Managing Water Resources in an Era of Hydrological Uncertainty:

The Application of Low-Cost, Open Source Environmental Sensors

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Independent Research Project*, Spring 2016

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CONTENTS

EXHIBITS

INTRODUCTION

The 21st Conference of Parties (COP) to the United Nations Framework on Climate Change yielded unprecedented unanimity concerning the vulnerability of the world's water resources to anthropogenic climate change. "Climate change is already affecting and will increasingly affect the quantity and quality of freshwater and aquatic ecosystems," declared representatives in the historic Paris Pact on Water and Adaptation to Climate Change, "especially through the intensity and greater frequency of extreme hydrological events, such as floods and droughts." Issuing a clear call to action, the Paris Pact continued with the statement that, "We recognize that adaptation actions should be undertaken without delay to minimize the impacts of climate change on the populations' health and safety, on economic development and the environment, considering the importance of the protection of water-related ecosystems." [1]

More than any previous climate summit, the complex linkages between climate change and life-giving water took center stage in Paris (Walton, 2015). Importantly, however, the diverse group of water management agencies and international organizations that signed on to the Pact were able to move beyond broad proclamations to the identification of a four-pronged action agenda backed by pledges for financial support. Leading off this agenda under the first objective of reinforcing capacity development and knowledge is the commitment of signatories to:

> Establish basin-wide networks for monitoring and data exchange and water information systems, which are integrated, permanent, reliable, open, representative, interoperable and accessible, as a decision making support tool for adaptation measures.

While all actions identified in Paris Pact are fundamental to water resources management in an era of an increasingly unpredictable climate, it is no accident that the road to sustainability begins with water data that is *integrated*, *open*, and *accessible*, among other characteristics. Indeed, many of the subsequent actions identified in the Pact—including the assessment of watershed climate change vulnerabilities, development of basin management plans, and participatory water governance—all hinge on access to hydrological and meteorological data.

Research Objective

Despite the importance of basin-wide hydrological and meteorological (hydro-met) information systems as identified in the Paris Pact, such systems remain inadequate in many areas of the world. Developing countries, for example, have long struggled to acquire basic information about their water resources due in part to the cost of such systems. While the thousands of stations operated by the USGS provide invaluable data to decision-makers in the United States, the establishment and operation of these systems is expensive and, as such, is frequently viewed as secondary to other public investments in less developed economies. Further, civil society groups, watchdog agencies, and environmental researchers in both developed and developing economies alike have lacked access to the technologies and collaborative tools necessary to detect water resource trends and advocate for better resource allocation and planning.

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[1] See http://www.circleofblue.org/wp-content/uploads/2015/12/COP21_-_Paris_Pact_ENG_-_INBO_V16.pdf for the complete two-page Pact (INOB, 2015).

Overcoming this "data deficit" in the face of climate change will require an innovative, locally-driven, watershed-level approach. One plausible component of this approach is the increased application of low-cost, open source environmental sensors. The open source movement—accompanied by the decreasing costs of technology as a whole—is now making it possible for communities, neighborhoods, and even individuals to more easily gather information about the world around them using, for example, customizable sensor hardware and programmable microcontrollers. Everything from precipitation gauges to remote sensing imagery, for example, is well within the reach of "citizen scientists" as they seek to better understand environmental challenges and protect finite resources. Further, communication and collaboration is facilitating the uptake of such tools by allowing citizen scientists to share programming code and collectively tackle problems in a manner never before possible.

Research Objective:

Can open-source environmental sensors contribute to the improved management of water resources over the near-term? Further, what are the potential advantages and limitations associated with these tools?

The objective of this research, then, is to assess the potential of low-cost, open source technologies in the planning and management of water resources. More specifically, the paper will seek to address the following question: Can open-source environmental sensors contribute to the improved monitoring, planning, and management of water resources over the near-term, and what are the potential advantages and limitations of these tools? To address this query we will combine (1) a review of existing published and unpublished literature and case studies on open source environmental hardware and citizen science with (2) the implementation of field tests of open source sensors in the Paint Branch Watershed in Montgomery County, Maryland. Specifically, we focus on two tools—a precipitation gauge and a stream level gauge—given their fundamental role in understanding hydro-met systems and managing water resources.

Report Structure

The content of the report is organized into four sections. Beginning on the following page, we review key trends in the literature on the importance of hydro-met data, the evolution of citizen science, and the growing application of open source sensors. The third section—Methods and Materials—details the deployment of the two hydro-met sensors, including the sensor development, coding, placement in the watershed, and testing. We then move to the Results in the fourth section, providing both quantitative and qualitative analysis of the performance of the fielded sensors over an approximately 30-day period. This analysis includes a comparison of sensor data with standard public sources such as the US Geological Survey. Finally, in the Discussion, we provide an overall assessment of the strengths and limitations of open source water sensors based on the literature review and field testing. The paper then closes with the identification of additional research priorities.

LITERATURE REVIEW

The following section provides a brief review of the literature pertinent to the application of open source environmental sensors in a world of unprecedented environmental change. Before delving into open source hydro-met sensors specifically, however, we first consider the broader importance of hydro-met data in managing water resources as well as the evolving role of citizen science in the collection, analysis, and dissemination of water resources information.

Water Resources Data in the Face of Climate Change

Obtaining data on meteorological and hydrological processes is axiomatic to understanding how a watershed functions and the manner in which those functions change over time. As noted in the Paris Pact action agenda discussed in the introduction, basin-wide hydro-met data collection networks underpin decision-support tools for selecting and implementing climate adaption measures. In the text *Water Resources Planning*, Dzurik (2003) discusses the increasing reliance on water resources decision support systems in the planning process, noting a "growing interest in expert systems programs that replicate the actual decision processes used by decision makers" (pg. 276). In other words, policymakers are looking to move beyond mathematical models alone to better understand the past, present, and future of their water resources.

Given the "hyper-local" nature of water resources data, the usefulness of water data is often a function of its spatial and temporal resolution. Sun, Hu, Yang, and Jia (2015) note the increasing concern with obtaining "fine grained and real-time" rainfall data—which they emphasize is critical for hydrological analysis—at the "micro level" in both an "effective and efficient way" (pg. 1). This need is due in part to the fact that, while annual or monthly rainfall amounts may appear stable in a changing climate, the daily intensity of precipitation may fluctuate dramatically. The researchers go on to state that a greater number of rainfall gauges need to be deployed "in order to achieve large spatial coverage" (pg. 2). Similarly, concerning stream flow measurement, Royem, Mui, Fuka, and Walter (2012) identify stream flow data as "essential for water resources planning and decision making," describing the extensive US Geological Survey (USGS) monitoring network as "invaluable to the development of a wide variety of water management strategies" (pg. 1).

A common theme across the literature is a need to expand—not contract—monitoring systems for key hydrological and meteorological data such as precipitation and surface water quantity and quality. Murphy et al. (2015) notes, for example, that climate change provides a "strong scientific and economic argument" for expanding aquatic monitoring given potential impacts on water quantity and water quality (pg. 520). Similarly, Burt, Howden, and Worral (2014) write, "In a world where change rather than stasis is increasingly the norm, monitoring is an essential way to discover whether there are significant undesirable changes taking place in the natural environment" (pg. 41). They further note that obtaining long-term data sets are critical to understanding trends and modeling future impacts, especially given that "models are only as good as the data used to calibrate and verify them" (pg. 42). Finally, Royem et al. (2012) aptly summarize the need for expanded water resources data collection as follows:

> We cannot sidestep the continuing need to advance our fundamental understanding of environmental systems and improve our modeling of climate related changes to the

> hydrologic cycle at scales relevant to decision-making…Such improvements necessitate continued, expanded, and long-term environmental monitoring. (pg. 1)

It is important to note that Royem et al. do not advocate for monitoring for the sake of monitoring, but rather as an irreplaceable means to understand changes to our water resources and, further, to use that understanding to make better plans, models, and, ultimately, decisions about how we manage and protect those resources. In other words, the collection of hydro-met data is, in many ways, step one to sustainable water resources management in the face of climate change.

Unfortunately, the call for better water data to prepare for climate change impacts is not being heeded. As early as 1999 the International Union of Geodesy and Geophysics noted that, "Around the world, the gauges that measure rainfall and stream height are slowly disappearing, victims of a slow erosion in funding" (Stokstad, 1999). Exhibit 1 provides a current example of this trend: while identifying potential field sites for this research, the USGS posted a list of 6 stream gauge stations at risk of closing as well as one station already closed in Maryland due to "lack of partner funding" (USGS, 2016). While station costs vary based on the site, the approximate expense according to Stokstad is $35,000 to set up as well as a further $10,000 per year to maintain. But while the challenge in the US may be keeping existing stations open, in many other areas of the world the problem is little to no hydro-meteorological monitoring networks at all. Further, as Stokstad also states, "Many of those countries whose hydrological networks are in the worst condition are those with the most pressing water needs" (pg. 2). Less developed economies have, in other words, long struggled to collect hydro-met data at a level relevant to decision-making. This acute lack of historical data makes it extremely difficult to downscale regional climate models to the local level given the absence of the data needed to statistically calibrate such models at the watershed scale.

Exhibit 1: USGS Stations in Maryland Slated for Closing in 2016 (USGS, 2016)

USGS Current Water Data for Maryland

USGS
science for a changing world

Click to hide state-specific text

Data collected by the MD-DE-DC USGS Water Science Center are reported in Eastern Standard Time (EST) year-round.

Updated **April 1, 2016**: USGS streamflow monitoring **will soon be discontinued** at the following sites:

- 01490200 FARM CREEK NEAR TODDVILLE, MD (2015 to present) **Data collection has been discontinued**
- 01487150 BUCKS BRANCH NEAR ATLANTA, DE (2014 to present) **Data collection discontinues July 1, 2016**
- 01594963 NYDEGGER RUN NEAR GORMAN, MD (2013 to present) **Data collection discontinues July 1, 2016**
- 01596050 SAVAGE RIVER NEAR AVILTON, MD (2013 to present) **Data collection discontinues July 1, 2016**
- 01597000 CRABTREE CREEK NEAR SWANTON, MD (1948 to present) **Data collection discontinues July 1, 2016**
- 03076700 BUFFALO RUN NEAR FRIENDSVILLE, MD (2013 to present) **Data collection discontinues July 1, 2016**
- 03076800 MILL RUN AT MINERAL SPRING, MD (2013 to present) **Data collection discontinues July 1, 2016**

Currently, data collection activities at these sites (map) are funded jointly by the USGS and partner agencies through the USGS Cooperative Water Program. Lack of partner funding for these sites will result in discontinuation of all monitoring activities. Questions or concerns can be directed to Jon Dillow (jjdillow@usgs.gov; 443-498-5524).

Citizen Science and Water Resources Management

The role of citizen science in the monitoring, planning, and management of finite water resources is likely to become all the more important in an era of increasingly erratic hydro-meteorological events. Broadly speaking, citizen science may be defined as the "participation of the general public (i.e. non-scientists) in the research design, data collection, and interpretation process" to generate new scientific knowledge together with scientists (Buytaert et al., 2014, pg. 1).

Citizen science—sometimes referred to as community-based monitoring—therefore covers a broad spectrum of public engagement in the scientific process, from basic sample collection to more complex roles in problem solving and policy change. Conrad and Hilchey (2010) identify three types of citizen science: consultative/functional, collaborative, and transformative. As the nomenclature implies, these forms progress from individual citizens as data collectors or sources of information (consultative); to multi-stakeholder engagement in analysis and decision-making (collaborative); to bottom-up, citizen-led monitoring, advocacy, and policy change (transformative). Bonney et al. (2009) proposes a similar categorization of citizen science initiatives: contributory projects, collaborative projects, and co-created projects. The final category introduces the notion of "co-creation" in which projects are co-designed and co-implemented by scientists and the public, with the public taking an active (if not leading) role in the process.

While citizens have long participated in the scientific inquiry process, the extent of their involvement has often been limited by the sophistication of available tools. Indeed, one of the most significant challenges to moving beyond purely functional citizen science is the acceptance and usage of community-collected data (Conrad & Hilchey, 2010). Importantly, this barrier is now rapidly lessening with the advent of open source tools and technologies accompanied by forums for citizen collaboration and communication. In an assessment of the future of citizen science, for example, Newman et al. (2012) states that, "Wireless sensor networks may connect the laboratory to the natural environment, shifting the focus from elite science to a reality where data collection, analysis, and interpretation are performed by everyday citizens…in partnership with professional scientists" (pg. 303).

The potential applications of open-source technologies to hydrology and water resources management—or, "citizen hydrology"—are especially noteworthy given the aforementioned paucity of hydrological data in many areas of the world. In the journal Frontiers in Earth Science, Buytaert et al. (2014) assess the potential of citizen science in water resources management, including in data collection (e.g. precipitation, stream-flow, water quality, soil moisture, water use, etc.), data transmission and processing, and scenario building/participatory modeling. Their conclusions (see text box) highlight the strong prospects of citizen hydrology to improve water resources management, thereby overcoming one of the most significant bottlenecks to "sustainable development and poverty alleviation" (pg. 16).

The Advent of Citizen Hydrology?

"Given the advanced technology needed for monitoring many aspects of the water cycle, hydrology is not an evident scientific discipline for the application of citizen science. But the development of more robust, cheaper, and lower maintenance sensing equipment creates new opportunities for data collection in a citizen science context." (pg. 4)

"Our review of technologies reveals a large potential for increasing the involvement of citizens in data collection because of the availability of inexpensive, robust, and highly automated sensors, and the possibility to combine them with powerful environmental models to create rich and interactive visualization methods" (pg. 16).

(Buytaert et al., 2014)

The Application of Open Source Environmental Sensors

Although the use of computers, sensor networks, and models to study our environment is well established, open-source hardware represents a recent addition to the environmental management toolbox. The Open Source Hardware Association describes this technology as follows:

> Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses

> readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs. (OSHWA, 2016)

In many ways, the open source hardware era was ushered in with the advent of the Arduino in 2005. Originally produced by the Interaction Design Institute in Ivrea, Italy to aid in student design, an Arduino is a programmable, credit-card sized microcontroller which is easily connected to digital and analog sensors (Mesas-Carrascosa, Verdu, Merono, Sanchez de la Orden, & Garcıa-Ferrer, 2015). As described in the OSHWA definition above, the Arduino represents the essence of "open source" in that it is designed with user control in mind. Fueled by the Maker Movement, the Arduino has evolved from a novelty to a line of brand name and imitation products targeted at tech-savvy makers, educators, and developers alike. Importantly, the adoption of open source tools and technologies has been enabled by code-sharing websites like github.com and codebender.com accompanied by collaborative forums such as publiclab.org.

Despite the relatively recent introduction of open source hardware, the opportunities presented by such tools and technologies have been rapidly embraced by the environmental science community. More specifically, the environmental research community has begun to investigate potential applications of open source hardware to sectors such as meteorology, agriculture, and water resources. Illustrative examples from the literature are as follows:

- Ferdoush and Li (2014) as well as Delamo, Felici-Castell, Pérez-Solano, and Foster (2015) both explore the potential of low-cost, wireless sensor networks that employ open source microcontrollers (including the Raspberry Pi and Arduino) for use in monitoring two fundamental environmental conditions: temperature and humidity. The former deployed a small, indoor network to demonstrate the utility of the sensors to reliably track environmental conditions. The latter developed a low-maintenance network of sensors (using TelosB motes) that was then validated through a long-term, outdoor deployment in which the sensors remained exposed to the elements. The research team used radio transmission (specifically a TI CC2420 radio chip) to send temperature and humidity data to a central receiver.
- Sun et al. (2015) investigated a third meteorological condition, focusing on real-time rainfall measurement as a means to better understand local hydrological conditions. The researchers developed a prototype rain gauge (termed "RealRain") that also utilized a TelosB mote with radio transmission capacity to capture precipitation data across a broad geographic area on a time-synchronized basis. The study demonstrated the efficacy and efficiency of the RealRain prototype in a laboratory setting, but did not undertake an actual deployment of the sensors to test the durability of the network in the field.
- Mesas-Carrascosa et al. (2015) applied an open-source hardware system to the monitoring of specific environmental parameters relevant to agriculture, combining hardware and software (in the form of a smartphone application) to monitor temperature and relative humidity of the soil and the ambient environment as well as the presence of sunlight. Concerning the system design, the prototype station was operated by an Arduino Mega ADK microcontroller which

sent data wirelessly to an android application using a Bluetooth signal. The research team co-located the open source prototype with a professional grade Davis Vantage Pro station in order to ascertain the quality of the data.

Overall, Mesas-Carrascosa et al. found no statistical difference between the data from the prototype versus that of the Davis station. They further concluded that the low cost of the system (under 100 Euros), ease of use, and flexible design (including ability to change sensor types, form of data transmission, time interval, and precision of data) made the station ideal for use in poor, rural areas.

- Also in the agriculture sector, Polo, Hornero, Duijneveld, García, and Casas (2015) deployed a network of nodes that measured temperature and humidity across a series of adjacent fields. Each node consisted of an Arduino microcontroller, a circuit shield, and XBee wireless communication device, and a HygroClip temperature and humidity sensor. Given the short communication range of XBee devices, the research team utilized an unmanned aerial vehicle (UAV) fitted out with an on-board Arduino node and Raspberry Pi computer to automatically upload ground-level data when it came within range. The use of the UAV had the added advantage of providing high resolution imagery of the fields which were useful in detecting threats to crops such as pests or flooding. Polo et al. concluded that similar networks could be used to supervise plantings as well as "any extensive cultivation in which it is difficult to use a traditional sensor network because of large field dimensions and when global measurements of the state of crops and soil are desired" (pg. 32).

- Murphy et al. (2014) focused directly on the water resources sector with the development of a low-cost optical sensor for water quality monitoring. The sensor used a light emitting diode array and two photodiode detectors to measure the opacity of surface water, information that was then used as a proxy for water quality. Rounding out the design was the open source Raspberry Pi single board computer, an integrated temperature sensor, and a communications antenna to connect to the cell phone network. The authors tested the sensor both in the lab as well as two field sites for its utility as a possible early warning system for pollution as well as the monitoring of environmental conditions.

  The results of the study demonstrated that the system was able to detect "both sudden and significant changes in water opacity arising from environmental events" (pg. 527), with further testing envisioned in tandem with professional-grade sensors in order to verify the quality of the data. The research team also concluded the ability to collect real-time water quality data at relatively low cost may be especially applicable to "lower income countries struggling with the effects of climate change and water related challenges" (pg. 527).

- Also in the water sector, Royem et al. (2012) developed a stream stage monitoring system and, similar to the work discussed in this paper, compared the results against a USGS monitoring station. Rather than using an open-source tool to directly measure stream height, however, the research team used a mounted digital camera and an in-stream ruler, with the camera programmed to photograph the ruler every three hours. The post-processing of these time-lapse images in MATLAB software resulted in a color map in which the exact height of the water against the ruler could be automatically distinguished (using a calibrated reference image). Following approximately one month of data collection, the combination of time-lapse photography and automated imagery processing showed a relative difference of 16% with known outliers included and 5% with outliers excluded. While the imagery itself was stored on the camera during the field-testing, in the future the authors intend to transition to an internet-based environment where citizen stream monitors can also upload their own imagery for post-processing and stream data archiving.

The above case studies from the literature highlight the growing interest in the application of open source hardware to environmental resource management. While the research is almost universally optimistic about the potential of open source tools and technologies, common challenges and areas of additional research also emerge from the existing body of examples, including complications associated with power management, time synchronization (especially when multiple nodes are used simultaneously), and the importance of verifying sensor accuracy against accepted data sources. In addition, it is noteworthy that the vast majority of research to date (Royem et al. excluded) has consisted of lab-based trials with only limited field deployment. This is a key gap given the importance of long-term data sets in deciphering environmental trends and better preparing for climate change (as noted by Burt et al., 2014). Field-based monitoring equipment must be sufficiently robust as to withstand exposure to the elements on a day-to-day basis while still steadfastly transmitting accurate data. While the field testing described in the following pages does not individually fill this gap, the medium-term deployment of the sensors (e.g. 30+ days) represents an important distinction in this research.

MATERIALS AND METHODS

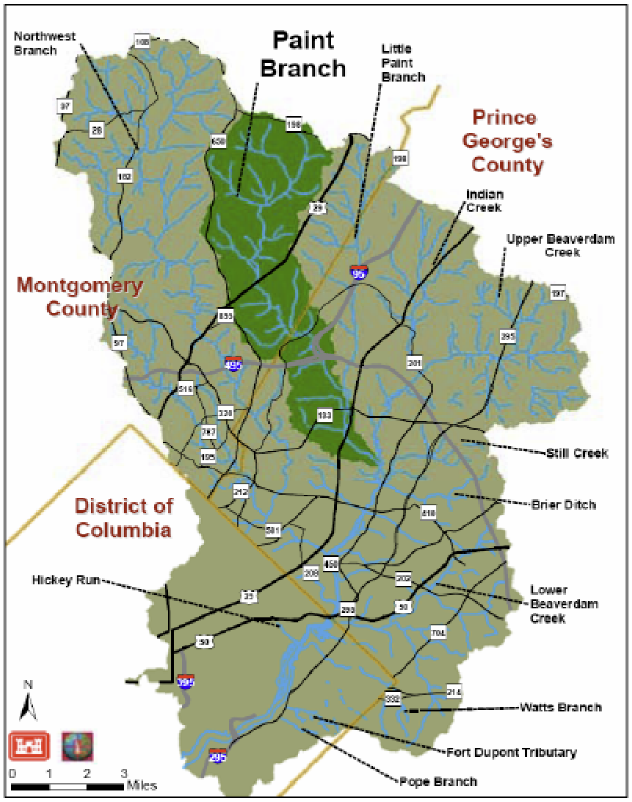
Building from the examples of open source sensors highlighted in the literature, we now turn to “hands-on” development, fielding, and data collection utilizing two hydro-meteorological sensor systems: an automated, real-time precipitation gauge and an automated, real-time stream height gauge. Precipitation and surface run-off levels are fundamental to water resources management, providing the basic building blocks for watershed analysis and modeling. Further, in a period of intensifying rain patterns, a precipitation gauge is critical to tracking the hyper-local impact of climate shifts while a stream height gauge can improve local flood warning systems. The following subsections describe the watershed in which the field testing was conducted accompanied by the steps taken to construct, code, and deploy the respective open source sensors.

Paint Branch Watershed

The precipitation gauge and the stream gauge were fielded in the upper reaches of the Paint Branch Watershed, a sub-catchment of the Anacostia River which crosses parts of Maryland as well as Washington DC (see Exhibit 2 from the Anacostia River Watershed Partnership and MWCG, 2010). The northern sections of this watershed are in Montgomery County, with the 11.4 mile long Paint Branch Stream crossing into Prince George’s County about two thirds of the way through its journey to the confluence with the Anacostia River (Hollenbach, 2013). The local climate is temperate, with four distinct seasons, including summers characterized by high levels of humidity. Given the proximity to the nation’s capital, it is no surprise that the Paint Branch is highly developed, with the vast majority of the land-use dedicated to residential areas.

Exhibit 3 on the following page depicts the specific locations of the gauges in Paint Branch’s upper segment. Notably, the highlighted area is referred to as the Upper Paint Branch Special Protection Area. According to the Paint Branch Environmental Baseline Conditions and Restoration Report (Metropolitan Washington Council of Governments, 2009), this area of the watershed was granted additional development restrictions in order to safeguard the integrity of the stream systems. The baseline report also noted that the Good Hope Tributary—which drains approximately 1.5 square miles—represents the primary spawning and nursery stream for the Paint Branch watershed, including ecologically sensitive brown trout.

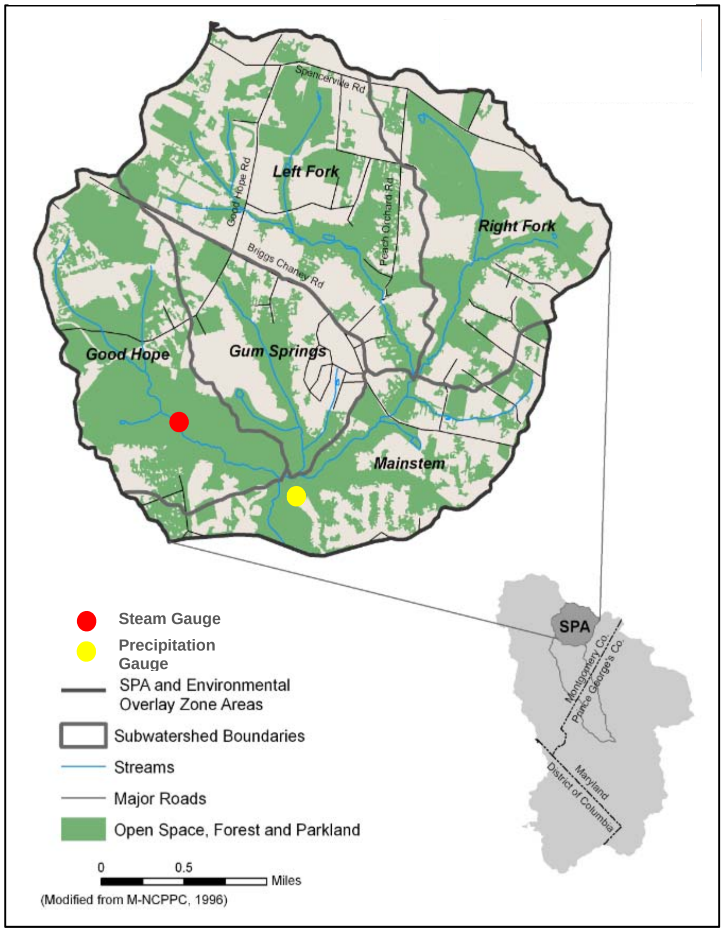
Exhibit 2: The Paint Branch Watershed



Source: Metropolitan Washington Council of Governments, 2010

As discussed in greater detail below, the stream height gauge tested herein was placed on the Good Hope Tributary, adjacent to a USGS hydrological station. This segment of the watershed has significant forest cover, with riparian buffers helping to protect the fragile stream ecosystems. Development pressure continues to alter the landscape, however, including the recent completion of a major highway that now cuts across the Good Hope and Gum Springs tributaries as well as the main stem of the Paint Brach itself. This major infrastructure project was completed in 2013, and thus is not yet included in Exhibit 3.

Exhibit 3: Gauge Locations within the Paint Branch Special Protection Area



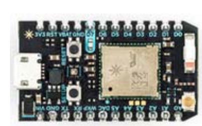
Source: Metropolitan Washington Council of Governments, 2009

Precipitation Gauge

The open source precipitation gauge prototype (also referred to as the "rain gauge") tested in this research is based upon the design and hardware tools of a complete weather station promulgated by Sparkfun.com, an online provider of do-it-yourself (DIY) electronics. While the weather station was fielded in its entirety, we focus here on the precipitation gauge alone as a tool for monitoring water resources.

Hardware. Exhibit 4 enumerates the key hardware elements that operate the weather station (and thus the precipitation gauge), including the cost of the unit, a brief description of its function, and the web link for more detailed information on the manufacturer's specifications.

Exhibit 4: Primary Hardware Components of the Precipitation Gauge

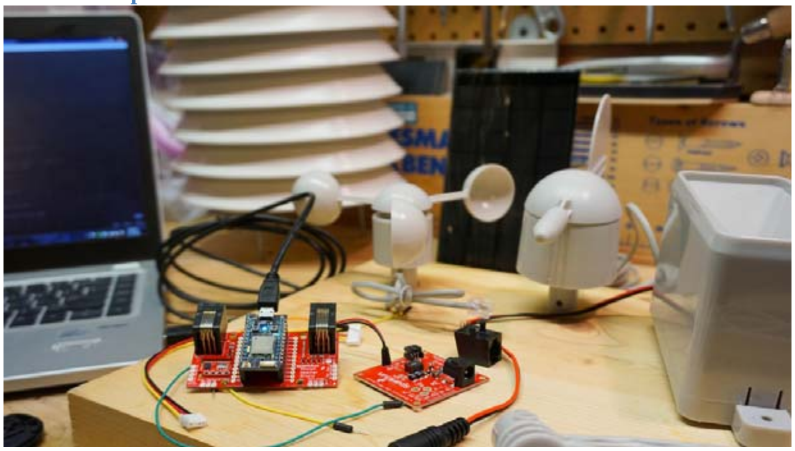
Hardware Unit	Cost	Function	Image
Particle Photon	$19	• With an STM32 ARM Cortex M3 microcontroller, the Photon is the "brain" of the gauge, using the uploaded code to operate the gauge and collect data; • Also houses a Broadcom Wi-Fi chip to allow for easy connection to a local wireless network. • Link: https://store.particle.io/collections/photon	

Hardware Unit	Cost	Function	Image
Sparkfun Photon Weather Shield	$33	• Add-on circuit board that enables easy connection to weather sensors, including on-board temperature and humidity sensors as well as jacks for rain and wind sensors; • Link: https://www.sparkfun.com/products/13630	
Argent Rain Gauge	$15	• The rain gauge uses a simple "tipping bucket" with a magnetic switch that closes each time the bucket fills and tips. Each tip is equal to 0.011 inches of rain. • The gauge is developed to connect to micro-controllers such as Arduino or Raspberry Pi. • Link: www.argentdata.com/catalog/product_info.php?products_id=168	
Total Cost:	**$67**		

The Particle Photon was selected as the microcontroller of choice due to its built-in wireless capacity, thereby making it relatively straightforward to stream the data from the precipitation gauge in real-time to the internet. Indeed, the Photon was developed specifically as a means to create projects for the "internet of things". While the above components alone require the availability of a nearby source of AC power, a user may elect to make the gauge energy-independent through the addition of a small solar panel. This will, however, drive up the cost through the panel itself (about $40), a lithium battery ($12), and a breakout board to regulate the charging of the battery ($25).

Development and Coding. The initial set-up of the unit was relatively straightforward given Sparkfun's online, step-by-step development guide[2]. Exhibit 5 shows the entire weather station unit on the workbench during the preparation process. The only soldering required was the wiring of the weather shield to the solar power board as we desired to run the station wholly off of solar energy. Concerning the programming code, all coding was performed in the Particle Build integrated development environment (IDE), which uses a variant of the C+ programming language. It was not necessary, however, to develop original code for the station as a whole (nor the rain gauge specifically) due to the ready availability of example code in online collaboration forums. We specifically used the sample code available on GitHub[3], a web-based platform for hosting, managing, and sharing open source code. GitHub has become, in many ways, the standard means for documenting and disseminating open-source projects across the maker community.

Exhibit 5: Open Source Weather Station on the workbench



[2] See https://learn.sparkfun.com/tutorials/photon-weather-shield-hookup-guide/ (Sparkfun, 2016)
[3] See: https://github.com/sparkfun/Photon_Weather_Shield (Bartlett & Sparkfun, 2016).

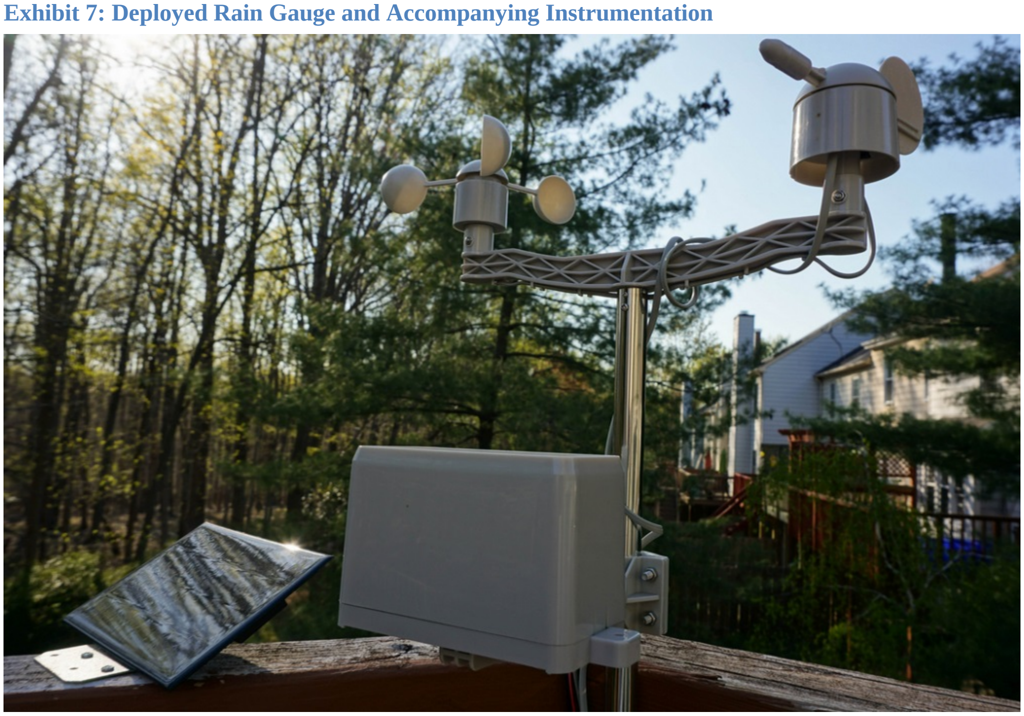
Exhibit 6: Sample code for the rain gauge in the Particle IDE

```
142 //******************************************************************************
143 void rainIRQ()
144 // Count rain gauge bucket tips as they occur
145 // Activated by the magnet and reed switch in the rain gauge, attached to input D2
146 {
147   raintime = millis(); // grab current time
148   raininterval = raintime - rainlast; // calculate interval between this and last event
149
150     if (raininterval > 10)      // ignore switch-bounce glitches less than 10mS after initial edge
151   {
152     dailyrainin += 0.011;       //Each dump is 0.011" of water
153     rainHour[minutes] += 0.011; //Increase this minute's amount of rain
154
155     rainlast = raintime;        // set up for next event
156     bool rain_event = true;     // Puts the flag up when the interrupt is triggered
157   }
158 }
```

Exhibit 6 provides a sample of the Particle Build coding environment. Lines 143 to 157 are specifically pertinent to the rain gauge itself, describing the actions that the microcontroller will take when the bucket fills with rain, tips, trips the magnet, and sends an electronic pulse to the microcontroller unit. The code for the weather station as a whole—which also included sensors for temperature, humidity, wind speed, and wind direction—was approximately 635 lines in length. Although originally developed by Bartlett and Sparkfun (2016), it has since been modified and adapted by many users in the maker community. While a degree of customization was required to connect the station to a weather data hosting site (www.wunderground.com), minimal changes to the sample code were necessary for the rain gauge itself. Also, the wireless capacity of the photon microcontroller allowed for the code to be transmitted directly to the weather station via the cloud, with no direct connection to the unit itself needed. This capability could be of particular significance were the unit to be placed in a location that is difficult to reach, such as a roof top.

Field Location. The precipitation gauge was fielded in a backyard setting within a residential neighborhood environment. The gauge was set up at N 39°4'48 ", W76°58'24 " at an elevation of 384 feet above sea level. The unit was placed about 20 feet off the ground (with no overhanging trees or rooftops) and within easy reach of a wireless network. Exhibit 7 shows the weather station in its entirety, with the precipitation gauge position on a metallic arm at the fore of the photograph.

Exhibit 7: Deployed Rain Gauge and Accompanying Instrumentation

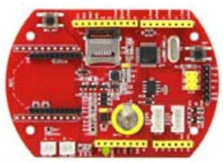


Stream Height Gauge

The stream height gauge prototype (also referred to as "the stream gauge") utilized in this research follows the open source design developed by Robert Ryan-Silva of the DAI Maker Lab[4] which seeks to apply the tools and approaches from the Maker Movement to international development work. The detailed designs of the stream gauge (named the "Hidrosonico" following initial application in Latin America) were accessed from GitHub[5], including the program code, the layout of a custom circuit board, a bill of materials, and the schematics for an optional frame and solar mount.

Hardware. Exhibit 8 enumerates the key hardware components of the stream gauge. The sensor used in by the gauge is the Maxbotix MaxSonar HRXL MB7369, a device that measures distance (range) using the return period of projected sound waves. The referenced model is designed to ignore small objects and default to the largest nearby surface, making it ideal for measuring the distance to the surface of a stream. The microcontroller of choice for the stream gauge is a Seeduino Stalker. While an Arduino microcontroller such as that used for the weather station developed by Mesas-Carrascosa et al. could be used for this gauge, the Seeduino offers a number of important advantages. First, the board can operate using as little as 3.3 volts, thereby minimizing the amount of power that is drawn from the battery. Second, the board has a built in battery charging system, meaning that no additional wiring is needed to connect a solar panel and a lithium battery. Finally, the Seeduino includes a real time clock on board, which is critical when the user requires measurements at precisely timed intervals.

Exhibit 8: Primary Hardware Components of the Precipitation Gauge

Hardware Unit	Cost	Function	Image
Seeeduino Stalker V3	$39	• Arduino-compatible microcontroller (ATmega328P) board which serves as the operating system for the stream gauge as well as storing data on an internal SD card; • Includes hook-ups for charging a LiPo battery using a solar panel as well as a real-time clock chip; • Link: http://www.seeedstudio.com/depot/Seeeduino-Stalker-v3-p-1882.html?cPath=6_7	
Maxbotix MaxSonar HRXL MB7369	$100	• Ultrasonic sensor that uses sound waves to calculate the distance (range) between the sensor and the object. According to the specifications, the sensor is designed to ignore small targets and report only the object with the largest acoustic return. • Link: http://www.maxbotix.com/Ultrasonic_Sensors/MB7369.htm	
Adafruit FONA 800 & Antenna	$40 & $5	• A GSM cellular module (using SIM800 technology) which allows for the transmission of data using any Global GSM network with a 2G SIM. Requires a prepaid SIM card on a 2G network. • Link: https://www.adafruit.com/products/1946	
6V Solar Panel	$39	• 6V 3.4 Watt solar panel which uses a high efficiency monocrystalline cell. Designed for long-term exposure to the outdoors; • Link: https://www.adafruit.com/products/500	

[4] DAI is an international development consulting firm based in the greater Washington DC metro areas. For more about the DAI Maker Lab, see: http://dai.com/our-work/solutions/dai-maker-lab
[5] See: https://github.com/DAI-Maker-Lab/hidrosonico (Ryan-Silva, 2015)

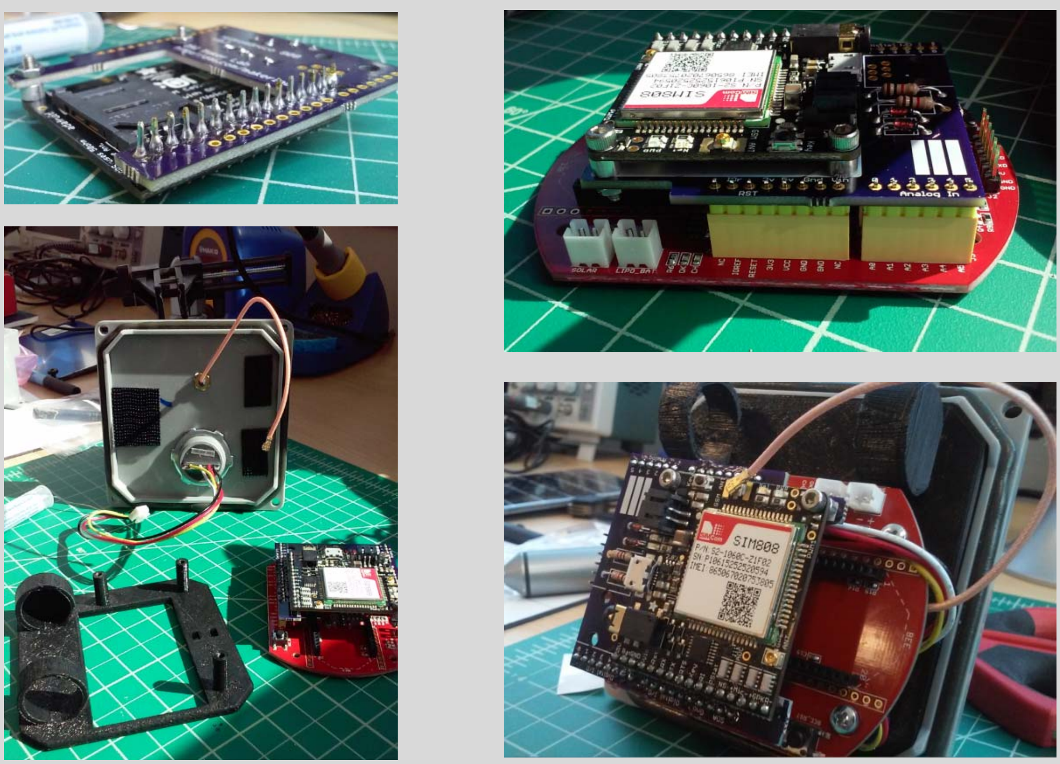
Hardware Unit	Cost	Function	Image
Lithium Ion Battery	$10	• Lithium Ion Cylindrical Battery - 3.7v 2200mAh which is used to run the sensor and power the cellular connection. • Link: https://www.adafruit.com/products/1781	
Total Cost:	**$233**		

In addition to the above hardware, the GitHub repository for the gauge also includes the designs for a custom printed circuit board (PCB). As noted in the bill of materials, such a circuit board—which is soldered directly to the microcontroller—is not absolutely necessary, as a user could elect to connect the cellular module, sensor, and microcontroller with wiring. The introduction of wires, however, increases the risk of system failure due to one or more of those wires coming loose during installation or otherwise. Using a custom printed circuit board eliminates this risk, yielding a more durable device which can better withstand long-term, outdoor exposure.

Development and Coding. The setup of the stream gauge required more upfront preparation given the greater complexity of the electronics involved. With guidance from the DAI Maker Lab, however, the setup of the stream gauge unit included the following key tasks:

- The Fona cellular module was soldered to the custom designed printed circuit board, thereby eliminating the need for any wiring (Exhibit 9, top left);
- The combined cellular module and custom circuit board were then mounted onto the Seeduino microcontroller board, with all pins soldered to solidify the mount and ensure the electrical connections (Exhibit 9, top right).

Exhibit 9: Stream Height Gauge Development



- The sonar gauge was then attached to the cover of a standard (commercially available) PVC junction box as well as cellular antenna. Further, a four-pin conversion cable was also affixed to the sonar for connection to the microcontroller (Exhibit 9, bottom left).
- Finally, the electronics were also mounted to the junction box cover using a custom designed frame. Notably, the frame was created by the DAI Maker Lab using a 3D printer, with the specifications made available on GitHub for easy replication (Exhibit 9, bottom right).

The programming code for the stream gauge was downloaded in its entirety from the GitHub repository as an Arduino sketch file. Also written in the C+ programming language, the roughly 1000-line code for the gauge required a limited degree of customization and updating prior to deployment such as the time interval for measurement and the instructions for sending data to the internet. In this regard, the stream gauge was programmed to take a reading at five minute intervals, with data then streamed in real-time to cloud storage at a free cloud-based site provided by Sparkfun.com[6].

Field Location. The stream height gauge was fielded on the Good Hope Tributary just under one mile from the confluence with the main stem of the Paint Branch Stream (at latitude 39°05'18.2", longitude 76°59'22.5", and an elevation of 366 feet). The gauge was co-located with USGS Station Number 01649150[7] which contains a water-stage recorder and a crest-stage gauge accompanied by a satellite data collection platform. The USGS station—which has been active since 2006—transmits a reading every five minutes to the National Water Information System.

Exhibit 10: The deployed stream gauge

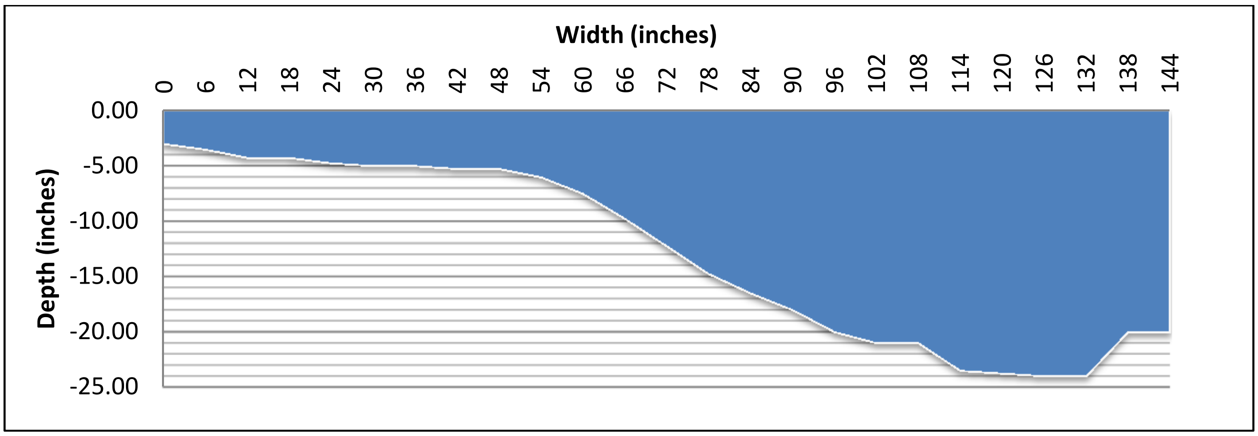
[6] http://data.sparkfun.com/paintbranch_stream_gauge.

[7] See station details and data at: http://waterdata.usgs.gov/md/nwis/uv?site_no=01649150

With a total drainage area of 1.04 square miles, the spring-fed tributary follows a meandering path through a well forested area. The stream is characterized by a series of riffles and slow-moving pools, with the USGS station located in the mid-section of a pool that stretches more than 50 feet. The stream gauge itself was deployed by mounting it on a concrete structure originally put in place to hold the USGS staff gauge. Situated on the western embankment, the open source gauge hangs over the surface of the stream giving the sonar sensor a clear path to the water's surface (see Exhibit 10 on previous page). In order to estimate the total discharge at the site, a profile of the stream was developed by measuring the depth every six inches from the west (left) bank to the east (right) bank. Exhibit 11 below depicts the profile of the 12-foot wide stream bed at the site during a period of base flow. A shallow section averaging 5 inches in depth extends from the west bank but then rapidly slopes downward midway across the stream, reaching a maximum depth of about 24 inches just prior to the east bank.

The stream gauge was deployed on the afternoon of March 12, and immediately began transmitting to the aforementioned site. In order to most closely mirror the data logged by the USGS, the sonar gauge registered a reading every 5 minutes commencing at the top of the hour.

Exhibit 11: Profile of Good Hope Tributary at the deployment site



RESULTS

The following subsections describe the results of the field deployment of the open source precipitation gauge and stream height gauge. For each prototype we present the data collected and an associated statistical analysis comparing the regularity, precision, and distribution of readings taken by the respective prototype with proximate public and private monitoring stations. More specifically, for the precipitation gauge we compare the daily levels of precipitation with those from adjacent privately operated stations on Weather Underground; similarly, for the stream gauge prototype, we compare depth measurements with the aforementioned USGS station. Following the presentation of the quantitative results, we briefly evaluate the development and fielding process on a more qualitative basis. We then conclude by using the datasets to calculate basic hydrological characteristics for the Good Hope tributary.

Precipitation Gauge

Quantitative Results.

As noted under the Materials and Methods, the precipitation gauge was deployed for approximately 30 days commencing in March 2016. While the gauge was initially set up the first week of March, difficulties with powering the weather station as a whole meant that precipitation measurements did not begin in earnest until the 15th of March. Over the course of this period, the gauge recorded a total of 1.85 inches of rain (spurious readings excluded), with data streamed continuously to Weather Underground. The minimum and maximum daily amounts recorded were 0 inches and 0.54 inches respectively, while the standard deviation of readings was 0.128. Importantly, it was an abnormally dry period, with the total rainfall for March and April far below the average amount.

Exhibit 12: Daily Rainfall Totals for 5 Stations

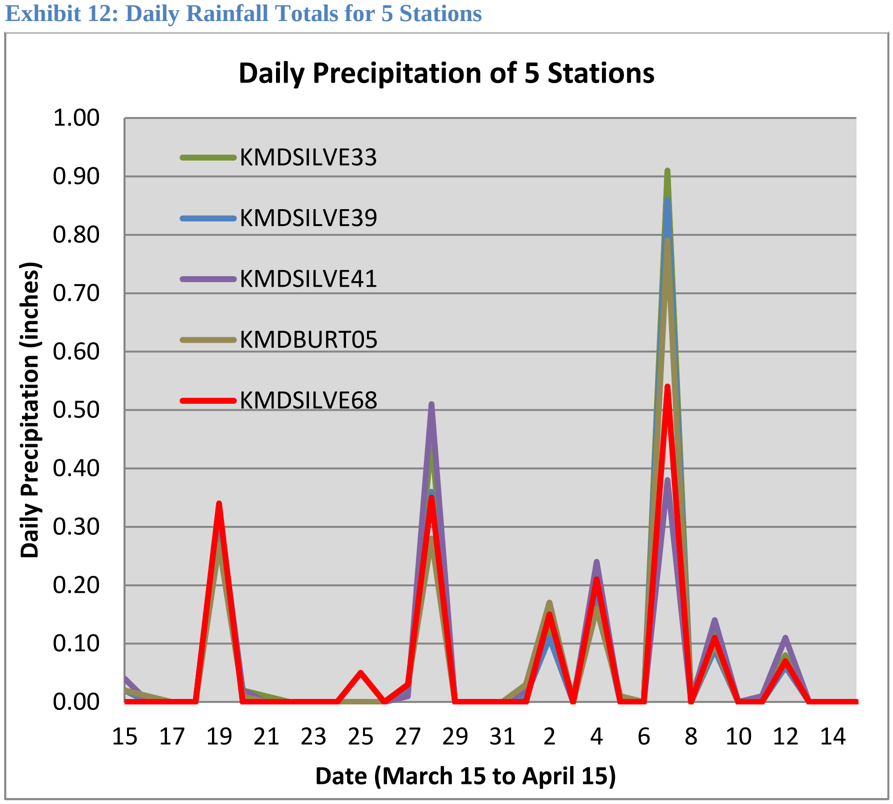


Exhibit 12 at right depicts the daily rainfall levels for the reporting period for the prototype gauge (KMDSILVE68, in red) as well as four additional privately operated weather stations located within close proximity (ranging from about 0.6 to about 2.1 miles) from the prototype gauge. While a weather station operated by the National Weather Service would have been preferable to the four privately operated stations, no stations exist within a nearby radius for comparison. Given the hyper-local nature of rainfall, then, we opted to utilize the four private stations which also streamed real-time data to Weather Underground. Notably, however, the type of instrumentation used by these private operators was listed on each station's respective website; three of the stations use consumer-grade, off-the-shelf-systems, while one station (KMDSILVE33) uses a semi-professional grade, off-the-shelf system.

Overall, once spurious data was removed (see performance and troubleshooting below), the prototype gauge followed the measurements of the four privately operated gauges quite closely. Exhibit 13 compares the 30-day totals across all five stations as well as the correlation statistics between all five stations. A regression analysis—with the prototype as the dependent variable—further demonstrated the strong relationship between the results with an R squared of 0.99 and a significance value of 9.74(E-28).

Exhibit 13: Total Rainfall and Correlations across 5 Stations

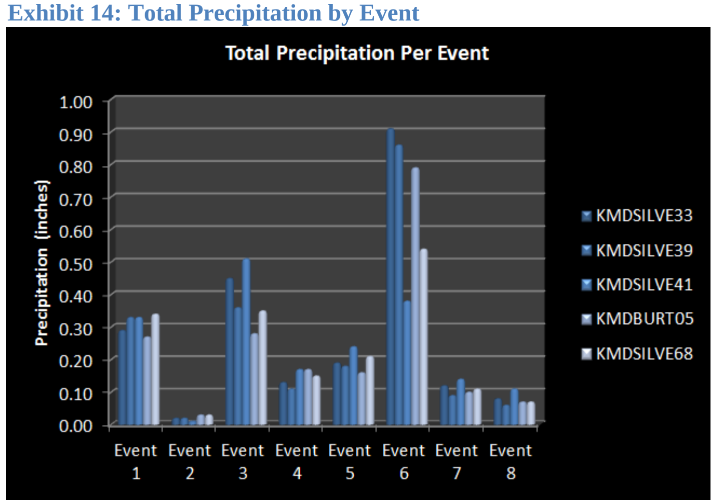
Station Name	*Instrument*	*30 Day Total (in)*	*KMD-SILVE33*	*KMD-SILVE39*	*KMD-SILVE41*	*KMD-BURT05*
KMDSILVE33	Davis Vantage Pro2	2.30	1	-	-	-
KMDSILVE39	Netatmo	2.04	0.995	1	-	-
KMDSILVE41	Ambient WS-1400-IP	1.98	0.861	0.845	1	-
KMDBURT05	Netatmo	1.95	0.989	0.994	0.823	1
KMDSILVE68	OS Prototype	1.85	0.959	0.962	0.941	0.951

Performance and Troubleshooting. While the cleaned data indicates a strong performance by the open source prototype, the set-up and operation of the gauge required a degree of troubleshooting on several fronts. First, the initial programming code did not include the necessary commands to zero-out the daily rainfall level at midnight (every 24 hours), resulting in cumulative amounts being carried over from the previous day. To resolve this issue, we turned to the DAI Maker Lab for assistance in inserting the appropriate algorithm.

Second, we encountered spurious readings on a regular basis in which a trace measurement on the order of 0.01 or 0.02 inches of precipitation would be transmitted to the station's dashboard on Weather Underground despite the complete absence of rain. The cause is not believed to be accidental movement of the tipping bucket itself within the gauge, but is possibly a circuit shortage within the wiring of the microcontroller. The spurious readings averaged approximately 0.03 inches per day, and were manually removed from the final data set. Troubleshooting of this issue remains ongoing as of the completion of this report.

Finally, providing a reliable power source to the station (inclusive of the rain gauge) proved to be more challenging than expected. The station was initially powered by a 2.5 watt solar panel which then charged a 3.7 volt lithium battery. While this source may have been sufficient for the gauge in and of itself, the Particle Photon microcontroller—which represents a relatively new and thus untested product—required more power than anticipated, causing the station to go offline after 48 hours. It is likely that the high power draw required by the Photon is due to the continuous Wi-Fi connection, but additional troubleshooting is needed. During the majority of the deployment period, then, the entire station was transferred to wall (AC) power. The utilization of AC power also caused an unexpected outage, however, during an unusually intense storm event which tripped a household circuit breaker. Exhibit 14 below shows that the greatest disparity in rainfall data occurred during precipitation event six, which brought about 1 inch of rain to the area over a two hour period on April 7. Both the prototype (KMDSILVE68) and station KMDSILVE41, however, show roughly half to two-thirds of the precipitation of the other three stations due to the fact that they both went offline during the most intense period of the storm event. It is highly likely, then, that the prototype would have registered at least an additional 0.40 inches of precipitation had it continued to measure rainfall throughout the storm event. In order to address the outage risk, a battery may be installed to serve as a temporary backup should AC power be interrupted in the future.

Exhibit 14: Total Precipitation by Event



Stream Height Gauge

Quantitative Results.

Over a performance period of approximately 35 days (March 12, 4:00 pm EST to April 15, 11:55 pm EST), the sonar-based stream gauge executed and uploaded more than 9,000 measurements, an average of approximately 262 readings per day. The mean reading over the period was a water depth of 1.70 feet, with a minimum of 1.61 feet and a maximum of 2.23 feet. The standard deviation for the readings was 0.04. Exhibits 15 and 16 depict stage hydrographs of the stream gauge readings over the entirety of the data collection period. More specifically, Exhibit 15 shows the raw data points while Exhibit 16 shows a 30-minute rolling average of the stream height. These can then be compared and contrasted with Exhibit 17, the hydrograph for the co-located USGS stream gauge station. Annexes A and B also contain statistics summarizing the daily readings for both the prototype gauge as well as the adjacent USGS gauge.

Exhibit 15: Prototype Stream Depth Measurements

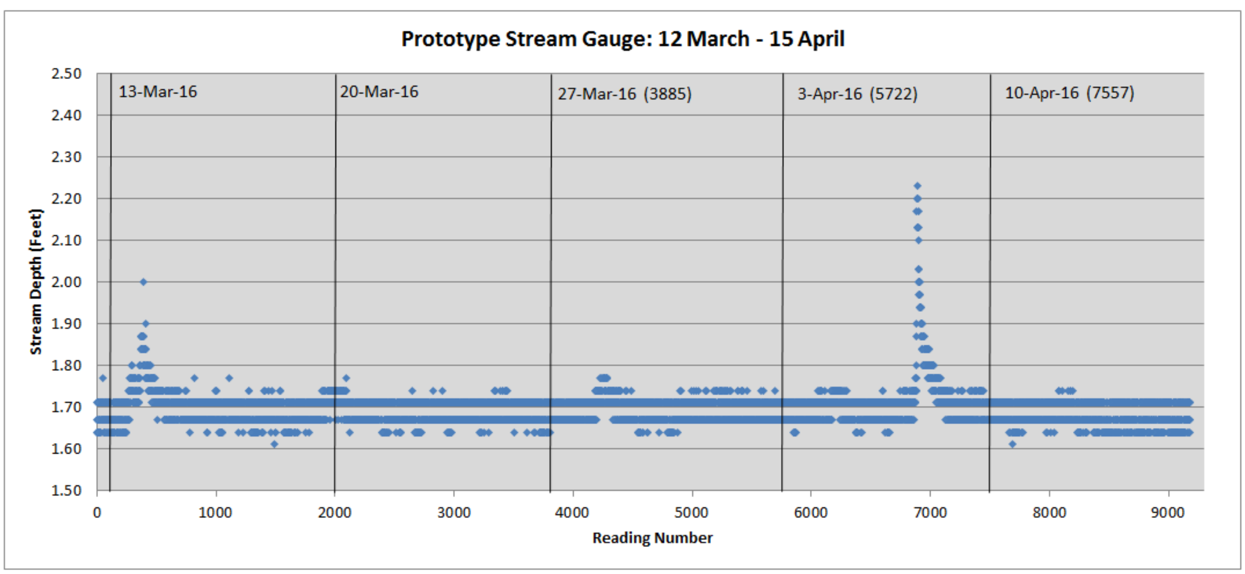


Exhibit 16: 30-Min Rolling Average of Prototype Stream Depth Measurements

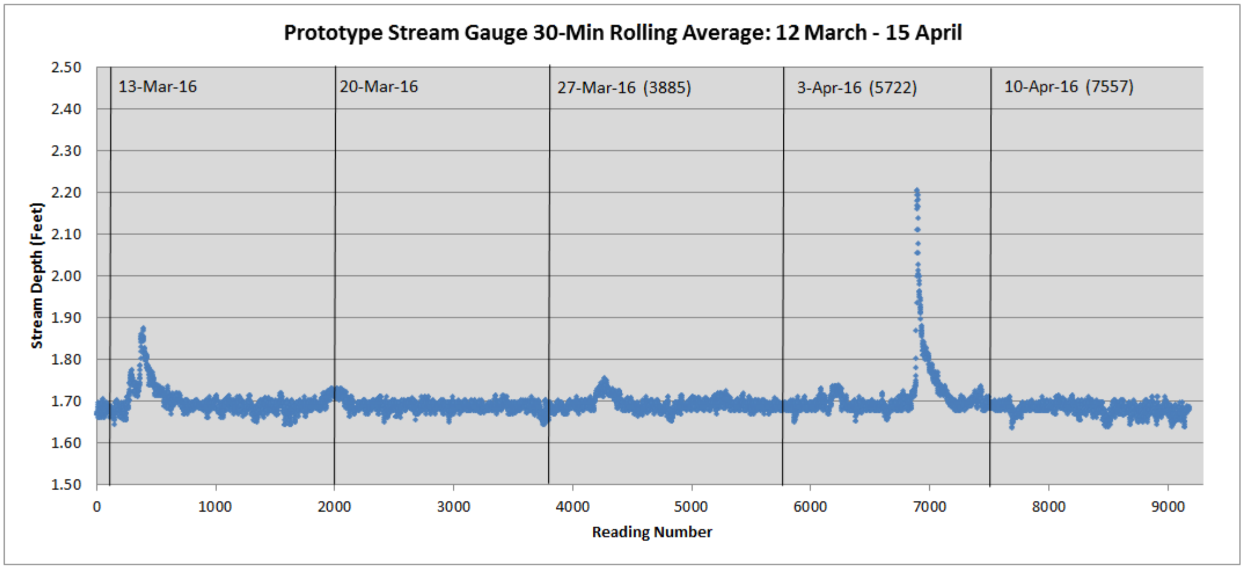
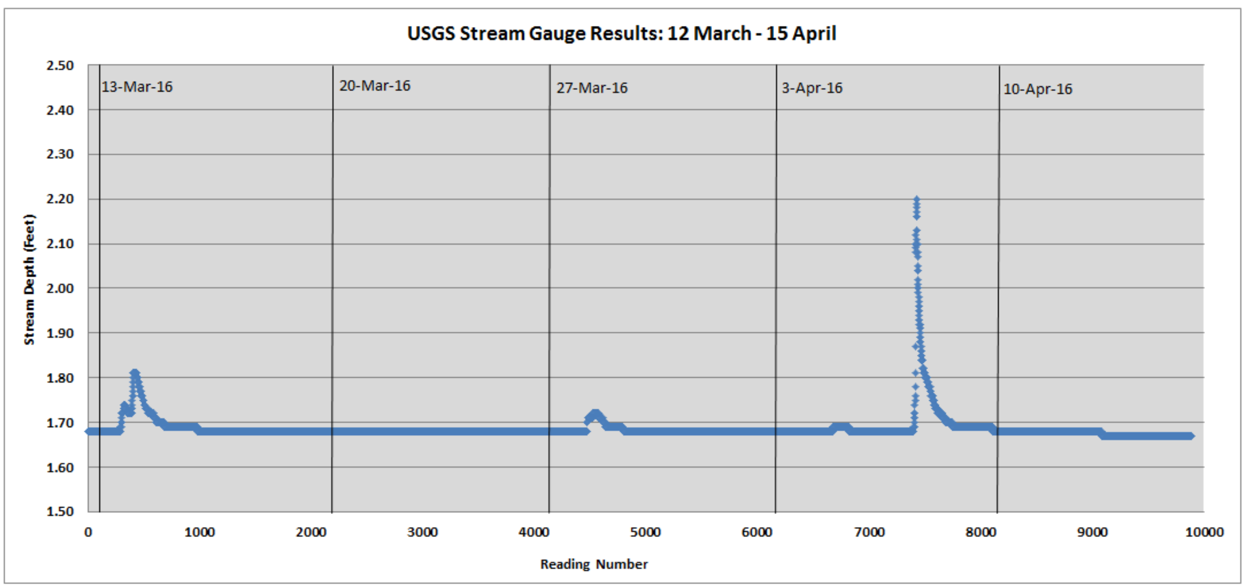


Exhibit 17: USGS Stream Depth Measurements

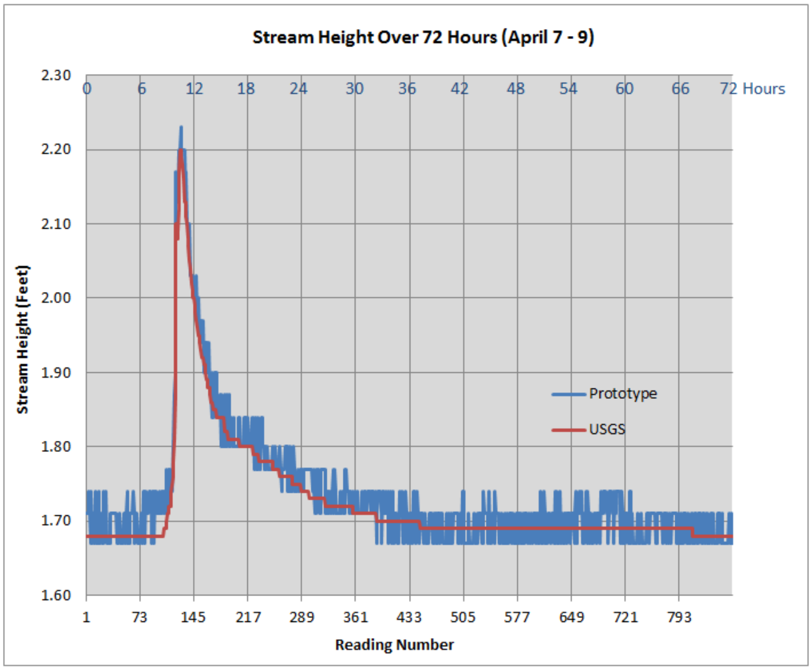


Given the overall dearth of precipitation during this period, it was not surprising that the fluctuations in stream height were relatively small. The principal exception occurred during the fourth week of data collection when a morning storm brought approximately one inch of rain in a short, two hour period. Averaging about 1.68 feet deep, the Good Hope Tributary rapidly spiked to about 2.2 feet, with the total discharge increasing from a flow rate of about one cubic foot per second to 16 cubic feet per second at the peak. Exhibit 18 on the following page shows a more detailed illustration of this period, with the USGS data overlaid on top of the prototype data.

To verify the relationship between the prototype and USGS datasets, we conducted several statistical analyses of the 864 readings taken by each gauge during the 72 hour period surrounding the storm event. First, an analysis of variance (Anova) test yielded an F statistic of

8.20 and a probability value of 0.0042. Given that the P-value is greater than the error (alpha 0.05) we can safely conclude that there is a statistically significant relationship between the two datasets. In addition, we also conducted a regression analysis using the prototype readings as the dependent variable (y) and the USGS readings as the independent (x) variable. The analysis also confirmed a statistically significant relationship between the two variables, with an R squared value of 0.92 and a significance value (F statistic) of nil (0).

Exhibit 18: Overlay of USGS and Prototype Stream Height over 72 hours



Performance and Troubleshooting. While a degree of troubleshooting was necessary to operationalize the prototype stream gauge[8], it performed well following deployment, especially considering the high frequency of readings and data uploads. The most notable performance issues in the field were as follows:

- During the first week of deployment we noticed relatively frequent spurious readings in which the measurements would jump from the baseline of 1.67 or 1.70 to approximately 3.90 feet. While no set pattern emerged, spurious readings could occur as often as once an hour. Tech advisor Robert Ryan-Silva suggested a change in the coding to remedy this which simply delayed to boot-up of the cellular module until *after* the current reading had been completed. The underlying hypothesis was that the power draw of the cellular module would sometimes affect the reading. This proved to be exactly the case, with spurious readings dropping to virtually nil after the sequencing of events was modified. As such, we have removed all such readings from the final dataset graphed in Exhibits 15 and 16.
- After a series of cloudy days the power level of the battery appeared to be on a steady trend downwards, with the solar panel providing insufficient power to fully recharge the battery during daylight hours. The situation resolved itself, however, as one day of full sun helped to reverse the trend. While the problem never resurfaced—even with further cloudy weather—it does represent a potential future risk, especially during the winter months.
- Over the course of the 35-day period of performance, the prototype skipped/missed approximately 8% of scheduled readings (a total of 733). There was no immediately discernable pattern to the missed readings, but it is more likely due to a problem contacting

[8] During initial testing we encountered problems with the activation and deactivation (sleep mode) of the cellular module, requiring a degree of recoding by the DAI Maker Lab.

the closest cellular tower than an inability to take the reading itself. This hypothesis could easily be tested by changing the location to one that is closer to a cellular tower.

On a broader level, the sonar-based gauge was, not surprisingly, somewhat less precise than the USGS stilling well gauge. Exhibit 15 shows most clearly the tendency of the sonar gauge to "bounce" upwards or downwards slightly from one reading to the next. During base flow periods, for example, whereas the USGS gauge was at a steady 1.68 feet, the prototype gauge would fluctuate from 1.67 to 1.70 feet and back to 1.67 feet again, with occasional movements down to 1.64 or 1.74 feet. The sonar sensor itself is accurate to approximately 1 cm (or 0.03 feet), which is likely the principal cause of these fluctuations.

The Hydrology of the Good Hope Tributary

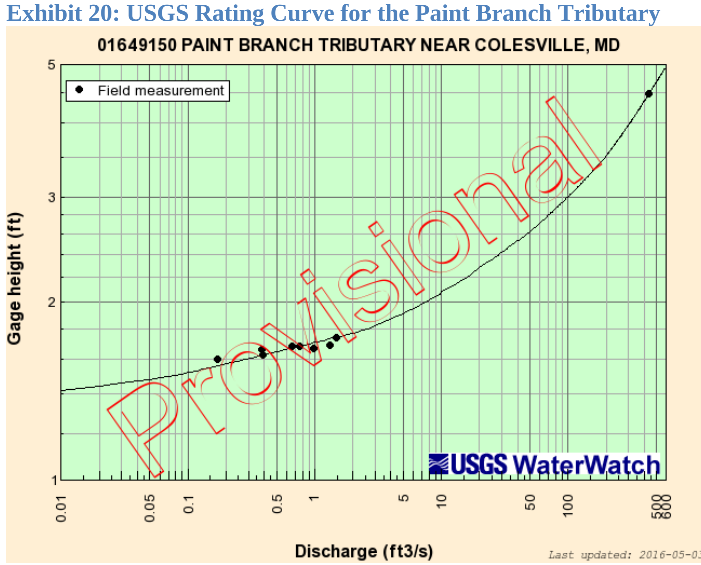
Once a stream height gauge is in place and the profile of the stream bed is measured, a critical next step in applying the data collected is to estimate the total discharge of the stream through the development of a rating curve. The calculation of discharge—and how this discharge changes with varying levels of precipitation—is necessary to determine the amount of water in a drainage area and the impact of weather conditions on that amount. This information can then support water allocation decisions, predict flood and drought conditions, and understand how land-use and climate change are impacting surface runoff. Toward this end, in the process of setting up and monitoring the stream gauge, we also took two flow rate measurements using a simple float and used the area of the channel to perform a rough calculation of discharge.

Exhibit 19: Observed Discharge Measurements vs. USGS Rating Curve

Date	Time	Prototype Stage	Observed Discharge	USGS Stage	Rating Curve Discharge 1	Rating Curve Discharge 2
26-Mar-16	3:30 pm	1.68 feet	1.14 ft3/sec.	1.68 feet	1.20 ft3/sec	0.73 ft3/sec
07-Apr-16	5:00 pm	1.81 feet	4.60 ft3/sec.	1.80 feet	3.30 ft3/sec	2.60 ft3/sec

As shown in Exhibit 19 above, the estimated discharge at 1.68 feet was 1.14 cubic feet per second while that at 1.81 feet was 4.6 cubic feet per second. When these estimates were originally compared to the USGS rating curve, the first was found to be just 5% below the USGS discharge estimate (of 1.20 cubic feet per second) while the second was roughly 39% above the USGS amount. Notably, however, the USGS later updated its rating curve for this station during the first week of April with significantly lower discharges (see "Rating Curve Discharge 2"), thereby significantly increasing the margin of error in the discharges estimated with the float. The differences between the manual (float-based) observation and the rating curve as well as the dramatic changes in the USGS's own rating curve highlight the challenges of measuring discharge and

Exhibit 20: USGS Rating Curve for the Paint Branch Tributary



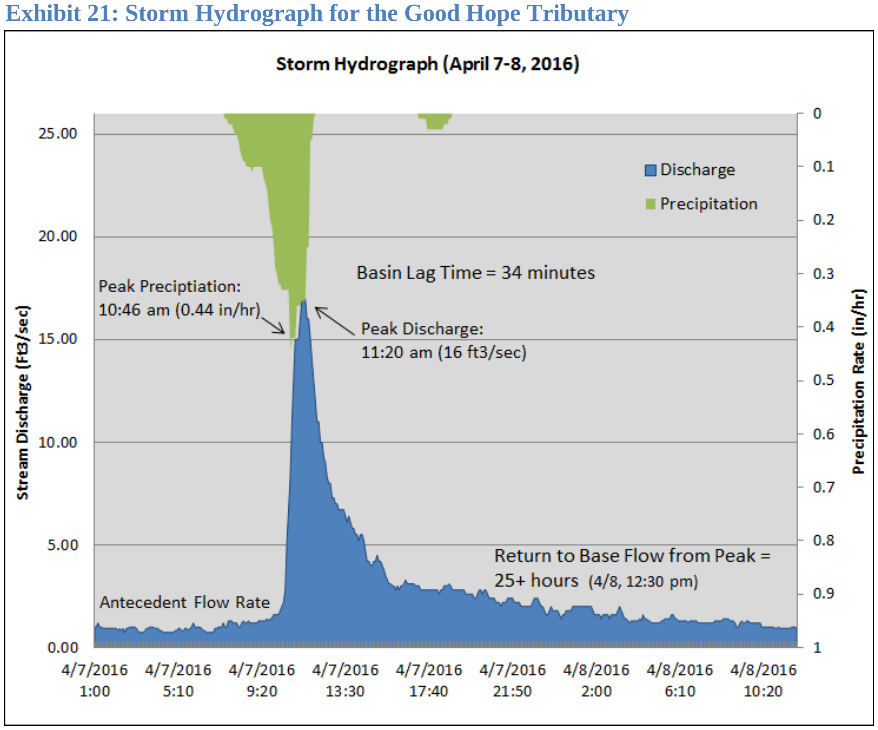
Source: www.waterwatch.usgs.gov

the importance of obtaining regular readings with actual flow meters. In this regard, Exhibit 20 depicts the updated rating curve for the station, including the 10 most recent field measurements (see black dots) that informed the development of the rating curve[9]. (USGS, 2016)

Once a rating curve for a given stream is calculated, we can then use the results to develop a hydrograph which illustrates how flow levels change over time. As noted by Ward and Trimble (2004), "the hydrograph tells more about the hydrology of a small catchment than any other measurement" (pg. 131). Exhibit 21 below depicts a storm hydrograph for the period of April 7-8 when the Good Hope Tributary experienced the most intense precipitation event of the data collection period. We constructed this hydrograph by relating the rolling (30 minute) average of the stream gauge prototype with the USGS rating curve (in Exhibit 20) to calculate the stream discharge every five minutes. Further, the rate and timing of the precipitation was then added using data from the rain gauge prototype as well as a nearby privately operated station.[10]

The hydrograph illustrates several important characteristics of the catchment area that are highly relevant to water resources management and planning. First, the short lag time between the peak precipitation and the peak discharge (approximately 30 minutes) is indicative of both a very small drainage area as well as one with developed, impervious areas which rapidly convey precipitation into the stream channel. This is further confirmed by the rapidity of the rise of the channel where flow increased exponentially over the course of a one hour time period (10:20 am to 11:20 am). It is notable that a major highway system was recently completed less than half a mile north of the gauge's location, undoubtedly contributing significantly to the runoff in the area. That said, the hydrograph also shows a more gradual return to base flow over a period of more than 24 hours. The above-average flow from mid-day on the 7th to mid-day on the 8th represents subsurface flow which is entering the channel from groundwater. This indicates that there is also a significant amount of infiltration occurring, reflecting the role played by the intact forested areas and riparian zones which enable greater groundwater recharge and runoff filtration.

Exhibit 21: Storm Hydrograph for the Good Hope Tributary



[9] The rating curve in Exhibit 20 is taken from: http://waterwatch.usgs.gov/index.php?id=mkrc. The "toolkit" on this website allows the user to access and customize a rating curve graph for any USGS station in the US.
[10] Note that the supplemental rain data was required from Wunderground Station KMDSILVE39 given that the prototype's power supply was cut during the peak of the storm.

DISCUSSION

The objective of the above research was to assess the potential of low-cost, open source technologies in the planning and management of water resources. More specifically, this paper sought to address the following question: Can open source environmental sensors contribute to the improved monitoring, planning, and management of water resources over the near term, and what are the potential advantages and limitations of these technologies? To address this query we undertook (1) a review of existing literature and case studies on open source environmental hardware and citizen science, followed by (2) the deployment of two open source sensors (a stream gauge and a precipitation gauge) in a suburban watershed in Montgomery County, Maryland. As we conclude the paper, we discuss the perceived advantages/benefits of open source sensors, the likely limitations, and the potential applications of such technologies both domestically and abroad.

The Promise of Open-Source Sensors

When taken together, the results presented by researchers in the literature and the first-hand experience presented herein point to a number of potential benefits of open source sensor hardware in an era of greater and greater climate uncertainty:

Low Cost, High Value. It is remarkable that a sensor unit costing under $250 USD has collected relatively accurate stream stage data every five minutes for 35+ days now (the unit remains up and operating as of day 44). The nearly 10,000 readings offer high temporal resolution data at a fraction of the cost of existing technologies. The USGS stations, for example, can cost as much as $35,000 to set up accompanied by an additional $10,000 per year in operating costs (Stokstad, 1999). While the actual equipment costs are lower—Campbell scientific, for example, sells a basic stream gauge for $3,000 to $3,500 (Royem et al., 2012)—it nonetheless demonstrates the high value that can be obtained from open source hardware sensors.

The literature and testing reported herein further reveals that quality, high resolution data can be collected by non-specialists (i.e. “citizen hydrologists”) when the right tools and technologies are made available. Timing is critical when it comes to understanding how a stream will react to a storm event, making it extremely challenging for a citizen hydrologist to manually measure, for example, the speed with which stream waters rise during intense precipitation. The option to cost-effectively deploy a stream height gauge to capture an event that may come at any time—such as on day 26 of deployment in the above case—greatly expands the possibilities for understanding the characteristics of a stream system and the surrounding watershed while still remaining within the financial means of a citizen or community-based environmental group.

Customizable and Adaptable. While customization represents the very essence of open-source products, it bears repeating that such technologies are designed to be manipulated, altered, and adapted for the needs of a specific user or group of users. A simple example using the stream gauge prototype is the timing of readings. For the field deployment, we desired to have a time interval between readings of five minutes in order the match the specifications of the USGS gauge, an adaptation that was easily made given that we can access, modify, and overwrite the code that directs the microcontroller when to take measurements. Building on this capability, a user could program a similar gauge to take readings more often during one time of year (such as the rainy season) and less often during another time of year (such as the dry season). Alternatively, one could also make reading intervals dynamic by increasing the frequency of measurements/uploads in accordance with fluctuations in the height of the water level. When stream height is increasing rapidly, for example, measurement frequency could be upped to once every minute instead of once every five minutes.

In addition to customizing specifications to the needs of a user, a prototype such as the stream gauge could also be adapted for a completely different use altogether. A researcher interested in understanding traffic congestion in the heart of a rapidly growing metropolis could, for example, access the code via GitHub and repurpose the program to count vehicular traffic as it passes beneath a bridge. This type of repurposing of projects and code shared through collaborative forums like GitHub is an important part of what drives innovation with open source tools and technologies.

Engendering Local Ownership and Learning. The development, programming, testing, and deployment of modular electronics and open source sensors offer excellent opportunities to engage users in a collaborative design process. As Ryan-Silva (2015) notes, the maker approach facilitates a "user-centered design process in which the equipment's end users are active participants in the process of setting the design priorities and operational parameters" thereby providing these stakeholders with the knowledge and confidence to independently operate and maintain the equipment.

This methodology stands in sharp contrast to the fielding of off-the-shelf equipment which, by definition, is fully built and programmed, requiring minimal learning on the part of the user to deploy and begin collecting data. The open source weather station depicted in Exhibit 7 provides a case in point—purchasing the microcontroller and meters, assembling the station and wiring, and reviewing/adapting the open source firmware code is a learning process which requires the user to gain an intimate understanding of the components of the equipment, how it operates, and the assumptions that are written into the program. This better positions the user to repair the unit were a component to fail by, for example, replacing a faulty individual meter or microcontroller instead of needing to replace the entire station.

In addition, the development of open-source prototypes demands that the user/designer adequately study the environmental parameter for which they are seeking to gather data. Designing a stream gauge, for example, requires the user to closely assess the frequency of data needed; understand the best-practices and varying approaches to measuring stream height; think through the sequencing of the data measurement, storage, and transmission process; evaluate the flow characteristics of the stream in order to best place the gauge; and the like. Such a level of engagement and learning is less likely when deploying a packaged unit.

Limitations and Implementation Considerations

While the potential benefits of open source sensor hardware in the monitoring and management of water resources are substantial, the application of such technologies is not without limitations. Specific constraints that arose in our own field testing and the literature accompanied by key implementation considerations are as follows:

Upfront Learning Curve. The very “blank canvas”, user-centered approach that makes these technologies so adaptable and facilitates stakeholder engagement also comes with an upfront learning curve. The use of open source sensors to gather information about water resources is not a “plug and play” or “fix it and forget it” option; instead it demands experimentation, tinkering, troubleshooting, and continual iteration.

In this regard, one of the motivations for this project was to better understand how challenging it would be for a complete novice to delve into the world of modular electronics and open source sensors and develop functional units. Following participation in a (two-day) training session on open source electronics accompanied by the deployment of sensors under this research, two realities are apparent. First, while it would have been possible to independently develop a simple sensor unit (to detect light, for example), the successful fielding of sensor units as complex as the stream and precipitation gauges would not have been feasible without assistance from the DAI Maker Lab. As a beginner in the C+ programming language, one can certainly discern the objectives, structure, and methodologies used by the code, but it is much more challenging to understand the nuances such that one can troubleshoot problems as they arise. The aforementioned glitch whereby the precipitation gauge was failing to zero-out the cumulative daily precipitation amount at midnight required the insertion of a new algorithm in which the microcontroller checked the time and returned the cumulative rainfall for the day to zero if (and only if) the time was equal to 12:00 am. The capacity to write this type of original code takes time to develop and is beyond that of a novice programmer.

Second, the development of an open source sensor to monitor hydro-met conditions is most likely to succeed when the stakeholders that are engaged in the process have an interest in the technology itself. In other words, given the intensity of user engagement and learning inherent in open-source technologies, it makes much less sense to introduce them when stakeholders simply desire the data but have minimal interest in *how* that data is collected and the supporting technologies that make it possible. It is therefore important to understand the underlying motivations, incentives, and interests of stakeholders prior to selecting an open source pathway to address a particular development problem.

Spurious Measurements and Data Precision. In line with the above learning curve and need for troubleshooting, it is noteworthy that both the stream gauge prototype and precipitation gauge prototype experienced spurious readings to one degree or another. In the case of the stream gauge, the underlying cause was addressed and the problem resolved with the assistance of the DAI Maker Lab. The spurious measurements from the rain gauge, however, required more intensive data cleaning and the root cause has not yet been determined. Additional experimentation will therefore be required to pinpoint the source of the daily “ghost” readings.

In a similar vein, while the stream gauge more than adequately tracked the changing depth of the stream over the period of performance, it did take less precise readings when compared to the USGS station. It is thus important for users to determine upfront what their objectives are and whether the proposed sensor will provide the necessary level of precision. While a margin of error of 1-2 centimeters may be more than acceptable for a flood early-warning system (where the overall trend and pace of change is what is most critical), it may not be appropriate for tracking the depth of a reservoir on which a water utility depends to meet the needs of thousands of customers.

Field Durability. No examples could be found in the literature of the *long-term* usage of open source sensors for the collection of water resources data. Importantly, although our stream gauge continued to operate after 45 days in the field, it was clearly less durable than the USGS station which was designed to withstand the elements for *years* (and not simply days or months). The sensor and electronics of the prototype were considerably more exposed than the stilling well and fully encased equipment of the USGS station. The prototype unit as a whole was also much easier to remove from the site undetected, a risk that would certainly escalate were the unit to be deployed in a low-income country where the parts may be perceived to have significant monetary value.

Beyond routine 2 to 3 day testing, the only multi-month deployment of the Maker Lab stream gauge to date was in Honduras where two units were tested as potential flood early-warning mechanisms. Highlighting the importance of unit siting and durability, one unit was placed on the top of an 18 foot pipe (to deter theft) on the banks of a river. Rising waters unfortunately overwhelmed the pipe mount, with the entirety of the unit ultimately washed downstream (Ryan-Silva, 2015).

Additional Implementation Considerations. Beyond the above constraints, the prototypes tested herein also highlighted several important considerations that are germane to most remotely operated, wireless sensor systems. First, power management represents a common challenge which was visible in both the stream gauge and the precipitation gauge. While the solar power ultimately proved sufficient for the stream gauge, it is likely that a larger, higher output panel will be needed to keep the entire weather station operational. Second, although wireless data transmission performed well in the current context, the technology must be adapted to the unique requirements of each local cellular network. Based on experience deploying the stream gauge in Honduras, for example, Ryan-Silva (2015) noted that pre-testing on a US cellular network was not necessarily predictive of success with a cellular network in another country, therefore requiring additional time for field testing and adjustment. Finally, an important characteristic of sensor units in the water sector is the ability to track time accurately. An in-depth understanding of hydrological events is inextricably linked to the timing of those events, meaning that similar prototypes should always include an onboard real-time clock or have the capacity to obtain the time from a cell network or the internet (through a cloud-based connection).

Conclusion

Despite the aforementioned limitations, we can confidently conclude that open source environmental sensors have significant potential to contribute to the improved management of water resources in the face of climate change. Both the growing body of case studies and the experience documented herein provide a clear demonstration of the capacity of open source hardware to help fill critical information gaps concerning real-time conditions and longer term trends.

Importantly, based on this initial research, open-source hardware prototypes such as the sonar-based stream gauge offer perhaps the greatest potential as a new set of tools for citizen science, community-based resources management, and advocacy both domestically and abroad. Empowered by cost effective and highly customizable water resources sensors, citizen scientists can move from a more functional/consultative role in management of local water resources, to one that is collaborative and even transformative (Conrad and Hilchey, 2010).

In this regard, such technologies are not necessarily to be viewed as replacements for the more permanent, “brick and mortar”, government-operated (and funded) water information systems, but as a means to supplement—and, in some cases, verify—the information provided by such systems. That said, in low-resource settings where investment in water resources data collection is non-existent or stagnant, open source tools can most assuredly help demonstrate the value of environmental data and, in doing so, stimulate investment in public systems. Moreover, there are undoubtedly ways in which the permanence and durability of public monitoring networks (such as the USGS stream stations) and the lower-cost, adaptable nature of open source modular electronics can be combined to develop systems that satisfy the need for both cost efficiencies and field permanence.

In addition to bolstering sensor fortitude for longer term installations, two further areas of research are apparent. First, we need to continue to research and design other innovative open source tools that complement those tested herein. The margin of error of manual, float-based estimates of flow are unacceptably high, while an off-the-shelf flow meter can cost over $1000. Might there be a means to develop, for example, a cheaper, open source flow meter that helps turn stream height data into an accurate calculation of discharge?

Second, it is critical that the water resources data collected by open source tools is then used to understand how climate change is shifting the baseline of surface flow within a given watershed. The action agenda laid out in the Paris Pact called for the establishment of basin-wide water information systems *as a decision making support tool for adaptation measures*. Put differently, we cannot stop with data collection, but must also look for ways to link that data to early warning systems and decision support systems. In this regard, a logical extension of open source data collection platforms is the use of open source hydrological modeling software to analyze the current status of a watershed and to predict how the watershed may be impacted by changing precipitation patterns. In order to be effective, however, such modeling must be done in a transparent, participatory manner in order that communities can independently modify predictions as more and more data becomes available.

In closing, we return to the call to action put forth by nations, environmental organizations, and donors in the Paris Pact on Water and Adaptation to Climate Change: “We recognize that adaptation actions should be undertaken without delay to minimize the impacts of climate change on the populations’ health and safety, on economic development and the environment, considering the importance of the protection of water-related ecosystems.” While low-cost, open source sensors represent just one piece of a broader adaption strategy, they can nonetheless help communities gain access to the hyper-local, high resolution water resources information they need to better prepare and plan for an increasingly uncertain hydrological future.

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ANNEX A: STREAM GAUGE PROTOTYPE SUMMARY STATISTICS

Date	# of Daily Readings	Average Stream Height (ft.)	Maximum Height	Minimum Height	StdDev of Height	Reporting Failures
12-Mar-16	86	1.68	1.77	1.64	0.029	10
13-Mar-16	261	1.70	1.80	1.64	0.038	28
14-Mar-16	273	1.75	2.00	1.67	0.053	15
15-Mar-16	279	1.69	1.77	1.64	0.024	9
16-Mar-16	280	1.69	1.77	1.64	0.023	9
17-Mar-16	270	1.68	1.74	1.64	0.026	18
18-Mar-16	276	1.68	1.74	1.61	0.026	9
19-Mar-16	281	1.70	1.74	1.64	0.024	7
20-Mar-16	264	1.70	1.77	1.64	0.025	21
21-Mar-16	274	1.69	1.71	1.64	0.023	16
22-Mar-16	274	1.69	1.74	1.64	0.024	14
23-Mar-16	269	1.69	1.74	1.64	0.022	20
24-Mar-16	267	1.69	1.74	1.64	0.022	21
25-Mar-16	256	1.69	1.74	1.64	0.022	33
26-Mar-16	274	1.68	1.71	1.64	0.025	14
27-Mar-16	281	1.69	1.71	1.67	0.020	9
28-Mar-16	265	1.72	1.77	1.67	0.026	23
29-Mar-16	249	1.69	1.74	1.64	0.023	41
30-Mar-16	259	1.68	1.74	1.64	0.024	30
31-Mar-16	261	1.69	1.74	1.67	0.022	29
1-Apr-16	263	1.70	1.74	1.67	0.024	25
2-Apr-16	259	1.69	1.74	1.67	0.021	30
3-Apr-16	274	1.69	1.71	1.64	0.022	14
4-Apr-16	258	1.70	1.74	1.67	0.026	34
5-Apr-16	254	1.69	1.74	1.64	0.023	34
6-Apr-16	266	1.69	1.74	1.64	0.023	22
7-Apr-16	264	1.80	2.23	1.67	0.120	26
8-Apr-16	264	1.71	1.77	1.67	0.031	25
9-Apr-16	256	1.70	1.74	1.67	0.024	32
10-Apr-16	274	1.68	1.71	1.61	0.024	17
11-Apr-16	260	1.69	1.74	1.64	0.021	30
12-Apr-16	254	1.69	1.74	1.64	0.024	34
13-Apr-16	271	1.68	1.71	1.64	0.030	19
14-Apr-16	278	1.68	1.71	1.64	0.029	11
15-Apr-16	285	1.67	1.71	1.64	0.029	4
Grand Total	**9179**	**1.70**	**2.23**	**1.61**	**0.040**	**733**

ANNEX B: USGS STREAM GAUGE SUMMARY STATISTICS

Date	# of Daily Readings	Average Stream Height (ft.)	Maximum Height	Minimum Height	StdDev of Height
12-Mar-16	96	1.68	1.68	1.68	0.000
13-Mar-16	288	1.69	1.74	1.68	0.021
14-Mar-16	288	1.74	1.81	1.70	0.037
15-Mar-16	288	1.69	1.70	1.69	0.002
16-Mar-16	288	1.68	1.69	1.68	0.003
17-Mar-16	288	1.68	1.68	1.68	0.000
18-Mar-16	288	1.68	1.68	1.68	0.000
19-Mar-16	288	1.68	1.68	1.68	0.000
20-Mar-16	288	1.68	1.68	1.68	0.000
21-Mar-16	288	1.68	1.68	1.68	0.000
22-Mar-16	288	1.68	1.68	1.68	0.000
23-Mar-16	288	1.68	1.68	1.68	0.000
24-Mar-16	288	1.68	1.68	1.68	0.000
25-Mar-16	288	1.68	1.68	1.68	0.000
26-Mar-16	288	1.68	1.68	1.68	0.000
27-Mar-16	288	1.68	1.68	1.68	0.000
28-Mar-16	288	1.70	1.72	1.68	0.014
29-Mar-16	288	1.68	1.69	1.68	0.005
30-Mar-16	288	1.68	1.68	1.68	0.000
31-Mar-16	288	1.68	1.68	1.68	0.000
1-Apr-16	288	1.68	1.68	1.68	0.000
2-Apr-16	288	1.68	1.68	1.68	0.000
3-Apr-16	288	1.68	1.68	1.68	0.000
4-Apr-16	288	1.68	1.69	1.68	0.004
5-Apr-16	288	1.68	1.69	1.68	0.005
6-Apr-16	288	1.68	1.68	1.68	0.000
7-Apr-16	288	1.79	2.20	1.68	0.124
8-Apr-16	288	1.70	1.74	1.69	0.015
9-Apr-16	288	1.69	1.69	1.68	0.004
10-Apr-16	288	1.68	1.68	1.68	0.000
11-Apr-16	288	1.68	1.68	1.68	0.000
12-Apr-16	288	1.68	1.68	1.68	0.000
13-Apr-16	288	1.67	1.68	1.67	0.004
14-Apr-16	288	1.67	1.67	1.67	0.000
15-Apr-16	288	1.67	1.67	1.67	0.000
Grand Total	**9888**	**1.69**	**2.20**	**1.67**	**0.031**