Using Low-Cost Microcontrollers with eTape® for Measuring Streamflow

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14. ABSTRACT
Autonomous dataloggers assembled from low-cost Arduino-style microcontrollers along with eTape® were investigated for their potential to continuously measure streamflow. This investigation tested streamflow measurement equipment at three sites alongside existing USGS streamflow gaging sites. Testing revealed that further investigation is needed to improve a method for using eTape® in a stream for flow measurement. Testing also revealed that low-cost microcontrollers can be unreliable unless significant effort is made developing a reliable datalogger.

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Contents

Page

Executive Summary

Continuous streamflow measurement data are critical for water resources planning. The availability of such data directly influences the confidence of hydrologic analyses used for land management. Although public entities such as the U.S. Geological Survey (USGS) collect and publish continuous streamflow data at many locations, hydrologic analyses can often benefit from additional data – even if only collected for a short duration. These specific data needs can potentially be met with low-cost, easily deployed equipment to collect continuous streamflow data.

This investigation evaluated using eTape® along with low-cost, microcontrollers for continuous streamflow measurement applications. eTape® is a passive, linear depth sensor (resembling a ruler) that is used for measuring water depth. This investigation evaluated eTape® alongside three USGS gage stations. This investigation also evaluated using a low-cost microcontroller as a datalogger and documents the level of effort in doing so. A mathematical comparison between the eTape® and the USGS gage is used for documenting the performance of the eTape® itself.

The results of this investigation revealed that the eTape® has some limitations for measuring streamflow because it must be mounted in an upright position. This limits the location of the sensor to areas within a stream that do not experience high flow velocities or eddies. Unfortunately, such locations experience higher sediment deposits, which can clog the sensor, preventing proper depth measurement. When the eTape® was properly functioning, it showed a strong correlation with USGS gage measurements. This investigation also evaluated an Arduino microcontroller for a datalogger. Because Arduino microcontrollers are not capable of datalogging without adding critical components for tracking time and storing data, considerable effort is needed to use these microcontrollers for datalogging. Field testing revealed that the Arduino microcontrollers were not reliable resulting in numerous failures and subsequent loss of data. Significant effort, beyond the scope of this investigation, is needed to develop a reliable datalogger from a low-cost microcontroller. This study does not recommend using low-cost microcontrollers as dataloggers for streamflow measurement without considering the effort to reliably do so.

Introduction

Continuous streamflow measurement data are critical for water resources planning. The availability of such data directly influences the confidence of hydrologic analyses used for land management. Although public entities such as the U.S. Geological Survey (USGS) collect and publish continuous streamflow data at many locations, hydrologic analyses can often benefit from additional data – even if only collected for a short duration. The additional data can be used to better understand a hydrologic or hydraulic process and increase the confidence of an analysis. Established streamflow measurement sites, such as the ones maintained by the USGS, are expensive to install and maintain. Furthermore, the USGS adheres to measurement standards, adding to the equipment, installation, and maintenance cost [USGS 2002]. Although the USGS streamflow measurement standards satisfy the general need, hydrologic analyses often have specific needs that do not necessarily require adherence to strict measurement standards. For example, calibrating a numerical model or monitoring streamflow when construction activity is occurring in a flood zone.

In 2019, Reclamation's WaterSMART program held a public prize competition and awarded $75,000 to five proposed solutions addressing the need for low-cost continuous streamflow monitoring. One of the awarded solutions, titled "Know Our Water Sponge Program," proposed using a low-cost, open-sourced microcontrollers paired with a linear hydrostatic depth sensor, specifically eTape® to collect continuous streamflow data [Trottier 2019]. eTape® is a linear sensor, resembling a ruler, that produces a resistive output, when excited with a voltage, that is inversely proportional to water depth [Milone Technology 2023]. The change in resistance is the result from the sensor's envelope being compressed by the hydrostatic pressure as it is immersed in water. The awarded WaterSmart solution estimated an 82-percent cost reduction when compared to equipment and methods commonly used by entities such as the USGS [Trottier 2019]. The purpose of this investigation is not intended to address the potential of replacing all the USGS stream gages with low-cost microcontrollers using eTape® but rather the feasibility of specific needs for deploying a low-cost solution. This report investigates the applicability of the concepts presented in the "Know Our Water Sponge Program" by evaluating these low-cost controllers with eTape® at three stream locations.

Methods

This investigation examines the feasibility of using eTape® sensors along with low-cost dataloggers for continuous streamflow measurement. The approach includes not only the quality of measurements but also the effort needed to deploy eTape® sensors. The effectiveness of the eTape® sensor was evaluated using the Pearson correlation coefficient between the eTape® voltage response and the USGS measured stream depth. The linear relationship between the voltage response and depth makes the Pearson correlation coefficient suitable for comparison. Streamflow is not calculated herein because the USGS stream gage locations considered for this investigation calculate flowrates from depth measurements, thus it is only necessary to compare depth measurements.

eTape® Sensor Assembly

The eTape® sensor assembly has two components: an eTape® (depth) sensor and a datalogger assembly. These assemblies were fabricated and tested at Reclamation's Technical Services Center (TSC) Hydraulics Laboratory prior to deployment at stream gage locations.

eTape® Depth Sensor

This project tested a 32-inch (nominal) eTape® (Figure 1). These sensors are calibrated by the manufacturer such that the voltage output will range linearly from 0-5V over the range of an active length of 32.4 inches. To protect the sensors while deployed in a streamflow environment, each sensor was fitted inside a 3-inch diameter PVC standpipe style stilling well (referred herein as "standpipe") fitted with a large-particle suction strainer to allow water entry at the foot of the standpipe (Figure 2). 1/8-inch slots were cut into the lower portion of the PVC standpipe for additional water entry. A rectangular acrylic plate was used to attach the eTape® to a fixed location inside the PVC standpipe and could be accessed using a threaded cap. Several holes near the top of the PVC allowed for venting. A heavy-sheathed, multi-conductor cable, held in place by a cord grip on top of the threaded cap, was used for connecting the datalogger using a water-proof connector (Figure 3 and Figure 4). The eTape® was mounted inside the PVC such that the bottom of the sensor was approximately 0.5 inches above the bottom of the suction strainer. This offset value was verified during laboratory calibration. The collective assembly of both the eTape® and PVC standpipe is referred herein as the "eTape® sensor."

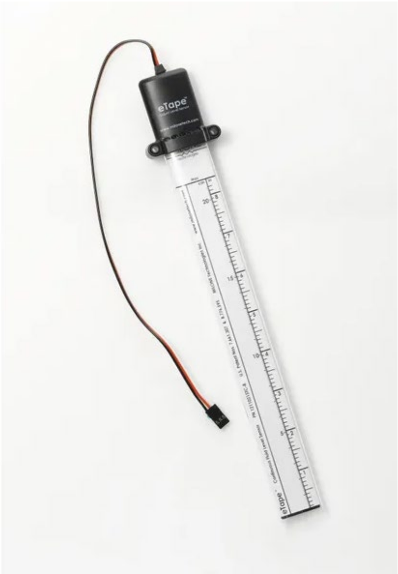

Figure 1 – eTape® depth sensor, photograph courtesy of Milone Technologies

Figure 2 – Photograph of the PVC standpipe housing the eTape®.

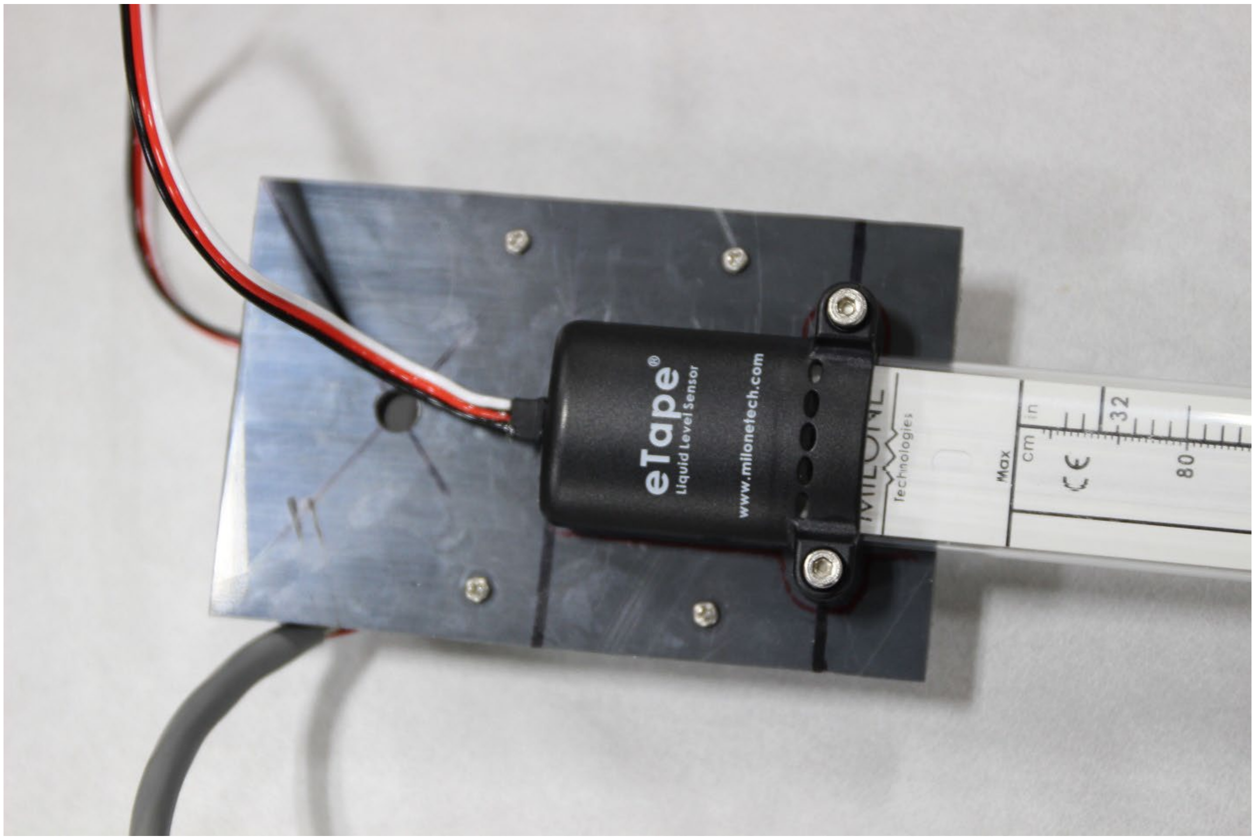

Figure 3 – Photograph detailing the rectangular acrylic plate used to attach the eTape® inside the PVC standpipe.

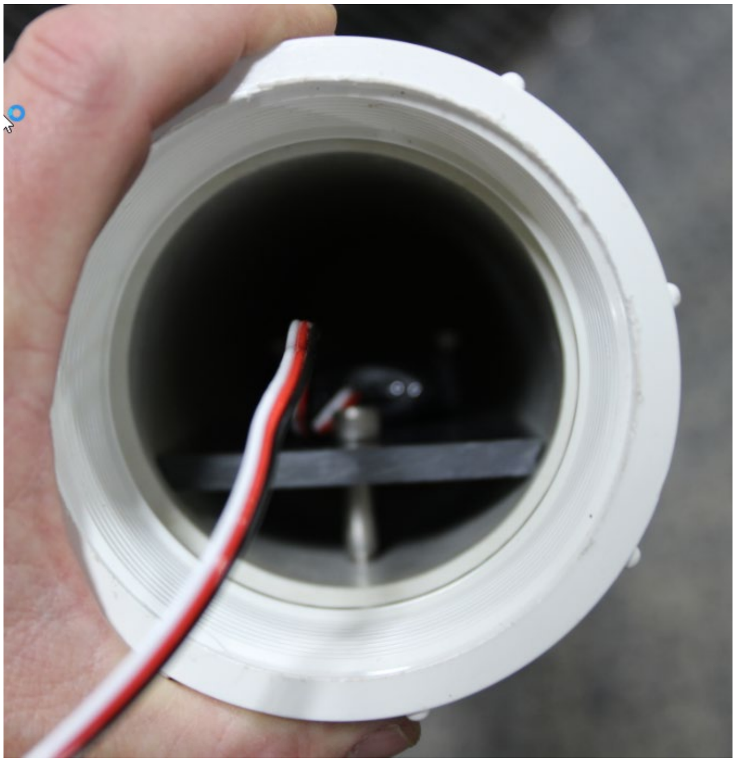

Figure 4 – Photograph looking down from the top of the 3-inch PVC standpipe showing the acrylic plate.

Datalogger

Autonomous dataloggers are commonly used in situ for collecting continuous data from sensors and, at a minimum, need to be able to do the following:

1. Consistently measure the analog response when a sensor is excited with a voltage. This is commonly done using an analog to digital converter (ADC) that is intrinsic to the microcontroller within the datalogger. The ADC converts a current or voltage into digital signal.
2. Record the actual time of the sensor measurement. This is commonly done using a real time clock (RTC) which operates independent of the microcontroller using a separate power supply.
3. Reliably store all the collected data.

This study investigates the feasibility of using a low-cost Arduino programmable microcontroller as the core component of an autonomous datalogger. Arduino microcontrollers, initially created as an educational tool for electronics and programming, are built on an open-source platform supported by a diverse community (Arduino SA 2023). The Arduino microcontrollers can be scaled up to perform specific tasks by adding modules. These modules, offered by a variety of manufacturers, are self-contained circuits designed to perform a special task in addition to the core functionality of the Arduino microcontroller.

The Arduino MKR Zero microcontrollers (referred herein as “MKR Zero”) was selected as the autonomous datalogger (Figure 5). The MKR Zero was chosen for having the following features:

- 32 KB of SRAM – allows for robust programming
- On-Board SD Card Reader – used for storing data
- 12-bit Analog to Digital Conversion (ADC) – allows for more precision (most MCUs considered for this project only had 8-bit ADC)

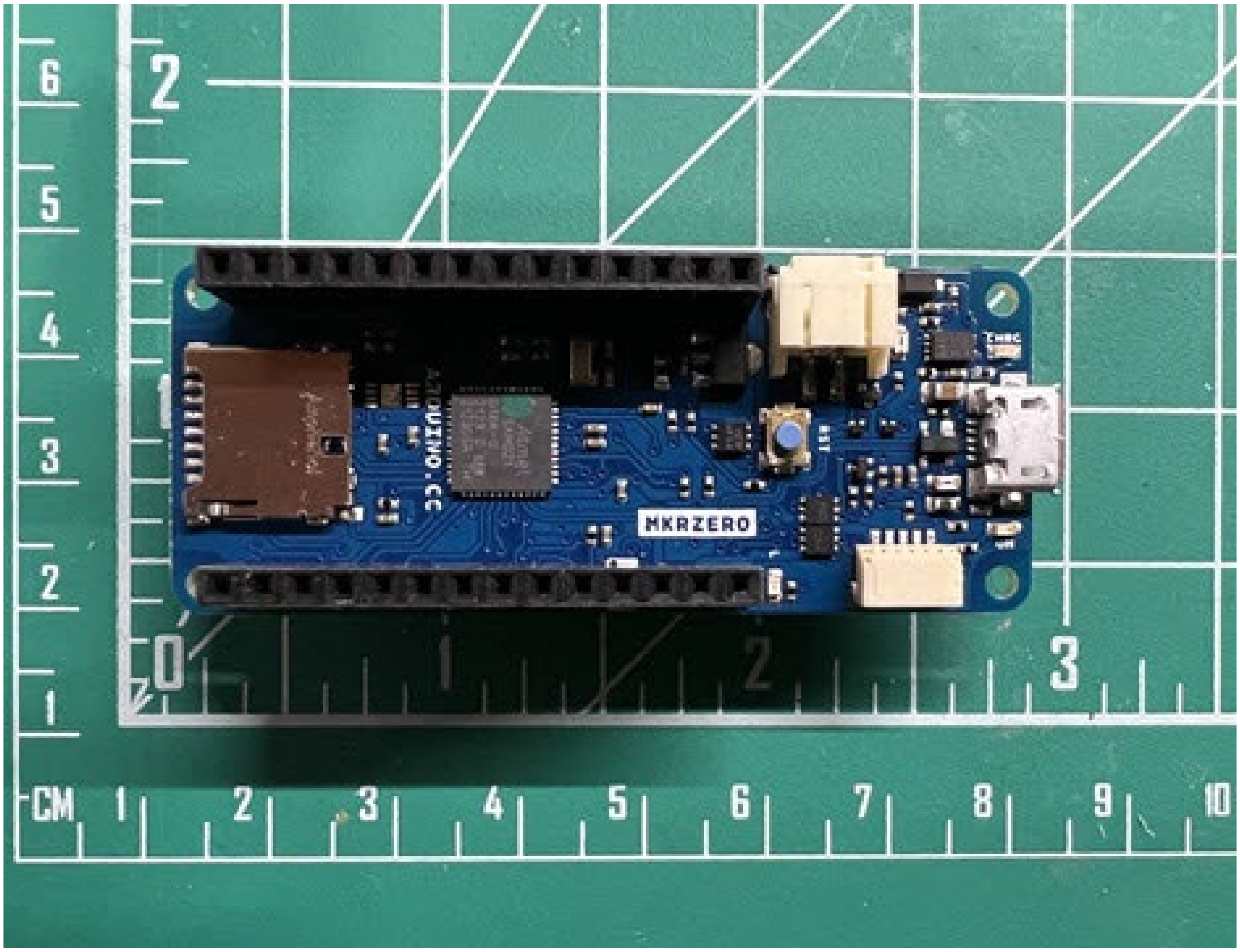

Figure 5 – Photograph of the Arduino MKR Zero Micro-Controller.

In addition to the MKR Zero, the following two modules were used in the datalogger assembly for increased functionality:

1. An RTC module with an independent power supply for timekeeping and
2. An independent current sensor to measure the battery voltage powering the datalogger.

Arduino microcontrollers come without any programmed functionality. All functionalities must be programmed using a free, open-source compiler available from the Arduino website [Arduino SA 2023]. This compiler utilizes the C++ programming language and requires a working knowledge of object-oriented programming. All the specialized components, including the SD memory card on the MKR Zero need additional complex programming for operation. Such additional programming is often in the form of independent, pre-packaged code libraries that can easily be added. The large development community for Arduino offers many of these complex code libraries that can be downloaded from cloud-based code repositories such as GitHub. Developing such complex code for specific components is beyond the scope of this investigation. As such, only components with freely available supporting code libraries were selected.

By itself, the MKR Zero is limited to a power supply of 5V. A separately purchased circuit board "shield" assembly allowed a direct connection to a 12V battery without over-powering (and potentially damaging) the MKR Zero (Figure 6). This circuit board shield also provided an easy method for mounting the MKR Zero inside a protective housing.

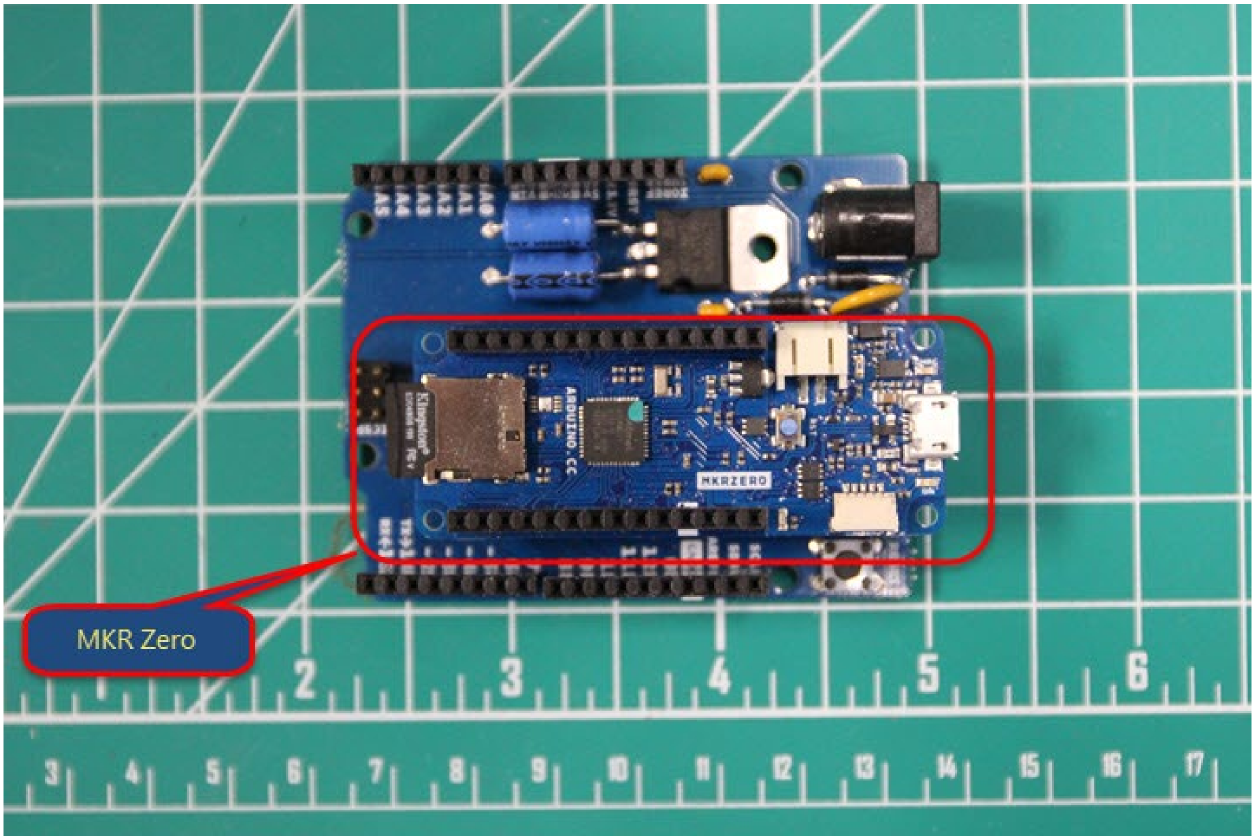

Figure 6 – Photograph of the Arduino MKR Zero attached to an Arduino "shield" assembly, which allows direct power from a 12V battery.

Both the RTC module and the current sensing module were wired into the MKR Zero using a through-hole circuit prototype breadboard. The breadboard allowed each component to share a common power terminal as well as the addition of screw-wire terminals for connecting the 12V battery and eTape® sensor without the need for fabricating a custom circuit board. The MKR Zero was connected to the various components and sensors using a Dupont-style wiring harness. Both the breadboard circuit and the "shielded" MKR Zero were mounted onto an aluminum backplane (Figure 7), which could be housed inside a water-tight Pelican case along with a 35 amp-hr 12VDC battery (Figure 8).

The datalogger was programmed to collect eTape® sensor data every five minutes along with the battery voltage and temperature (taken from a thermocouple onboard the RTC). Code libraries were downloaded from GitHub for controlling the SD card reader, the RTC module, and the current sensor module. Two LEDs on the breadboard circuit were programmed to indicate the status of the program while running. Recorded data were saved to a file on the SD card requiring its removal for data transfer to a PC. Prior to deployment, the datalogger was tested in the laboratory by collecting data from test sensors for two weeks. Four identical dataloggers were assembled for this investigation.

Figure 8

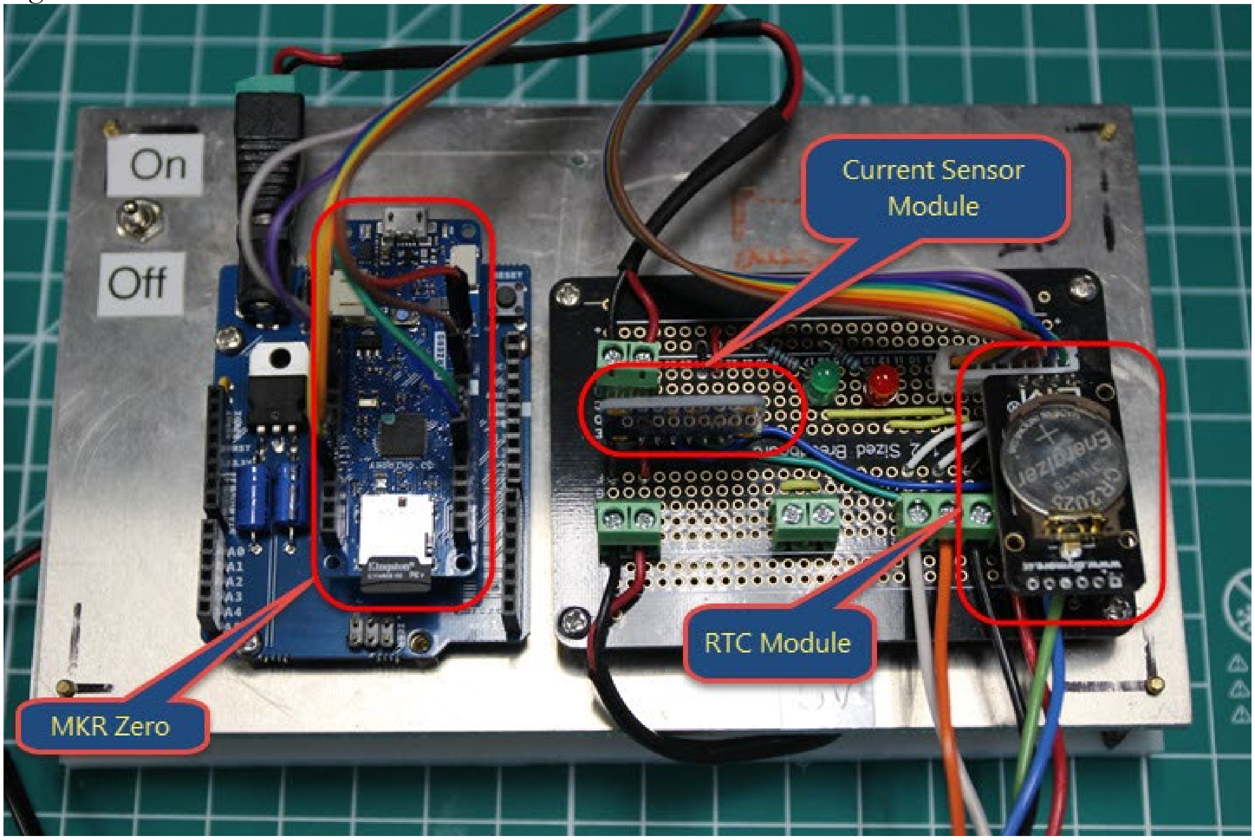

Figure 7 – Photograph of the “shielded” Arduino MKR Zero and the breadboard circuit assembly attached to the aluminum backplane.


Figure 8 – Photograph of the entire datalogger assembly showing the backplane assembly along with a 12 VDC, 35 amp-hr battery. A water-tight connector (left) was used for connecting the eTape®.

Field Testing

The eTape® sensors were tested at three nearby active USGS continuous gaging sites:

1. USGS #06730200 – Boulder Creek at 75th Street, elevation 5106
2. USGS #06718550 – North Clear Creek at mouth near Blackhawk, elevation 6910
3. USGS #06714800 – Leavenworth Creek at mouth near Georgetown, elevation 9280

The three sites were chosen based their elevations to represent three different climate zones: plains (lower elevation), foothills (mid elevations), and mountainous (high elevation). These climate zones are common to Colorado's Front Range and capture a wide range of conditions that affect the performance of streamflow measurement devices throughout the western United States. The eTape® sensors were located as close as possible to the USGS gage locations, however, to protect the eTape® sensors from strong water currents, the assemblies were attached to existing features to protect them from such currents. The dataloggers were located safely above the expected median flood elevation near the USGS gage housings. All dataloggers were identical allowing them to be removed and replaced with one having a fully charged battery. An offset value which accounts for the height of the sensor above the bottom of the stream was calculated using the eTape® sensor depth and the USGS depth for the day the sensor was deployed or when the datalogger was swapped.

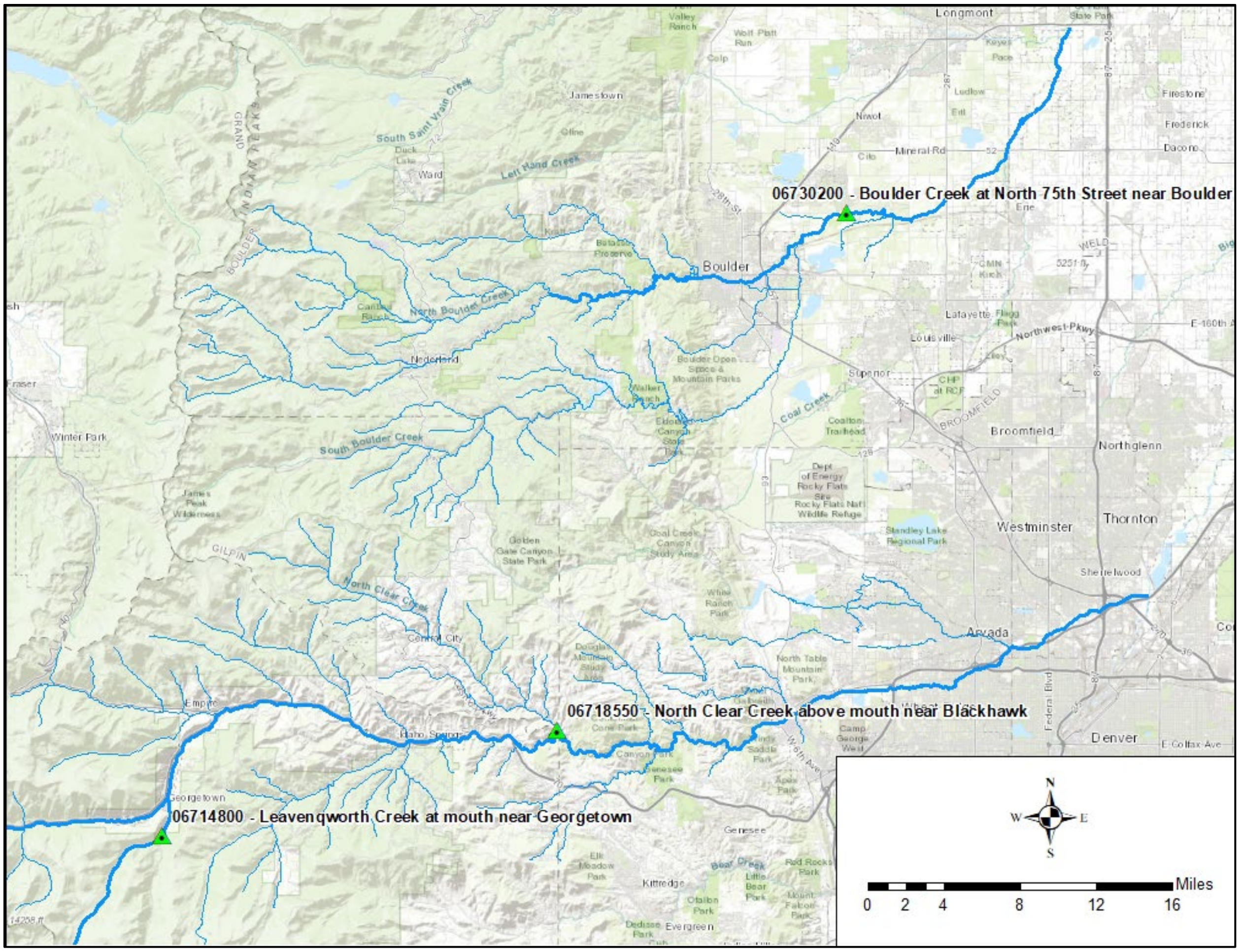

Figure 9 – Map showing the locations of the three USGS stream gage sites used for testing the eTape® sensors.

Boulder Creek: Plains Elevation

An eTape® sensor was located alongside USGS gage #06730200 – Boulder Creek at North 75th Street near Boulder, CO. The sensor was attached to a fencepost in an eddy along the north side of Boulder Creek (Figure 10), behind a large, fallen cottonwood stump. The datalogger was securely located next to the USGS gage housing. The expected depth of Boulder Creek at this location exceeds the height of the eTape® sensor. An extension of PVC pipe above the top of the eTape® was used to visually assess the eTape® sensor during these high flow periods. This sensor remained deployed for approximately two years.

Figure 10 – Photographs showing the eTape® sensor installed at the Boulder Creek location.

Clear Creek: Foothills Elevation

The second eTape® sensor was located alongside USGS gage #06718550 – North Clear Creek near Blackhawk, CO. The sensor was attached to a well anchored fence post on the downstream side of a conduit used for the USGS gage (Figure 11). The USGS conduit provided protection from the stream's swift current and floating debris. The datalogger was securely located underneath a wooden platform next to the USGS gage housing. Although the USGS gage was in a deeper location in the stream channel, eTape® sensor depth measurements can still be compared provided it is submerged. This sensor remained deployed for approximately two years.


Figure 11 – Photograph showing the eTape® sensor installed at the Clear Creek location.

Leavenworth Creek: Mountainous Elevation

The third eTape® sensor was located alongside USGS gage #06714800 – Leavenworth Creek near Georgetown, CO. The sensor was attached to a post near the USGS staff gage (Figure 12). The datalogger was secured underneath the wooden platform of the USGS gage housing. A solar panel was added to this gage to extend the battery life of the datalogger. An early November snowfall prevented deployment at this location during the first year of this investigation, resulting in this sensor only being deployed for a year.

Figure 12 – Photograph showing the eTape® sensor installed at the Leavenworth Creek location.

Results

Level of Effort

All eTape® sensors were assembled using commonly available tools and equipment. The effort assembling the sensors can vary depending on availability of similar resources. However, the assembly effort does not include selecting and deploying these eTape® sensors in streamflow locations. Considerable time is commonly used for determining the best location for measuring streamflow. Such factors towards this selection include ideal stream hydraulics, site accessibility, and sensor attachment.

eTape® Depth Sensor

Assembling the eTape® depth sensor required minimal effort. The 3-inch schedule 40 PVC was readily available at most hardware stores along with all the pipe fittings. The suction strainer can be found in most farming supply stores. A heavy-duty sheathed seven conductor cable was available in the laboratory and was soldered and sealed with heat-shrink tubing inside the 3-inch PVC. A waterproof Amphenol circular connector was attached to the other end of the cable for connecting to the datalogger. Each depth eTape® depth sensor was assembled in about 4 hours.

Datalogger

By itself, an MKR Zero (or any low-cost microcontroller) is not capable of autonomous datalogging without additional components. Furthermore, such microcontrollers are not supported directly by Arduino but rather supported through a community of online users. Without specialized knowledge of microcontroller-based systems, time is needed to sort through the large amount of information presented by this community to select and program the necessary modules needed for assembling a datalogger. Much time was spent during this investigation researching and testing various components. The autonomous datalogger design presented in this study is only one of many possible combinations of various components. The library code needed to program these components is constantly changing to accommodate changing microcontroller technology.

Assembling the datalogger requires limited knowledge in electronics as well as the necessary skills for building a circuit, primarily soldering. Designing and fabricating a printed circuit board is beyond the expected capability of hydraulic engineers. A through-hole prototype circuit breadboard is commonly used to overcome this limitation. Such circuit boards are readily available online along with the various components used for assembling the datalogger. Soldering the components onto the circuit boards took more time than any other task to fabricate each datalogger assembly.

Laboratory Testing

eTape® Testing

Milone Technology specifies the eTape® 0-5VDC modules will correctly respond to an expected voltage within 5% at full scale [Milone Technology 2023]. For an eTape® having an active length of

2.7 ft, this amounts to an accuracy within ±0.135 ft. A completely assembled eTape® sensor was tested in the laboratory using a 48-inch acrylic standpipe. The MKR Zero recorded eTape® output voltage for nine water depths. The following linear equation was used for describing the relationship between the eTape® output voltage and water depth:

$$Depth = \beta_0 V_o + \beta_1$$

Where β_0 is the linear relationship between voltage, V_o, and depth (in feet) over the active length of the eTape® sensor (2.7 ft), and β_1 is the sensor offset relative to the depth of water. The laboratory calibration resulted in values for β_0 and β_1 of 0.56 ft/VDC and 0.04 ft, respectively. Results from laboratory calibration are presented in Figure 13. The maximum residual from this fitted equation is 0.048 ft, well within Milone's reported accuracy of ± 0.135 ft.

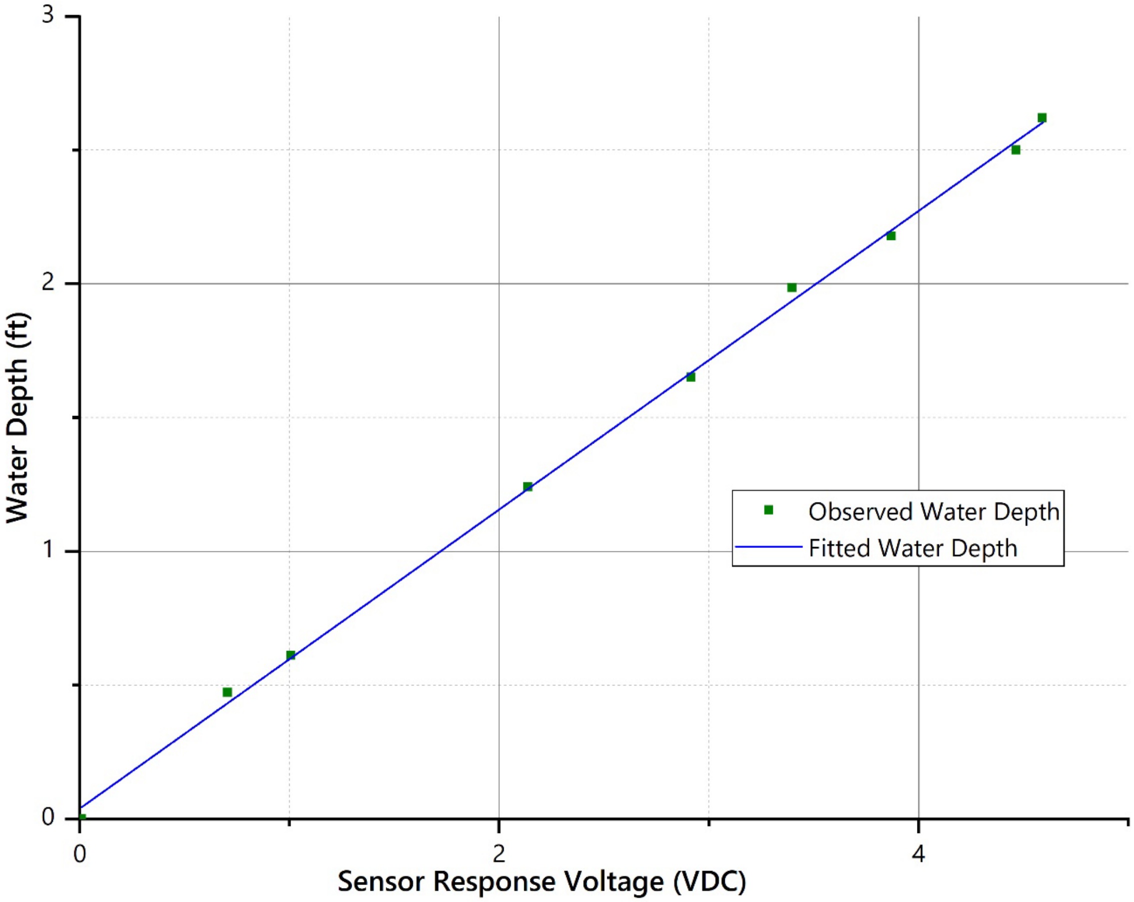

Figure 13 – Laboratory results for eTape® sensor calibration.

eTape® Sensor Test

The eTape® sensor was subjected to a long-term test in the laboratory. Over a period of two weeks, the eTape® depth sensor remained in a 48-inch standpipe collecting data from the eTape® as well as the current and temperature sensors. The purpose of this test is to assure expected functionality of the sensor assembly and to monitor power drawdown from the battery. Time-stamped sampling occurred every five minutes, as intended for field deployment, recording depth, battery voltage, and temperature. The water depth in the 48-inch standpipe was held constant at around 17.5 inches. Results from this test are presented in Figure 14.

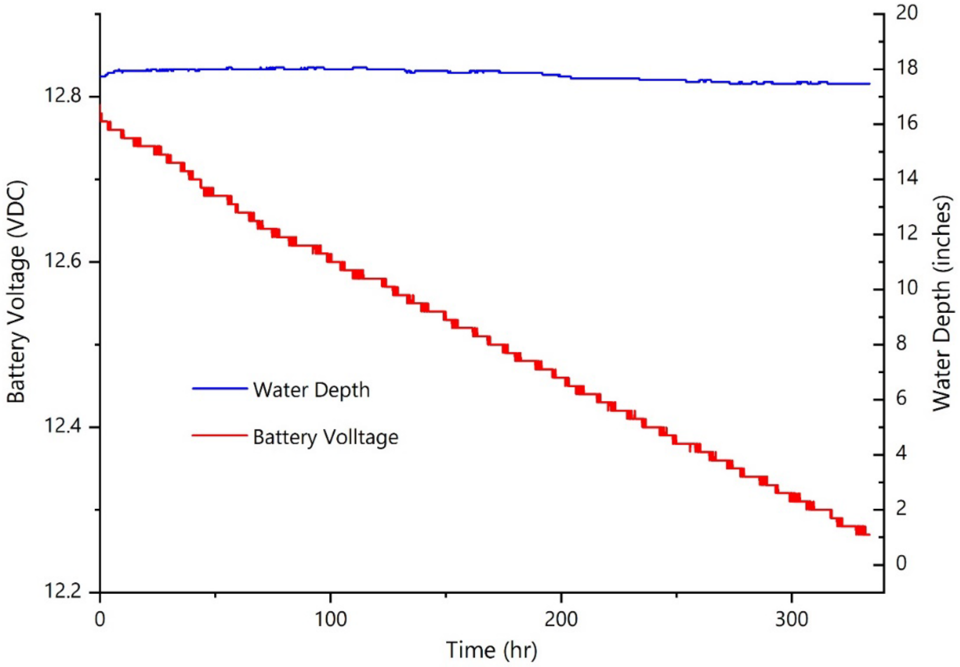

Figure 14 – eTape® sensor data collected during a two-week laboratory test.

Figure 14 shows the battery voltage dropping only 0.52 volts over a two-week period. The test showed the water level remained constant at approximately 18 inches, lowering only slightly due to evaporation loss in the laboratory. Not shown in Figure 14, the average recorded temperature was 74.1˚F with minimum and maximum values of 72.5˚F and 77.0˚F, respectively, both reasonable for the laboratory environment.

Stream Testing

The results from testing the eTape® sensors at three USGS stream gage locations varied significantly. Numerous problems with the datalogger resulted in minor modifications over the testing period. Most problems resulted from one or more of the three primary MKR Zero components (SD card reader, RTC, and current sensor) failing, resulting in near complete failure of the data collection. The cause of failure was often difficult to determine, or indeterminant. Each failure resulted in refabricating the MKR Zero circuit board assembly. The C++ code for the MKR

Zero was also modified several times because of these failures. The failures were most often discovered at the Boulder Creek site. The other sites have longer periods without data because of their limited access.

This investigation did not measure the height of the eTape® sensor location. This is commonly done using survey-quality measurements to determine the stream depth, and then subtracting the same-time sensor depth. This value, commonly referred to as an offset value, is the height of the sensor above the bottom of the stream and can be used with the cross-sectional geometry to calculate flow. Because the voltage response from a sensor such as eTape® is linear relative to depth, a fair comparison between the USGS depth and the eTape® voltage response can be measured using a Pearson correlation coefficient without converting the response voltage into a depth. A Pearson correlation coefficient is a measure of the linear relationship between two variables, and can be calculated as the covariance of the two variables divided by the product of their standard deviations as follows:

$$COR(X,Y) = \frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2 \sum(y-\overline{y})^2}}$$

For this study, both depth and voltage are positive, thus the Pearson correlation coefficient can only range from zero to one. A value of zero depicts no linear relationship whereas a value of one depicts a perfect linear relationship. Plots of the data visually reveal such linear relationships for values of 0.5 and above. Although there is no definitive guidance for acceptable values of th Pearson correlation coefficient, if enough samples are taken from two variables resulting in a value of at least 0.8, a linear equation can be computed to describe the relationship with minimal prediction error (Sheather, 2009).

Boulder Creek

The eTape® sensor located alongside USGS gage #06730200 – Boulder Creek at North 75th Street near Boulder, CO. collected 57,027 samples at 5-minute intervals (79.2 days) from December 8, 2020, through September 11, 2022. Power at this site was not augmented by solar panels, however, this site was accessed often enough for battery charging such that the battery voltage never dropped below 11.75 VDC. The collected data for this sit are presented in Figure 15.

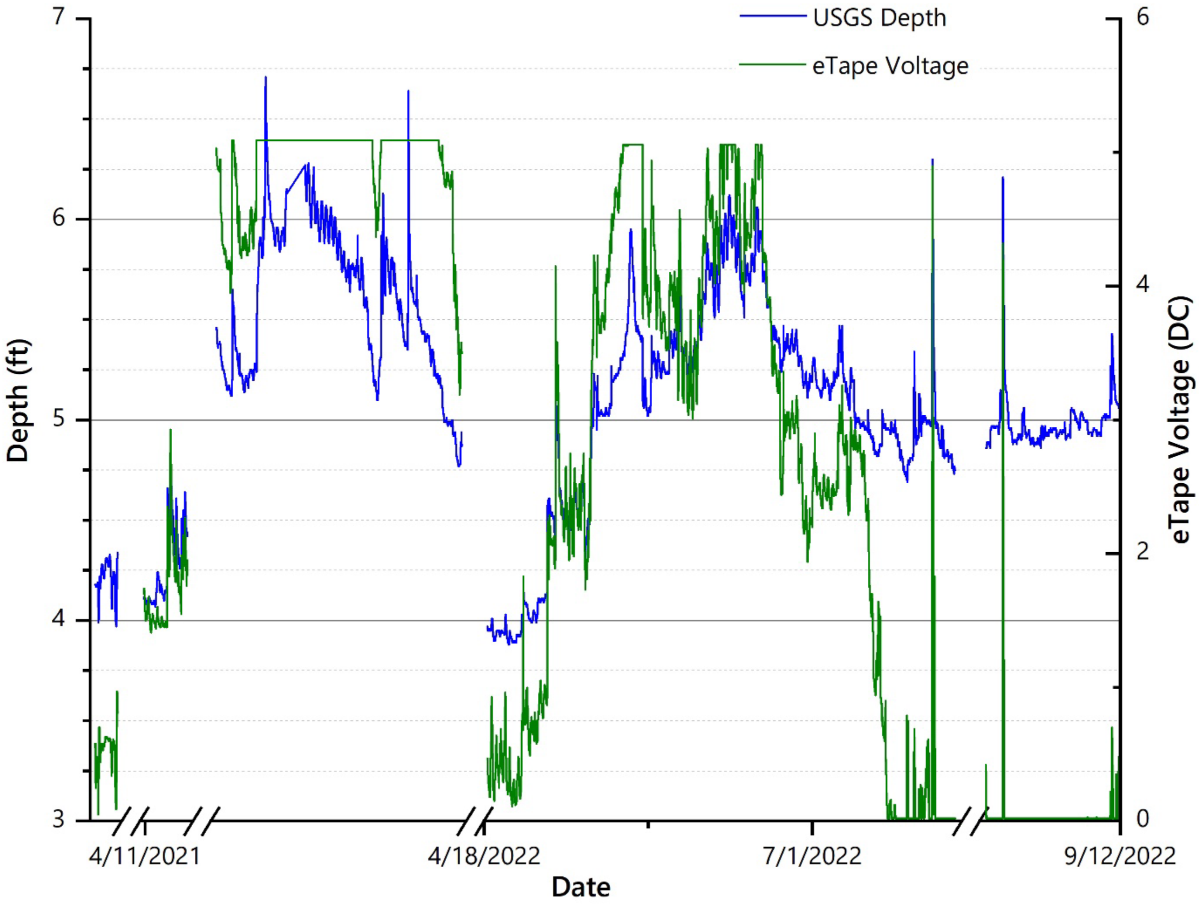

Figure 15 – eTape® sensor data collected at the Boulder Creek site with concurrent USGS depth measurements.

The data presented in Figure 15 illustrates problems encountered with the eTape® sensor. One such problem occurs when the water depth exceeds the range of the eTape®. When this happens, the eTape® inside the PVC housing is submerged and its voltage response is at a maximum of 5.1 VDC. Ideally, the voltage response continues to function when the submergence subsides, however, data collected during May and June of 2021 show this did not happen (Figure 16). The eTape® response remained constant. One possible reason for this malfunction could be that sediment clogged the suction strainer attached to the PVC housing preventing the standpipe to drain below the eTape®. Figure 17 presents a photograph taken on June 8, 2021, show high flows in Boulder Creek. The annual peak discharge for Boulder Creek at this location occurred on May 30th. The same problem occurred again in 2022, however, the eTape® recovered from the high water quicker than the previous year.

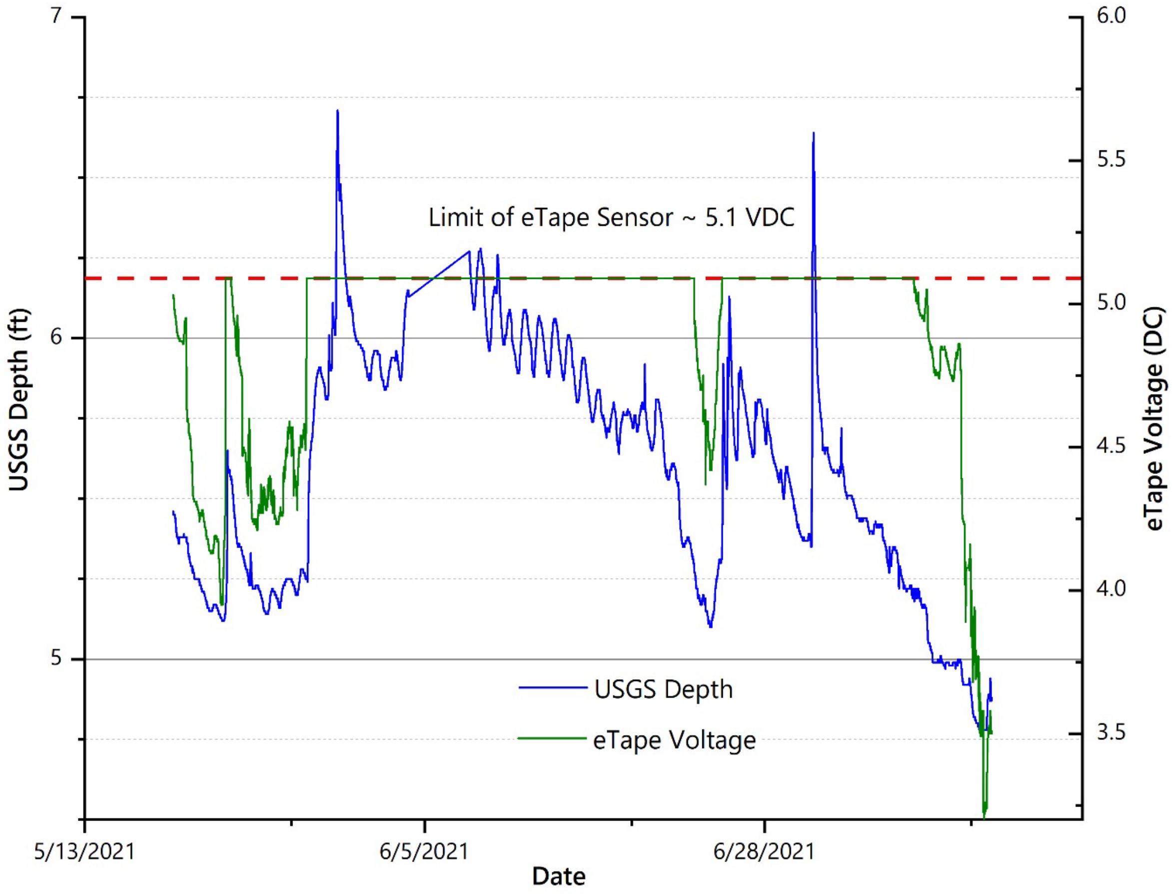

Figure 16 – An excerpt of the data collected at the Boulder Creek site showing high flow depths exceeding the range of the eTape® sensor.

Figure 17 – Photograph of the Boulder Creek site taken shortly after the occurrence of the peak annual flow. The eTape® sensor is circled in red.

After nearly two years testing in Boulder Creek, the eTape® sensor response voltage started dropping to zero. This started occurring during June 2022 and eventually remained near zero for the remainder of the test. When the sensor was removed in September 2022, it was observed to be submerged in water within its measuring range. The cause of this failure is unknown. Restarting the datalogger corrected this problem.

Neglecting the problems encountered during the testing period at Boulder Creek, the Pearson correlation coefficient between the eTape® sensor voltage response and the USGS depth was 0.72 suggesting a significant linear relationship. Measurements taken by the eTape® sensor in May and June of 2022 can be ignored because the water depth exceeded the upper limit of the eTape® sensor, increasing the Pearson correlation coefficient to 0.78.

Clear Creek

The eTape® sensor located alongside USGS gage #06718550 – North Clear Creek near Blackhawk, CO collected 16,072 samples at 5-minute intervals (22.3 days) from April 11, 2021, through June 24, 2022. Power at this site was augmented with a 10-watt solar panel. The datalogger was removed from this site on May 16, 2021, with the intention of redeploying a different datalogger soon after, however project complications prevented the datalogger from being deployed until June 3, 2022. Figure 18 presents the data collected at this location.

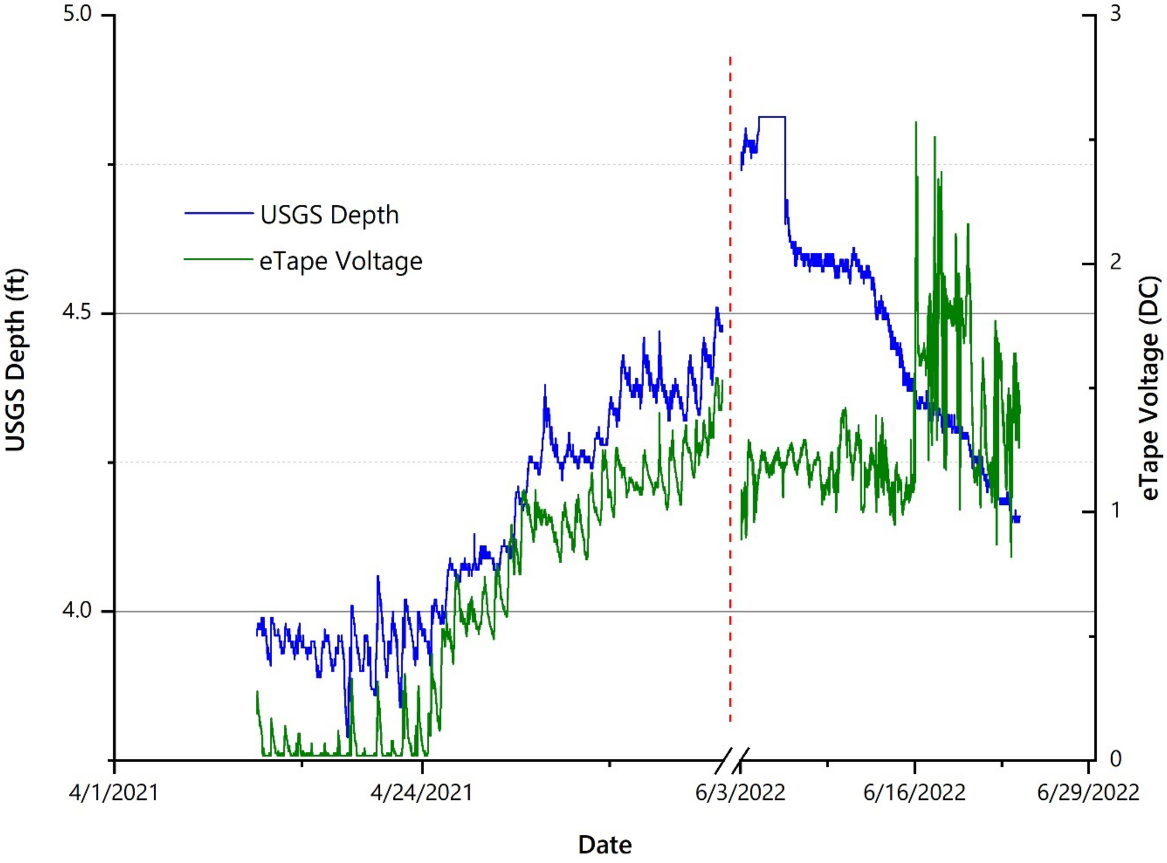

Figure 18 – eTape® sensor data collected at the Clear Creek site with concurrent USGS depth measurements.

As seen in Figure 18, the data collected at Clear Creek in June 2022 seemed erroneous with a lot of noise. An investigation into this problem revealed the noise came from the eTape® itself, the datalogger appeared to function correctly. The circuit embedded in the eTape® sensor is sealed in a potting solution by Milone Technologies and could not be inspected without damaging the sensor. The exact cause of the failure is unknown. Data collect at Clear Creek during April and May of 2021 did, however, have a strong Pearson Correlation of 0.97 (Figure 19).

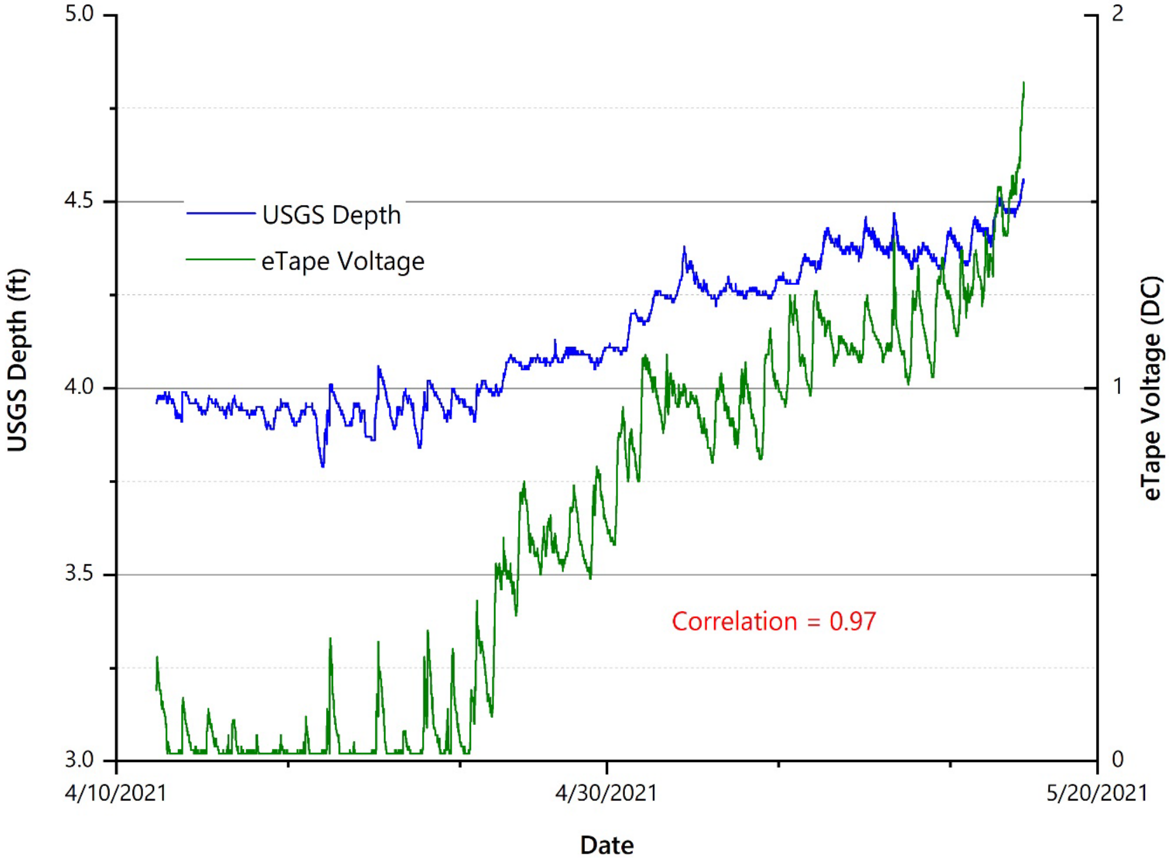

Figure 19 – 2021 eTape® sensor data collected at the Clear Creek site with concurrent USGS depth measurements.

Leavenworth Creek

The eTape® sensor located alongside USGS gage #06714800 – Leavenworth Creek near Georgetown, CO collected 6,309 samples at 5-minute intervals (8.76 days) from May 17, 2022, through June 27, 2022. Power at this site was augmented with a 10-watt solar panel. Although a relatively smaller amount of data was collected at Leavenworth Creek, the data show a strong correlation between the eTape® sensor voltage response and the USGS depth, having a Pearson correlation of 0.94. June 2022 USGS depth measurements appear to have some noise, slightly lowering the Pearson correlation (Figure 20).

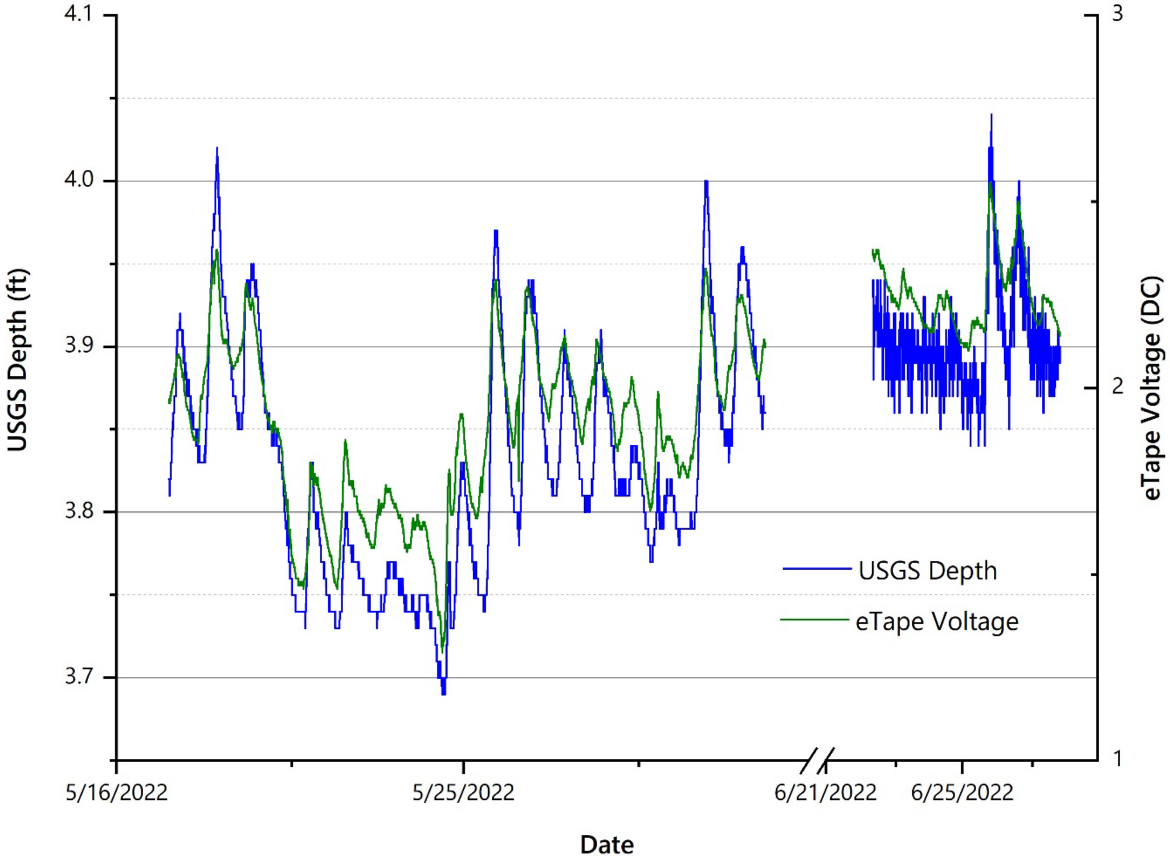

Figure 20 – eTape® sensor data collected at the Leavenworth Creek site with concurrent USGS depth measurements.

Discussion

Although the awarded WaterSmart proposal targets replacing more costly, permanent streamflow sensors such as the USGS gaging stations, assessing the practicality of such a concept requires further analysis beyond the scope of this investigation.

Design and Deployment

The eTape® sensor can be difficult to install because it must be vertical in the water column. This limits its location in the stream channel to protective eddies or stilling wells. This investigation assumes stilling wells are not available at the desired location because of their high cost, limiting the installation option to protective eddies. Because the eTape® itself is too fragile for directly submerging into a stream, a protective housing is needed. Such housing takes little effort to fabricate using readily available parts from local hardware stores. Ideally, the housing can be attached to an existing structure or object in the stream such as a large boulder, pier, or wingwall. The deployment difficulty increases if no such object or structure exists. Attempts made during this investigation to drive a fence post into a stream channel revealed increasing difficulty with increasing elevation. This likely because there are fewer sediment fines in streambeds at higher elevations. The eTape®, however, proved easy to calibrate. It only needs to be submerged in water. A ruler printed on the eTape® can be used to visually observe the depth of water. Other passive depth measurement devices such as pressure transducers require specialized equipment and knowledge for calibration.

During the two-year period of testing in Boulder Creek, the eTape® sensor experience some problems due to freezing water during colder temperatures as well as clogging due to sediment movement during higher flows. Both problems could be mitigated with further design modifications. Other types of passive depth sensors are also expected to encounter such problems and are typically mitigated through frequent maintenance. Many USGS streamflow sites in higher elevations only report seasonal flows that are mostly from snowmelt. Sediment clogging can also be mitigated by locating the sensor higher above the streambed and away from sediment deposits. The eTape® sensors ultimately failed at both the Boulder Creek and Clear Creek locations. Unlike the senor at Leavenworth Creek, both the Boulder Creek and Clear Creek sensors experienced conditions from all four seasons, suggesting the eTape® sensor might not be suitable for year-round deployment.

Designing and fabricating a functioning datalogger from an Arduino-style microcontroller proved more difficult than expected. More time was needed selecting a microcontroller along with the necessary components needed for fabricating a datalogger. During laboratory testing, many component combinations failed, despite meeting all the required specifications. This resulted in a “trial and error” design approach which took much longer than expected to complete. Design modifications were also needed after additional failures occurred at the USGS stream gage sites. More time was needed than expected programming the datalogger. Although publicly available libraries used to control the various components were used, additional time was needed to fully understand their use. Furthermore, these libraries were not without code errors, especially when used with different libraries for other components. Each time a design revision was made, the entire datalogger program, including the libraries required revision.

Competitively priced dataloggers offered by various companies should also be considered. These companies have invested considerable effort in developing their devices, which have a proven record of reliability. While the cost of proven datalogger technologies is greater than the eTape® sensor datalogger presented in this study, the effort required to assemble and operate dataloggers purchased from these companies is much less. For many projects, the labor costs for assembling dataloggers using low-cost microcontrollers often exceed the material cost of purchasing a datalogger from a manufacturer. Loss of data can be a costly consequence from an unreliable datalogger failing and should be considered when choosing to use low-cost microcontrollers.

Data Quality

This investigation revealed the quality of data collected is directly related to the accessibility of the stream site as illustrated by the amount and quality of the data collected in Boulder Creek compared to the other two, less assessable sites at Clear Creek and Leavenworth Creek. The Boulder Creek site was visited nearly four times more often than the other sites. This allowed for more frequent design corrections resulting in fewer data collection interruptions. Such frequent visits might reduce the risk of losing large amounts of data. If accessibility is difficult, however, this investigation reinforces the need for reliable datalogging.

Although Boulder Creek collected the most amount of data during its two-year deployment, it had the lowest Pearson correlation coefficient of 0.72, suggesting a linear relationship between the eTape® sensor voltage response and the USGS stream gage depth. This lower value implies that the sensors are in locations having different hydraulic conditions. The correlation is further affected by the erroneous data collected during high flows. Removing this data increases the value slightly to a value of 0.78. Data collected at the Clear Creek and Leavenworth Creek locations had much higher Pearson correlations coefficients of 0.97 and 0.94, respectively. Such high values suggest a strong linear relationship between the USGS depth and the eTape® sensor response. Despite problems encountered with the eTape® housing and the datalogger, the eTape® sensor performed well when functioning correctly.

Conclusions

Using eTape® might be suitable for some continuous streamflow measurement applications but further development is needed for widespread deployment. While the PVC standpipe housing is easy to fabricate, there are limited options for securing them in a stream. These requirements are typically encountered by those who have specific data needs, not for permanent continuous stream gage locations such as those constructed by the USGS. The infrastructure cost for such permanent stream gage sites is significantly greater than the flow measurement equipment, resulting in higher earned value from the collected data, or consequentially, a higher value lost if data are not collected due to equipment failure. The USGS commonly uses an active depth sensor that pressurizes a submerged tube in the stream. Such devices are relatively easy to maintain because none of the electronic components are submerged in the stream. These devices, however, are complex and costly, making them impractical for unique data needs.

Using the Arduino-style microcontroller as a datalogger is beyond the capability of most end users. A datalogger needs to be reliable. Developing, testing, and fabricating these microcontroller dataloggers comes with a significant cost. Purchasing a datalogger from a reputable vendor is likely a more cost-effective solution.

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