Building a Low-Cost, Internet-of-Things, Real-Time Groundwater Level Monitoring Network

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Abstract

A community-based, real-time, groundwater level monitoring network consisting of eleven sites was built in Nova Scotia, Canada, using privately-owned domestic wells and low-cost, custom-made water level meters. The real-time meters use an ultrasonic sensor to measure water levels and an Internet-of-Things device to transmit the data to the Internet by WiFi or cellular connection. The water level data are plotted in real-time on a time-series graph and are available immediately for online viewing and downloading. Based on observations at three sites, the real-time water level meter data compare well to pressure transducer measurements, with mean absolute errors of less than 0.02 m. The meters are simple to build, and components are readily available from online suppliers. The cost of the components needed to build the meter is US$150 for the WiFi version and US$225 for the cellular version. Step-by-step instructions are available for building the meter.

Introduction

Groundwater is increasingly being relied upon for water supplies around the world due to population growth and socio-economic development. Over the last 50 years, it is estimated that global groundwater extraction has increased fourfold (FAO 2016). This trend is likely to continue, especially with the expectation that groundwater, which is more resilient to drought than surface water, will play an important role in climate change adaptation (IAH 2019; Rivera 2019). As our reliance on groundwater grows, so too will the need to improve monitoring networks that provide the data that is required to manage this resource.

Measurements of groundwater levels are the most fundamental indicator for assessing the status and trend of the quantity of water stored in aquifers (Taylor and Alley 2001). Although remote observations using satellites can be used to assess groundwater depletion, in-situ water level measurements are needed to calibrate and validate satellite measurements and there is no substitute for ground-based monitoring networks (Famiglietti et al. 2015). Despite this reality, groundwater is often poorly monitored (Famiglietti 2014) and there has been a global decline in groundwater monitoring (van der Gun 2018) as well as growing concern that monitoring networks are being abandoned (IGRAC 2019).

Recent advances in technology, such as the development of low-cost sensors, microcontrollers, and Internet-of-Things (IoT) devices, and the widespread availability of WiFi and cellular networks, can help hydrogeologists overcome traditional barriers to collecting, transmitting and providing access to real-time groundwater monitoring data. Equipment and operational costs can be significant barriers to developing groundwater monitoring networks. However, there is a growing number of researchers using low-cost, do-it-yourself electronics, such as the popular Arduino and Raspberry Pi microcontrollers that are available for less than about US$50 and can be connected to sensors and programmed to collect and transmit data (Cressy 2017). Water researchers have also advocated the use of low-cost sensors, do-it-yourself equipment, and citizen-science to reduce the costs of water monitoring programs (Paul and Buytaert 2018; Tauro et al. 2018).

Community-based groundwater networks have grown in popularity in recent years as a low-cost approach for supplementing government-owned groundwater monitoring networks. Examples in Canada include the Groundswell network in Nova Scotia (Ecology Action Centre 2019), the Rocky View County network in Alberta (Little et al. 2016), the Columbia Basin network in British Columbia (Living Lakes Canada 2019) and the Nanaimo volunteer observation well network in British Columbia (The Regional District of Nanaimo 2019). A community-based approach to groundwater monitoring can help keep costs low by using volunteer domestic wells rather than installing dedicated monitoring wells. Most domestic wells are used as active water supplies and, therefore, care must be taken when collecting and interpreting water level data from these wells. When interpreting the data, it should be considered that the water level in the well is influenced by both seasonal groundwater level trends and drawdown from domestic pumping. The influence of pumping can be minimized by ensuring that measurements are collected during low water-demand times (e.g., late at night) so the water level has had as much time as possible to recover to static conditions (SADC-GMI 2019).

Background

A drought in the province of Nova Scotia, Canada, during the summer of 2016 caused over

1,000 water wells to go dry (Kennedy et al. 2017). In the southwestern part of the province it was the driest summer recorded in 137 years. Most of the residents in this part of the province rely on domestic wells for their water supply and a high proportion of these wells (estimated >30%) are shallow dug wells (<8 m deep) that are vulnerable to water table declines. During the drought, there was a need for emergency management staff and the public to have up-to-date information on groundwater levels. However, the existing provincial groundwater observation well network, which consists of 40 drilled wells spread out across the province, was not equipped with real-time monitoring equipment and, therefore, was not able to provide regular updates on aquifer water levels. In response, the Nova Scotia Geological Survey developed a real-time, shallow groundwater level monitoring network for dug wells so that up-to-date water level data would be available to help manage future droughts. The data from the network is also used to validate a provincial groundwater drought impact prediction model (Nova Scotia Department of Energy and Mines, 2017).

To keep costs low in the Nova Scotia shallow aquifer monitoring network, a custom-made, low-cost groundwater level meter was developed and deployed in a network of domestic wells provided by community volunteers. The custom-made water level meter uses an ultrasonic sensor to measure the depth to groundwater and an IoT device to transmit data in real-time to the Internet. The cost of the components to build the water meter is approximately US$150 for the WiFi version and US$225 for the cellular version. The components are readily available from online retailers.

The use of volunteer domestic wells helped keep the cost of the Nova Scotia shallow aquifer monitoring network low by avoiding the cost of constructing new wells for the placement of monitoring equipment, and also keeps the real-time data transmission costs low because the volunteers allow the water meters to connect to their home WiFi network to transmit the water level data to the Internet. Although community-based networks reduce costs by using existing domestic wells, they can still face challenges associated with monitoring equipment costs. Community networks that strive to keep monitoring equipment costs low by supplying volunteers with manual water level meters have reported challenges associated with volunteers being able to regularly collect and report their results and difficulties with volunteer retention due to declining interest over time (Little et al. 2016). The network described here reduces these challenges by automating data collection using low-cost, real-time monitoring equipment, which requires significantly less maintenance and involvement by network administrators.

Methods

The water level meter developed for this project was based on a do-it-yourself meter for measuring water levels in a household water storage tank (Ousley 2015). The original design was modified to operate on four AA batteries and to plot the water level data in real-time on an online, time-series graph. The water meter is housed in a case made of 50 mm diameter ABS pipe and has a total length of 320 mm (Figure 1). The four main components of the meter include an ultrasonic sensor to measure the water level in the well, an IoT device to control the sensor and transmit the water level data to the Internet, a battery pack and antenna (Figure 2). The meter is simple to construct, requiring only an antenna and five other wires to be connected to the IoT device (two battery pack wires and three sensor wires). Step-by-step instructions for building the meter, including a parts list and code for the IoT device are available to anyone interested in building the meter (Drage 2020).

Figure 1. External view of water level meter.

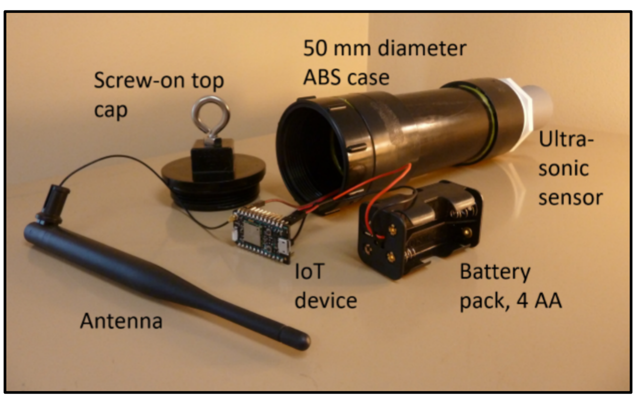

Figure 2. Water level meter with top cap off, showing internal components.

The meter uses an ultrasonic sensor to measure water levels as an alternative to a pressure transducer, which is currently the most common approach for monitoring groundwater levels. The meter is installed inside the well under the well cap with the sensor pointing downwards towards the water surface (Figure 3). Ultrasonic sensors use the time-of-flight method to measure the distance to water by measuring the two-way travel-time for an ultrasonic pulse to travel from the sensor to the water surface and back to the sensor. They are widely used in industrial applications for measuring liquid levels in storage tanks and to a limited extent in commercially available groundwater level monitoring equipment. They have the advantage of being accurate, low-cost and do not need to be compensated or vented to account for atmospheric pressure changes, as required for pressure transducers. The ultrasonic sensor used for this project (Maxbotix MB7389) costs approximately US$110. It has a 5 m range (10 m range is also available) and a manufacturer-reported accuracy of ±0.5% (Maxbotix Inc. 2012). The sensor is designed to report the distance to the largest target (i.e., the water surface in the well), rather than smaller objects such as pipes and electrical wires inside the well.

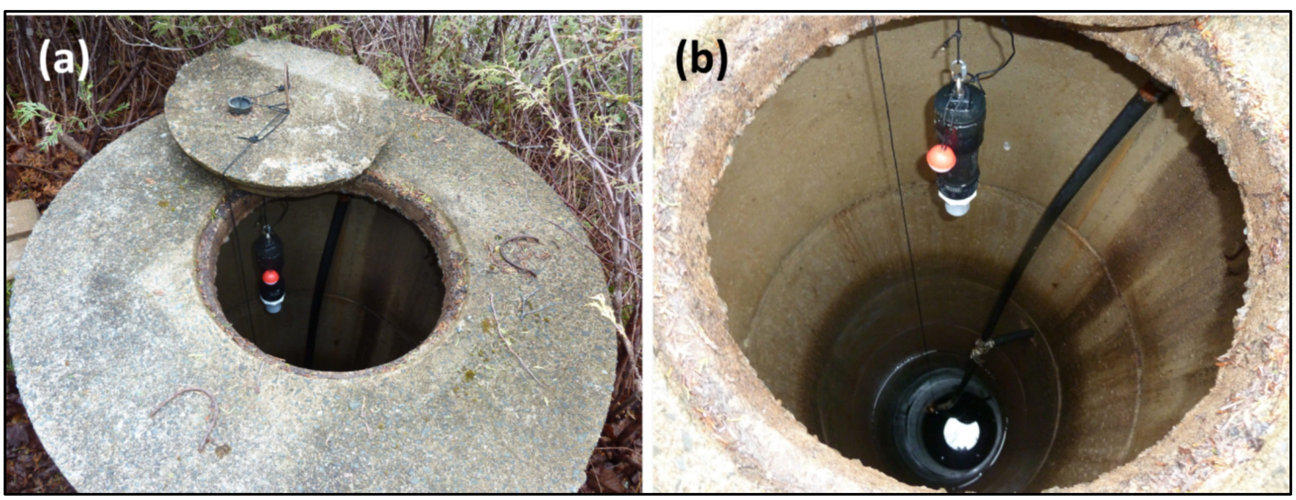

Figure 3. Water level meter installed inside a dug well. The red object is a fishing float used to help retrieve the meter if it is accidentally dropped into the well. (a) View from outside the well. (b) View inside the well.

Although ultrasonic sensors can be a useful technology for measuring water levels in wells, they also have important limitations. Water level measurements made by ultrasonic sensors may be inaccurate if there are too many obstacles or other sonic targets inside a well. An example is the presence of rocks used to construct the walls of the well, which is common in older dug wells. An uneven rock wall lining can reflect the ultrasonic pulse and cause incorrect water level measurements. Other limitations include the need for a vertical (not angled) and straight (not crooked) well so the ultrasonic pulse reflects off the water surface in the well rather the walls of the well, the need for a minimum well diameter, and the potential for condensation or frost development on the sensor face when air temperatures drop below freezing. With respect to well diameter, the manufacturer of the ultrasonic sensor used in this project recommends a minimum inside diameter of 200 mm if the sensor is deployed in a pipe to ensure the water surface represents a significant target. The sensors can work in smaller diameter pipe or casing if the walls are smooth and seamless, however, pipe slots, perforations, joins, or even water droplets on the casing wall can act as ultrasonic reflectors and cause inaccurate water level measurements.

For the current project, the minimum pipe diameter of 200 mm recommended by the sensor manufacturer was exceeded because the meters were installed in dug wells, which had a typical inside diameter of greater than approximately 900 mm. Prior to developing the monitoring network, a pilot test was used to test the accuracy and limitations of the water meters in dug wells. The pilot test was carried out by installing the custom-made, real-time water level meters in three different dug wells and comparing the results to pressure transducer and manual water level measurements.

The water level meters in this project transmit water level data in real-time to the Internet using the private WiFi network at each volunteer's house. To do this, the well needs to be located close enough (within about 50 m) to the household WiFi router to successfully connect to the Internet. In cases where the WiFi signal was too weak, an external antenna was attached to the water meter and/or a WiFi range extender was installed in the volunteer's house (the additional cost to add an external antenna and WiFi range extender is approximately US$25 and US$30, respectively). A cellular version of the water meter was also developed for situations where no WiFi network was available. The cellular version is more expensive to build and operate than the WiFi version. The parts for the cellular version of the meter cost approximately US$225. It also needs a data plan which comes with the IoT cellular device and costs approximately US$3 per month. Instructions for building the cellular version of the water meter are included in the instructions referenced earlier (Drage 2020).

An IoT platform service is used to receive, store and view the real-time water level data from the meter. There are many IoT platform services available for IoT sensors. This project uses ThingSpeak (https://thingspeak.com/), which is free to use for small non-commercial projects. The ThingSpeak webpage for each water meter in the network includes a time-series graph that allows the water level data to be downloaded for importing into a spreadsheet. In addition to time-series graphs, ThingSpeak has several widgets available to display the data in different visual formats (e.g., gauge, numeric display, lamp indicator). It can also send an automated message if a critical level in the well is recorded.

Volunteer well-owners were recruited for the network by word-of-mouth, newsletter, and radio and television interviews. The goal was to build a province-wide network with approximately 10 monitoring locations. Volunteers were selected based on well type (the objective was to monitor water levels in dug wells), the presence of a WiFi signal at the wellhead, and household location (so that good spatial coverage across the province was achieved). The network was designed to monitor dug wells because their shallow depths make them more vulnerable to drought than drilled wells. During the 2016 drought in Nova Scotia, survey information indicated that 93% of the wells that were reported to have gone dry were dug wells (Kennedy et al. 2017).

Results and Discussion

The recruitment program for the network was able to attract more volunteers than could be accommodated, and the real-time network currently has 11 active monitoring sites across Nova Scotia (Figure 4). The first wells were added to the network in 2017 and additional wells were added in 2018 and 2019. Ten of the wells use a WiFi version of the water meter and one well uses a cellular version. The meters are programmed to measure and report water levels once a day, although any monitoring frequency can be used. The online interactive map for the network (Figure 4) provides public access to the water level data (Province of Nova Scotia, 2018). A screenshot of the online results from one of the wells is shown in Figure 5.

The wells in the network are typically visited once a year to verify water level measurements and to change the meter batteries, if required. The battery life is calculated to be approximately two years for the WiFi version of the meter with a monitoring frequency of once a day. At the time of writing, the longest battery life observed in the field is 19 months and counting.

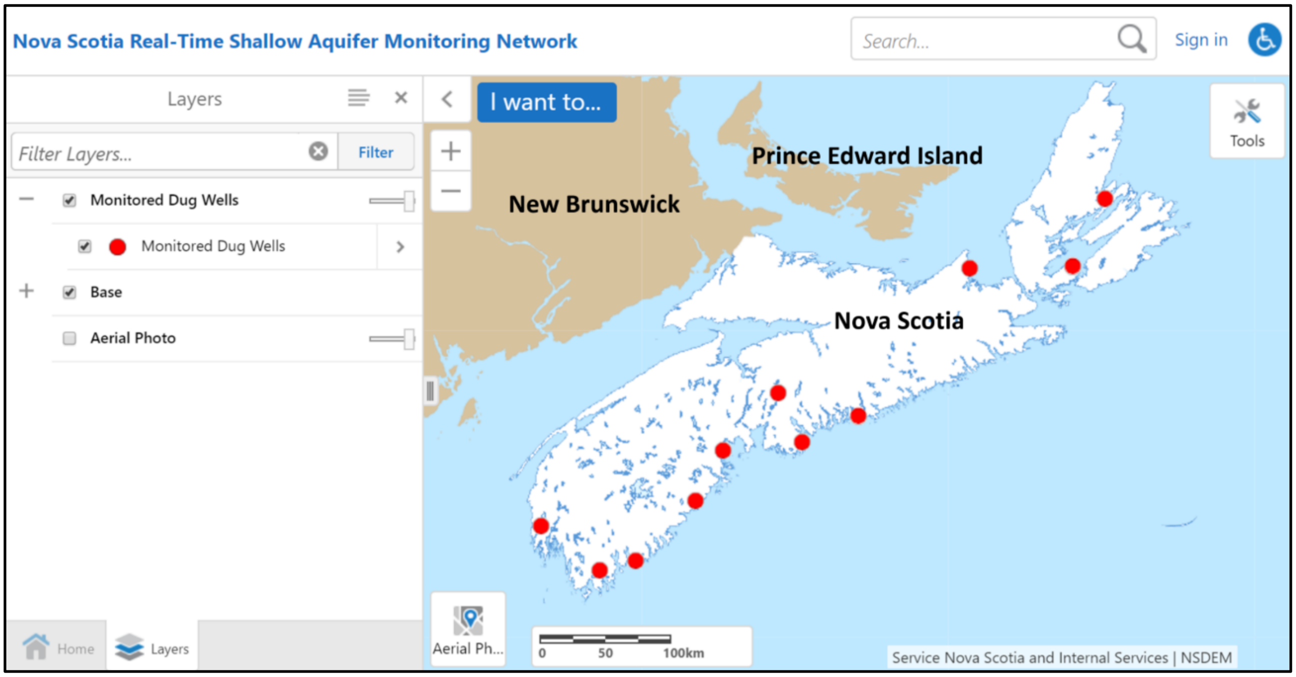

Figure 4. Online interactive map for the Nova Scotia real-time shallow aquifer monitoring network (https://fletcher.novascotia.ca/DNRViewer/index.html?viewer=Aquifer_Monitoring.Aquifer_Monitoring).

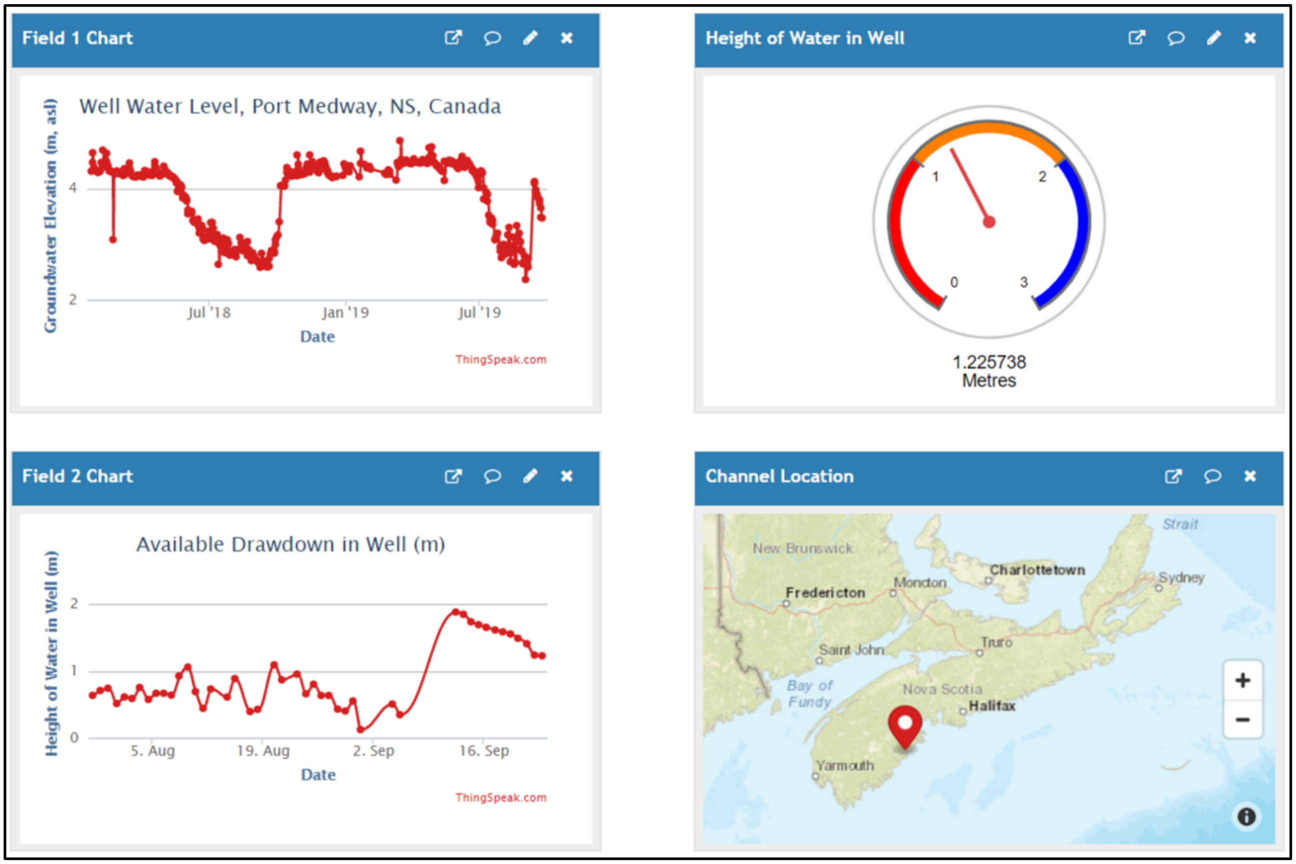

Figure 5. Screenshot of online water level results from a dug well in Port Medway, Nova Scotia, Canada (https://thingspeak.com/channels/368729).

Figure 6 presents water level data from one of the real-time monitoring sites compared to pressure transducer and manual water level measurements. The pressure transducer data were corrected for drift using the manual water level measurements, assuming a linear transducer drift between manual measurements. The real-time water level meter results in Figure 6 compare well with pressure transducer measurements, with a mean absolute error of 0.014 m. The two other pilot test monitoring sites had mean absolute errors of 0.014 m and 0.020 m. The water level data in Figure 6 show a typical annual pattern observed in shallow aquifers in Nova Scotia, with higher groundwater levels occurring in the winter and spring (January to May), followed by a summer groundwater recession (June to August) when precipitation and recharge rates are low, followed by rising water levels in the fall (September to November) when rainfall returns.

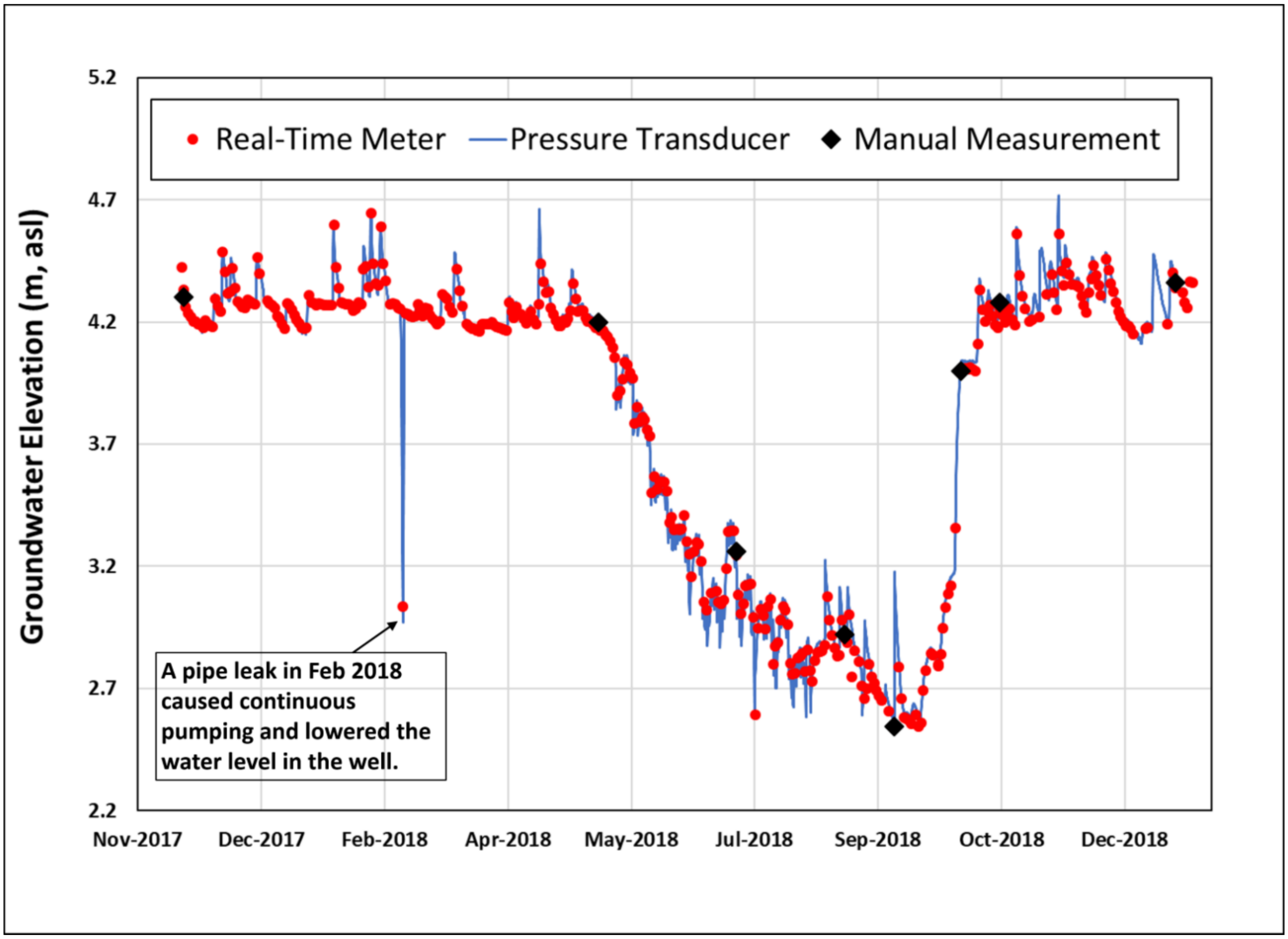

Figure 6. Real-time water level meter results from a dug well in Port Medway, Nova Scotia, Canada, compared to pressure transducer and manual measurements.

Although the real-time meters have generally performed well in the field, several challenges and limitations have been identified. One problem identified during pilot testing was inaccurate water level measurements in dug wells that were constructed with rock walls. New dug wells in Nova Scotia are typically constructed with casing made of precast concrete rings, and the real-time meters made accurate water level measurements in wells with this type of construction. However, older dug wells were commonly constructed with rock walls and this type of well construction resulted in inaccurate water level measurements. It is likely that this problem was caused by the ultrasonic signal reflecting off the rocks used to construct the walls of the well. This issue was solved by installing a 75 mm diameter PVC pipe in the well that the water level meter was inserted into. The pipe extended from the top of the well to below the water surface and acted as a sleeve that contained the ultrasonic pulse, thus preventing ultrasonic reflections from the rock walls.

Another challenge was frost formation on the ultrasonic sensor face during the winter when air temperatures dropped below freezing. In this case, the frost blocked the ultrasonic pulse and caused an incorrect water level measurement (i.e., the depth to water was reported as zero). This problem occurred in several, but not all wells. Installing the water meters deeper (1 to 2 m below ground surface) in the well where temperatures are warmer during the winter solved most of these problems. The water meter code was also modified so that depth-to-water readings of zero were not reported. Lowering the water meter into the well required an external antenna (at an additional cost of US$25) to be attached because the WiFi signal became too weak when the meter was below ground surface.

An important limitation of the real-time water level meter design presented here is that it does not include a data logger. Therefore, if there is a WiFi connection problem (e.g., the Internet or power is off at a volunteer's home) the water level data is not transmitted and is permanently lost. A data logger could be added to solve this problem, although it would increase the cost of the meter. Instructions for building a low-cost (approximately US$100) data logger designed for environmental monitoring and field research have been published by

Wickert (2014) and Wickert et al. (2019).

Another challenge has been changes to the volunteer's WiFi networks, including routine changing of internet providers and changing of WiFi network names and passwords. Once a WiFi network name or password has been changed at a volunteer's home, the water meters can no longer connect to the Internet and a field visit is required to update the meter. These types of issues are fairly common (they have affected a few wells each year in the current network) and, therefore, in the long-term it may be more cost-effective to operate the network using the cellular version of the meter rather than the WiFi version. Although the cellular version of the meter is costlier to build and there is a monthly data plan cost, it may be less expensive in the long-term because field visits are not needed to re-establish WiFi connections.

It should be noted that the technology used in the real-time water level meter can potentially be used for other types of low-cost, real-time monitoring. The IoT device used in the meter described here has 18 input and output pins available to connect sensors, only two of which are used for the ultrasonic sensor. Therefore, many more input pins are available to connect additional sensors. Examples of low-cost sensors that could potentially be added include temperature and electrical conductivity. Furthermore, although this project focused on measuring water levels in dug wells, the same technology could potentially be used for measuring water levels in other types of wells (e.g., drilled water wells, environmental monitoring wells) and surface water bodies. Further testing would be needed to confirm the accuracy of the meter in these settings, especially considering the manufacturer's recommended minimum 200 mm pipe diameter for the deployment of the sensor.

Conclusions

There is a need for improved groundwater monitoring worldwide as our reliance on aquifers increases due to population growth, increased drought frequency, and expectations that groundwater supplies can play an important role in climate change adaptation. Citizen-science and technological advancements, such as low-cost sensors, IoT technology, and the widespread availability WiFi and cellular networks, can help hydrogeologists collect the data required to ensure groundwater resources are wisely managed. This project demonstrates how low-cost, real-time groundwater level monitoring networks can be developed using simple, easy-to-construct monitoring equipment made with readily available components from online suppliers. The approach can potentially be expanded to include water quality parameters and monitoring in other settings such as surface water bodies.

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