitoring solution for dam safety, as we have presented here.

We look forward to seeing where this path will lead and what advances for dam safety and safeguarding the public, it will bring.

LIST OF ACRONYMS AND ABBREVIATIONS

CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
DIY	Do It Yourself
EAP	Emergency Action Plan
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HOA	Homeowners Association
IoT	Internet-of-Things
kHz	kilohertz
LTE	Long-Term Evolution
MQTT	Message Queueing Telemetry Transport
MSL	Mean Sea Level
NAVD88	North American Vertical Datum, 1988
NGVD29	National Geodetic Vertical Datum, 1929
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
RDG	Rapid-Deployment Gage
RTK	Real-Time Kinematic
SIM	Subscriber Identity Module
STEM	Science, Technology, Engineering, and Math
UofSC	University of South Carolina
USD	United States Dollar ($)
USGS	United States Geological Survey
V	Volt

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