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Field application of inexpensive custom-built programmable dataloggers for routine instrumentation needs

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ABSTRACT
A low-cost datalogger was built using open-source materials and installed in place of commercially available dataloggers at three sites in western Canada. Data collected with commercial units and the prototype datalogger were compared to determine the accuracy of low-cost units. Testing of the low-cost datalogger has demonstrated adaptability to various sensor types. The study experimented with negative pore water pressure (matric suction), volumetric water content, and temperature from SDI-12 sensors as well as positive pore water pressure and temperature from vibrating wire piezometers. Assembly, installation, and monitoring using the low-cost datalogging system has occurred over the past two years, proving their durability and suitability for field application. Field deployment of these low-cost dataloggers has encountered some challenges and limitations, which are discussed.

RÉSUMÉ
Un enregistreur de données à faible coût a été construit à l'aide de matériaux open source et installé à la place d'enregistreurs de données disponibles dans le commerce sur trois sites dans l'ouest du Canada. Les données recueillies avec des unités commerciales et le prototype de l'enregistreur de données ont été comparées pour déterminer la précision des unités à faible coût. Les tests de l'enregistreur de données à faible coût ont démontré l'adaptabilité à divers types de capteurs. L'étude a expérimenté la pression négative de l'eau interstitielle (aspiration matricielle), la teneur en eau volumétrique et la température des capteurs SDI-12 ainsi que la pression positive de l'eau interstitielle et la température des piézomètres à fil vibrant. L'assemblage, l'installation et la surveillance à l'aide du système d'enregistrement de données à faible coût ont eu lieu au cours des deux dernières années, prouvant leur durabilité et leur pertinence pour une application sur le terrain. Le déploiement sur le terrain de ces enregistreurs de données à faible coût a rencontré certains défis et limites, qui sont discutés.

1 INTRODUCTION

Instrumentation monitoring is a key part of nearly every geotechnical investigation. The costs associated with instrumentation can be significant and project budget overruns often result in instrumentation cutbacks which can be detrimental to monitoring programs. Cost savings can be vital to profit margins, or they can allow the engineer to develop a more detailed instrumentation network at the same relative cost.

While designing sensors is often complex and requires expensive materials/proprietary knowledge, the collection and analysis of data from these sensors is often straightforward and easily automated. Low-cost versions of commercial dataloggers offer a solution to rising costs of conventional units that have limited storage space and flexibility. Many commercial units contain peripheral equipment and special cables to collect data in the field. The present study documents a low-cost datalogging unit developed using open-source materials and components that are readily available to anyone who wants to build their own datalogger.

Focus is placed on the Arduino microcontroller due to its accommodating learning environment and ability to adapt to many instrumentation sensor output signals. Arduino microcontrollers have shown significant promise as a low-cost alternative to commercial units in the field of hydrology (Hut 2013). Automation of a double ring infiltrometer (Fatehnia et al. 2016) and the use of commercial sensors for temperature and humidity (Sadler et al. 2016) have demonstrated their feasibility for simple data collection, storage, and transmission. As these microcontrollers are relatively inexpensive, vast monitoring networks of sensors can be implemented (Wickert 2014, Tauro et al. 2018). Furthermore, they can be installed in remote locations where field accessibility is an issue (Hund et al. 2016).

A few common types of geotechnical sensors were studied as potential suitors for a low-cost datalogging system including:

- Vibrating wire piezometer (VWP) pressure gauges
- Matric suction and water content sensors (SDI-12); and
- Thermistors

Measurements from each sensor were compared between a commercial datalogging unit and the low-cost datalogging system. While the list excludes some sensors used in geotechnical engineering, computer microcontrollers have the potential to be used with any sensor with an electrical output signal. One must simply take advantage of the excess of open-source tools, resources, and sharing capabilities made available by the Internet. Numerous web forums exist with the sole purpose of developing and sharing code for worldwide collaboration. These tools are freely available and have the potential to drastically reduce costs and improve efficiency for simple datalogging processes over a wide range of conventional sensors.

2 DATALOGGING SYSTEM

2.1 Overview

The Arduino project began in 2005 and focused on providing a low-cost learning environment for students to interact with various sensors and circuits (Cressey 2017). In the past 15 years, the Arduino project has developed several types of open-source hardware, including the Arduino Mega 2560. These computer microcontrollers have no operating system, are completely programmable using C++ programming language, and have limited power consumption, rendering them useful to field application. Arduino computer microcontrollers have gained a significant following among novice computer programmers and amateur hobbyists for their versatility and widely available hardware, attachments, open-source libraries, and support forums (Banzi and Shiloh 2015). The Arduino Mega 2560 was chosen over other options (Raspberry Pi and Arduino Uno) due to its low power requirements, computational ability (compared to Uno), and programming simplicity along with its reliability.

The automated datalogging system combined several components that were wired internal to the datalogger (Figure 1):

- Datalogging shield (including real time clock and SD card interface) – stacking headers were installed to promote compact wiring and data transfer interface with the microcontroller board
- Solar charger shield – charge controller that regulates current from solar panel to feed the battery or microcontroller
- “Breadboard” – wiring interface used to connect sensors to microcontroller’s digital pins
- Arduino Mega 2560 – executes C++ script and sends data to the SD card
- Lithium polymer rechargeable battery – variations between 2500 to 6000 mAh were tested
- 3G telemetry shield – uses a SIMCom 5320A modem to transmit data over a cellular network

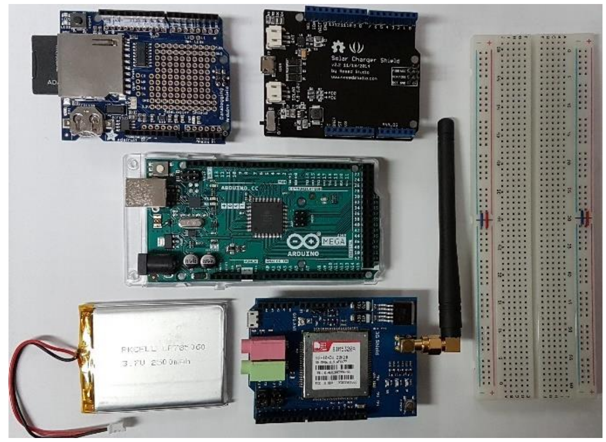

Figure 1. Internal components of the computer microcontroller datalogger

2.2 External Hardware

The internal components of the datalogging system are enclosed in a waterproof case with a gasket seal. The case has customizable tear-away foam allowing the user to securely hold the internal components in place. Mounting brackets have been attached to the back of the case allowing the system to be connected to a sturdy post and oriented in any direction. Holes were drilled in the bottom of the case to allow sensor cables to be fed into the “breadboard” connections. A 9W solar panel was found to provide enough recharging power to the battery when the datalogger was placed in exposed locations that receive adequate sunlight (no shadows) throughout the year. The solar panel was mounted with hinges on the lid of the waterproof case creating a 45-degree angle with the ground. Grommets placed in these holes help to maintain a watertight seal.

After mounting the case to a close-ended post, the sensor cables were securely wrapped around the post. Protective cable wrapping is recommended, especially in areas that are heavily trafficked by wildlife. Finally, the loggers are oriented due south for a northern hemisphere installation to take advantage of the solar radiation throughout the year. Where human vandalism is a concern, these cases can be locked with a padlock to minimize disturbance.

2.3 Vibrating Wire Piezometer (VWP) Pressure

The programmable datalogger was connected to a VWP and successfully used to measure pore water pressure and temperature in the subsurface. Development and manufacture of vibrating wire sensors requires specialized knowledge, equipment, and techniques. However, the data collection from these instruments can be reproduced with limited technical background and inexpensive materials.

The working principle for VWPs centers around a tensioned steel wire attached to an internal diaphragm. External pore water pressure acts on the diaphragm through a porous stone, altering the tension in the attached steel wire. The vibrating steel wire induces alternating voltage current in a set of pickup coils positioned around the wire. Signal processing of the induced current is used to determine the pressure on the diaphragm. Calibration factors are specific to individual sensors, allowing the user to determine the associated calibrated pore water pressure.

There are several methods of inducing current that may be used to conduct a pore water pressure measurement using a VWP (Viman et al. 2004, Pop et al. 2013, Porfirio et al. 2014). A common method is to "pluck" the tensioned steel wire in square wave pulse trains that are relayed at rapidly increasing frequency over a set period. The designated range encompasses the expected natural frequency of the steel wire. After a short period of time, all frequencies die out except the natural or resonant frequency (Kovacs et al. 2012). By shifting the analog pin reference to accommodate the alternating current output from the sensor, it was possible to determine the resonant frequency from the maximum and minimum voltage peaks using Fast Fourier Transform (FFT) analysis. The resonant frequency (f_r [Hz]) is used to calculate "B-units" which can be used in the calibrated equations supplied by the sensor manufacturer to determine the equivalent pressure:

$$B_{units} = (f_r)^2 x 10^{-3} \qquad [1]$$

Initially, testing was conducted in Matlab using data output from an oscilloscope that sampled at 200 MHz. The methods were extended to the Arduino datalogger using an open-source library known as "arduinoFFT" available through GitHub (Condes 2020). After determining the most suitable analysis parameters through the initial testing, the code was programmed for VWP signal processing. The accuracy of the measurement is greatly improved with higher rates of sampling resulting in larger quantities of data storage for the FFT algorithm. The significant use of random-access memory (RAM) was one of the main reasons the Arduino Mega was chosen over the more basic Arduino Uno. The data was improved by rapidly testing for the resonant frequency multiple times and averaging the results. Further verification of the data validity was conducted by comparing the results to measurements taken by commercial dataloggers.

2.4 VWP Thermistor

VWPs contain an internal thermistor that provides indication of the soil temperature at the sensor depth. Thermistors have variable resistance based on temperature. By measuring the voltage drop across the thermistor with one of the analog pins on the computer microcontroller, it is possible to determine the equivalent resistance of the thermistor. One end of the thermistor must be grounded while the other end is connected to a resistor of known resistance in series. A jumper wire is inserted between the thermistor and the known resistor. The jumper wire is connected to an analog pin and measures the analog-to-digital conversion (ADC) value which can be converted to a voltage. The other end of the known resistor is connected to a digital pin that cycles power through the circuit. All other parts of the circuit are known (such as voltage supplied to the circuit and the resistance of the known resistor). The thermistor's resistance is converted to temperature based on the Steinhart and Hart (1968) equation:

$$T^{-1} = A + B \log(R) + C (\log(R))^3 \qquad [2]$$

where,
T is the temperature [K];
A, B, and C are constants; and
R is the thermistor resistance [units based on constants].

2.5 Water Content and Soil Suction

Many types of soil water content and soil suction sensors transmit measurements to the datalogger using the serial-digital interface standard at 1200 baud (SDI-12). A primary advantage of this form of data transmission is that data from multiple sensors can be sent over a single cable and no further processing is required to correct the measurements. Furthermore, sensors do not need to be connected to the datalogger in any pre-determined order as each sensor is programmed with an individual identification number during setup.

Sensors with SDI-12 compatibility are readily available from several environmental instrumentation suppliers. Open-source libraries have been specifically developed to interface SDI-12 sensors to an Arduino microcontroller and are accessible on GitHub, such as "EnviroDIY/Arduino-SDI-12" (Stroud Water Research Center 2020). These repositories provide example code and forums to discuss issues with the source code and proper methods for implementation. At part of this study, the example code was modified to permit the use of multiple sensors with separate identification numbers. Measured data was written to an SD card to allow for more universally accessible data collection.

2.6 Optional Telemetry

Telemetry attachments have been added to the datalogging system where a cellular network signal is present. Telemetry enables data to be collected remotely and limit expenditures on travel to site. The current setup used a telemetry shield set up on a 3G cellular network to transmit data via instant messaging. These shields contain modems with the added capability of transmitting data to cloud storage and private servers. More advanced telemetry shields are being produced every year with added functionality and better data transmission rates. One of the current drawbacks is the additional power consumption required when operating a cellular modem. At the present, the primary use of the telemetry module is focused on occasional transmission of datapoints that verifies the ongoing operation of the datalogger and identifies potential issues in the data collection process.

3 RESULTS AND DISCUSSION

3.1 Analysis of VWP Signal

Testing was conducted in the laboratory to determine the most effective amplitude, frequency, and interval for excitation voltage on the tensioned steel wire in a 0.35 MPa VWP sensor. Signal processing of the return wave required knowledge of the wait time necessary to analyze the resonant frequency. A digital storage oscilloscope manufactured by Agilent Technologies was used to sample the output voltage signal. Data points were exported to Matlab to determine the ideal pulse wave and delay resulting in repeatable estimation of the resonant frequency.

A square wave pulse train of 0 V to 5 V incrementing by 50 Hz at 4 millisecond (ms) intervals was found to be effective in producing repeatable results. The frequency increased from 1400 Hz to 3500 Hz over a period of approximately 172 ms. Following a 20 ms delay, the induced voltage was analyzed over a 40 ms period. The voltage data points were sampled and binned using an FFT algorithm to determine the frequency at which the maximum amplitude occurs. The frequency of maximum amplitude is the resonant frequency of the tensioned steel wire. The following figure demonstrates the process from initial collection to analysis of the induced voltage and determination of the resonant frequency (Figure 2).

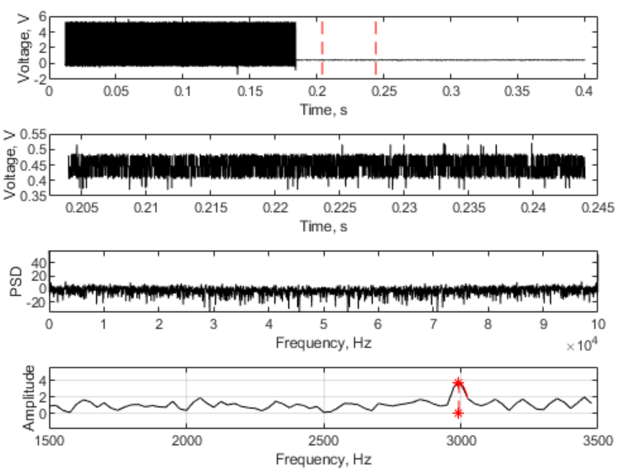

Figure 2. FFT analysis of induced voltage after square wave pulse train at zero pressure

3.2 VWP Pressure Data Verification

A side-by-side comparison of the VWP signal processing from the low-cost datalogging system and a commercial datalogger (Slope Indicator VW data recorder) was conducted to verify measurements. A poly vinyl chloride (PVC) pressure chamber rated to 2000 kPa was built in the laboratory to compare the two datalogging systems at elevated pressures (Figure 3). A standard VW2100 model piezometer was sealed inside the pressure chamber and the entire chamber was filled with water. The apparatus was pressurized up to 150 kPa using a pressure-volume (PV) controller that enabled constant pressure in the chamber. At approximately 10 kPa increments, both the low-cost datalogger and conventional datalogger were attached to the VWP and a pressure reading was conducted. The commercial readout unit and the low-cost datalogger demonstrated a high degree of correlation, verifying the validity of the low-cost datalogger measurements (Figure 4).

Figure 3. Pressure chamber with commerical readout unit and low-cost datalogger

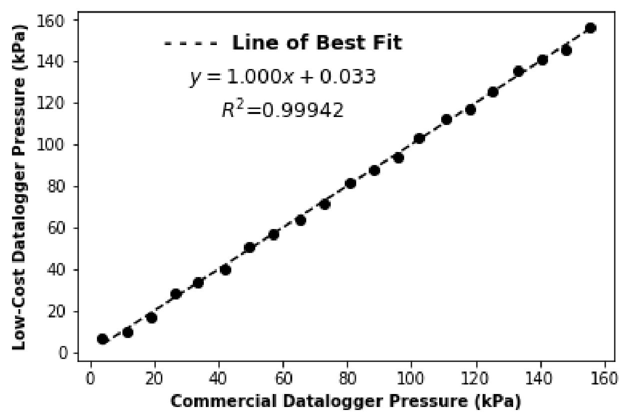

Figure 4. VWP pressure comparison between two datalogging systems

3.3 VWP Temperature Data Verification

After determining the validity of pressure measurements by the low-cost datalogger, a side-by-side comparison of temperature measurements was completed. The same VW data recorder from the previous section was employed as the commercial datalogger comparison for the purposes of this test. As ground temperatures do not fluctuate to the same extent as surface temperature, a smaller range of testing would be required. However, accuracy and durability of the datalogger was tested by conducting a series of temperature changes to both the sensor and the datalogger. Testing was conducted with a dry VWP sensor that did not have water between the porous stone and diaphragm. Frozen water in VWP sensors can cause irreparable damage to sensors.

A simple test was carried out by exposing the VWP sensor and low-cost datalogger to a series of temperatures while taking measurements with the low-cost datalogger and the commercial readout unit at 2-minute intervals.

Initially, the VWP was placed in a refrigerator with a mercury thermometer allowing time for the temperature to equilibrate around 2.5°C. The sensor was then removed from the refrigerator and allowed to equilibrate around 25°C. Once acclimatized at 25°C, the sensor was placed into a deep freezer along with the low-cost datalogger. The commercial readout unit was left outside the deep freezer for comparison. The temperature in the deep freezer began to stabilize around -6°C after an hour. Finally, the sensor and datalogger were removed from the deep freezer and allowed to equilibrate at room temperature (Figure 5). Comparison of the measurements from the low-cost datalogger and the commercial readout unit over this period indicated that there was a high degree of correlation between the two datalogging systems (Figure 6).

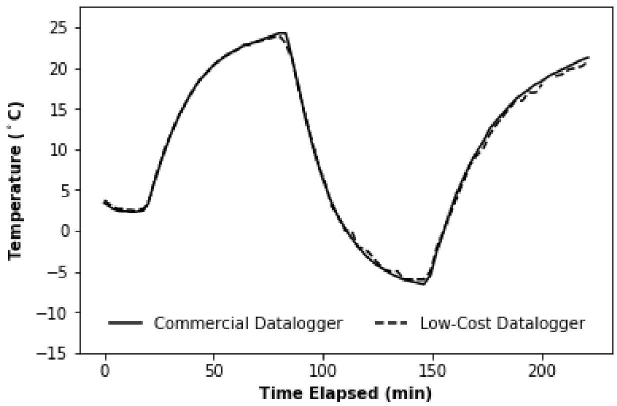

Figure 5. Time series of VWP thermistor temperature from both dataloggers

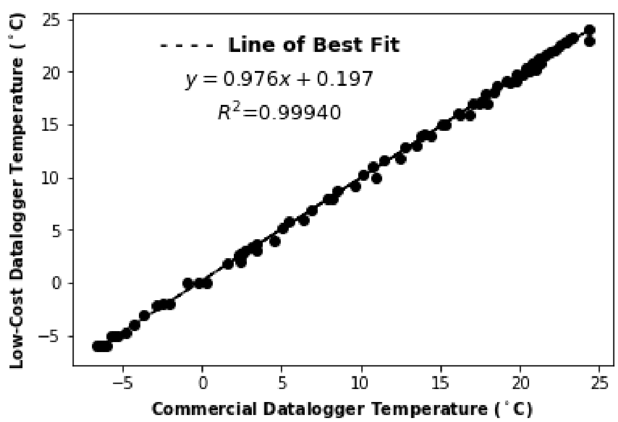

Figure 6. VWP thermistor temperature comparison between two datalogging systems

3.4 Low-Cost Datalogger Field Application

The low-cost datalogging unit was installed in field sites at three locations across western Canada. Initial deployment logged VWP measurements near the Borden Bridge northwest of Saskatoon on Highway 16. A second deployment included matric suction (TEROS 21 obtained from Meter Group) and volumetric water content (5TE from Meter Group) sensors at the Ripley Slide near Ashcroft, British Columbia in November 2018 (Figure 7). A subsequent installation of water content sensors was conducted in the summer of 2019 at MI 158.75 on the Canadian Pacific (CP) Scotford Subdivision northeast of Edmonton, Alberta. In November 2019, matric suction sensors and water content sensors were installed and connected to the low-cost datalogging system at the Borden Bridge site.


Figure 7. Low-cost datalogger installation at Ripley Slide near Ashcroft, British Columbia

The low-cost datalogging system has been exposed to a wide array of atmospheric events, solar radiation challenges, drastic temperature fluctuations, and wildlife disturbance. Damage to the dataloggers has been minimal over the past two years. Loose cables have been known to attract curious deer. Cable armouring is a necessity is high traffic wildlife locations. Temperature fluctuations have been found to impact the low-cost datalogger no more than commercial dataloggers installed on the same site. For example, in February 2019 the Borden Bridge site experienced extremely cold temperatures consistently dropping to -40°C which caused several batteries in the commercial dataloggers to die. The low-cost datalogger measuring the VWP sensors also died around the same time as the commercial dataloggers (although this may have been due to solar elevation). The winter of 2020 was slightly milder at the Borden Bridge site and did not experience such extreme low temperatures for a sustained period. As a result, none of the dataloggers lost power due to low temperatures. At the Scotford site, a wire became brittle and broke, but the datalogger was still operational at -40°C as solar radiation is not obstructed during the day.

Solar radiation seems to be the biggest concern when operating the low-cost datalogging system. The system relies on solar radiation which minimizes the need to change expensive batteries. However, the system is then restricted to where it can be placed. Raised ground south of dataloggers cast shadows during the winter months which can present challenges when logging through the winter. Where the dataloggers are not shadowed during the winter, operation persists with no issues. As a result, datalogger location is an important factor in terms of winter solar radiation. If the installation is to be placed in hilly terrain, one must consider the solar elevation as the days approach winter equinox. It is also important to remember that increasing the number of sensors will increase the required power consumption and the datalogging location should be planned accordingly.

Standard data collection (without telemetry) is very straightforward. The low-cost datalogging system case forms a sort of platform when opened allowing the user to pull the SD card, copy the .txt file to a laptop computer, and re-insert the SD card (Figure 8). Data collection by the datalogger is automatically skipped while the SD card is not inserted and resumed when the SD card is replaced. There is no additional software required to access the data. No programs need to be downloaded before travelling to the field. The only requirement is an SD card reader which comes standard on many laptops.

Figure 8. Accessing data from low-cost datalogger installation at Borden Bridge

4 FUTURE WORK

The development and testing of any new datalogging system always involve challenges that need to be addressed and revised in future installations. Over the past two years, significant improvements have been achieved in the low-cost datalogging system. However, power requirements remain higher than conventional datalogging systems. Improvement to coding efficiency and limitation of unnecessary power usage in the computer microcontroller would reduce power usage making the system more reliable in the winter months. Furthermore, future revisions of the low-cost datalogging system can be combined with conventional power sources to enhance reliability.

Telemetry attachments for the Arduino are currently in their infancy. Additional development and expansion to 4G and 5G networks in the future will increase data transmission rates and reduce our reliance on third parties. Cloud storage has been introduced in recent years, allowing for more efficient data collection and personal ownership of data without the need to route through an outside server.

Additional sensor types may be connected to the datalogging system in the future. Adjustment of sampling rates and long-term shift in the real time clock will help to determine the interval required between site visits. Continued testing and installation at additional field sites will further the development of the low-cost datalogger solution.

5 CONCLUSION

Geotechnical monitoring programs are regularly forced to scale back instrumentation plans based on financial constraints or cost overruns. Commercial datalogging systems can be cost-prohibitive. However, open-source materials and knowledge are readily available that can help to ease the financial burden for basic datalogging needs on low budget projects. Alternatively, a low-cost datalogging system may be deployed in geotechnical investigations to increase the size of monitoring networks for the same relative cost.

The present study developed a low-cost programmable datalogger using several open-source libraries and online forums. The present datalogging system has been installed at three sites across western Canada, collecting data over the past two years. The datalogging system has been programmed to operate with VWP pressure gauges, thermistors, water content and matric suction sensors, although any type of sensor with electrical output could be measured using a similar datalogging system. Furthermore, the number of sensors attached to the datalogging unit is only limited by the number of ports of the computer microcontroller. For SDI-12 sensors, data is sent through a single cable and the number of sensors is only limited by coding efficiencies.

Lab and field testing confirmed the accuracy and durability of the low-cost datalogging system. The system is highly adaptable which makes them particularly advantageous to the field of geotechnical engineering. These dataloggers are customizable, require no proprietary peripherals, and have standard expandable storage space. The development of a low-cost datalogging system offers consultants and researchers the ability to save budget space or expand their monitoring networks which is critical in an increasingly competitive market.

6 ACKNOWLEDGMENT

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7 REFERENCES

Banzi, M., Shiloh, M. 2015. *Getting started with Arduino*. Maker Media, Inc.

Condes, E. 2020. kosme/arduinoFFT. In: Github. Available from: https://github.com/kosme/arduinoFFT (accessed May 2020)

Cressey, D. 2017. Age of the Arduino, *Nature*, 544: 125-126.

Fatehnia, M., Paran, S., Kish, S., Tawfiq, K. 2016. Automating double ring infiltrometer with an Arduino microcontroller, *Geoderma*, 262: 133-139.

Hund, S.V., Johnson, M.S., Keddle, T. 2016. Developing a hydrologic monitoring network in data-scarce regions using open-source Arduino dataloggers. *Agricultural and Environmental Letters*. 5 p.

Hut, R. 2013. New observational tools and datasources for hydrology. PhD thesis. Delft University of Technology, Netherlands.

Kovacs, I., Mircea, M., Gyurka, B., Balogh, S. 2012. Vibrating wire sensor measurement method by simulation with steps of variable frequency sinusoidal pulse trains, *In* Proceedings of 2012 IEEE International Conference on Automation, Quality, and Testing, Robotics, Cluj-Napoca, Romania.

Pop, S., Ciascai, I., Bande, V., Pitica, D. 2013. High accuracy method for measurement of vibrating wire transducer, *In* Proceedings of the 36th International Spring Seminar on Electronics Technology, Alba Iulia, Romania.

Porfirio, V.G., Vicente, H.K.M., de Gortari, A. 2014. Comparison of excitement methods of vibrant wire sensors, *African Journal of Physics*, 3(4): 78-80.

Sadler, J.M., Ames, D.P., Khattar, R. 2016. A recipe for standards-based data sharing using open source software and low-cost electronics. *Journal of Hydroinformatics*, 18(2): 185-197.

Steinhart, J.S., Hart, S.R. 1968. Calibration curves for thermistors, *Deep-Sea Research and Oceanographic Abstracts*, 15(4): 497-503.

Stroud Water Research Center. 2020. EnviroDIY/Arduino-SDI-12. In: GitHub. Available from: https://github.com/EnviroDIY/Arduino-SDI-12 (accessed May 2020).

Tauro, F., Selker, J., van de Geisen, N., Abrate, T., Uijlenhoet, R., Porfiri, M., Manfreda, S., Caylor, K., Moramarco, T., Benveniste, J., Ciraolo, G., Estes, L., Domeneghetti, A., Perks, M.T., Corbari, C., Rabiei, E., Ravazzani, G., Bogen, H., Harfouche, A., Brocca, L., Maltese, A., Wickert, A., Tarpanelli, A., Good, S., Alcala, J.M.L., Petroselli, A., Cudennec, C., Blume, T., Hut, R., and Grimaldi, S. 2018. Measurements and observations in the XXI century (MOXXI): innovation and multidisciplinarity to sense the hydrological cycle, *Hydrological Sciences Journal*, 63(2): 169-196.

Viman, L., Ciascai, I., Dabacan, M., Pop, S. 2004. Using an embedded microcontroller system to excite vibrating wire transducers, *In* Proceedings of the 27th International Spring Seminar on Electronics Technology, Bankya, Bulgaria.

Wickert, A.D. 2014. The ALog: Inexpensive, open-source, automated data collection in the field, *Bulletin of the Ecological Society of America*, 95(2): 166-176.