Enabling Distributed Storm Water Monitoring for Smart Cities

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ABSTRACT

Stormwater management is a significant and expensive problem for American cities. Impervious surfaces such as roofs and parking lots prevent water from being absorbed into the ground and result in large volumes of runoff. Stormwater runoff carries pollutants such as oil and chemicals across the urban landscape and into waterways and can lead to the overflow of combined sewer systems. Large volumes of stormwater can also lead to flooding and the erosion and sedimentation of waterways. Conventional systems of managing stormwater are centralized and expensive. Many communities across the country have been moving away from centralized stormwater management systems and toward distributed solutions such as rain gardens. These strategies are designed to absorb urban runoff before it can leave the site. However, the distributed nature of these installations poses a major management challenge for cities and communities. There is a pressing need for low-cost monitoring solutions that enable a continuous understanding of the operation of these installations. In this work, we present our design, construction and first results of a wireless sensing systems that allows basic monitoring of stormwater flows for rain gardens.

1. INTRODUCTION

Over the past 20 years, American communities of all sizes have moved away from large, centralized storm water management systems and toward small-scale decentralized solutions. Decentralized strategies require a network of green infrastructure features such as rain gardens, swales, green roofs, and porous pavement which infiltrate and evaporate most of the runoff on-site, reduce the volume of runoff, and prevent the concentration of pollutants in waterways. Site-scale green infrastructure, also known as low impact development (LID) or site-based best management practices (BMPs), is designed to approximate the pre-development hydrology of a specific site (US EPA 2017). Decentralized, green infrastructure, approaches can reduce the burden on existing centralized systems and delay or prevent the need for costly expansions or upgrades (Thurston et al. 2003, Villareal et al. 2004, Keeley 2007). A combination of green and gray infrastructure projects can result in a lower total system cost than a centralized gray infrastructure system of tunnels, pipes, and treatment plants (Thurston et al. 2003). Green infrastructure also provides an array of ancillary environmental benefits and ecosystem services, such as wildlife habitat and reducing the urban heat island effect.

Despite a wide variety of benefits to this type of stormwater management, the distributed nature of the installations make monitoring a challenge and creates a barrier to broader adoption. Municipalities across the United States now require on-site stormwater management for new developments and provide financial incentives for landowners to retrofit existing properties with decentralized stormwater management. The result is tens of thousands of small-scale stormwater facilities distributed throughout the landscape. While these facilities may be small, each plays an important role. If an installation overflows or malfunctions it could lead to flooding, overloading of centralized stormwater systems, and the contamination of local waterways. Yet, it is difficult to know if these facilities are functioning properly. Stormwater managers must visually inspect each rain garden and green roof in the network. For local governments, who are accustomed to a few large centralized facilities, but are now depending upon the functionality of each component of a distributed network, this is a time-consuming and costly change. The monitoring challenge discourages further adoption of this promising strategy. As a consequence, there is a need to develop new means for understanding the functionality and efficacy of distributed stormwater facilities.

There is a pressing need for a technology-based approach to monitoring distributed management stormwater systems, particularly for rain gardens, which are among the most popular facilities. For these systems, where an area covered with especially chosen vegetation absorbs the collected stormwater, it is possible to design monitoring solutions by taking advantage of current low-cost sensing and wireless technologies. In such solutions it is desirable to monitor the incoming water flow and ground humidity. The rate at which water is discharged into the garden can be used to understand if, and how well, the water collection system is operating. Ground humidity is also useful for estimating how much and how fast water can be absorbed by the garden. To monitor these variables, low complexity devices can be designed with a set of off-the shelf sensors, integrated with basic cellular communications boards. We designed, constructed, and evaluated a first version of such a system which currently allows the monitoring of stormwater flow and communicates real-time results to a cloud-based Internet connected data repository through a third generation wireless connection. All the components of the system were selected taking into consideration performance, accuracy and cost.

2. Motivation

Recent technological advances have allowed urban planners to think about infrastructure in new ways and catalyzed a "smart cities" movement. Smart city strategies use digital technologies to improve the efficiency and efficacy of city services and enhance the livability of urban areas. These technologies allow the remote monitoring of broadly distributed infrastructure like roads, bridges, and sewer systems.

While monitoring of all types of decentralized stormwater facilities would be useful, this study focuses on rain gardens, a prominent type of bio-retention. Bio-retention installations, such as rain gardens and grass swales, are vegetated depressed areas designed to receive, hold, and absorb stormwater. Research has confirmed the ability of bio-retention areas to reduce the volume and contamination of stormwater (Davis et al. 2001, Dietz 2007, Hunt and Lord 2006). Rain gardens, in particular, are common in lower density urban and suburban areas where there is sufficient green space to support them. They can also be inexpensive, attractive, when well cared for, and require little investment or technical expertise to maintain. Many cities offer rain garden workshops or publish technical manuals to show landowners how to install and manage small bio-retention facilities. They are one of the more accessible strategies. But, while rain gardens are increasingly common, the must be carefully maintained to ensure that plantings survive and to any manage erosion or sedimentation that could inhibit stormwater management functions. Poor maintenance can easily yield inadequate stormwater management. To ensure the overall stormwater system remains effective, local stormwater managers must be able to monitor the status of rain gardens.

There are currently no means to monitor distributed stormwater management systems implemented through rain gardens. While it should be possible to use sensing technology used to monitor centralized stormwater systems, this would certainly be cost prohibitive for a distributed solution. Consequently, there is a need and an opportunity to create a low-cost monitoring solution that facilitates management and enables the collection of real-time data.

3. Related Work In The Area

Current literature incorporates a variety of laboratory and field studies that have examined the ability of bioretention areas to reduce the volume and contamination of stormwater. Reviews of bioretention literature conclude that reductions in runoff volume and peak flow range between 40 and 90% (Ahiablame and Engel, 2012). A 2011 study found that a bioretention facility reduced the flow volume and rate from a parking lot by up to 99% (DeBusk and Wynn, 2011). Bioretention can also manage total suspended solids, bacteria, and temperature, if specifically designed to do so (Hunt and Lord, 2006). For example, average bacteria reduction for bioretention facilities with appropriate media ranges from 70 to 99% (Ahiablame and Engel, 2012). Studies also agree that bioretention is highly successful at removing metals, but identify variations in management of nutrients, particularly nitrate.

Early research using laboratory prototypes suggested that bioretention could reduce metal concentrations by over 90% and many nutrients by between 60 and 80% (Davis et al. 2006). Nitrate was most problematic with 24%. Field studies have been similar. Results suggest that bioretention facilities are successful at removing nutrients and other pollutants, but the magnitude of those reductions varies. Researchers applied synthetic stormwater runoff to two bioretention facilities in Maryland and found removal of metals to be very high and nutrient management lagging. Total nitrogen and phosphorous loads declined by between 49 to 59% and 65 to 87%, respectively [10] A field study of six bioretention cells in North Carolina showed the facilities reduced metal and nitrogen loads, but were less successful with phosphorous (Hunt and Lord, 2006).

While the use of green infrastructure to manage stormwater is being employed in numerous locations around the U.S. (US EPA Green Infrastructure, 2017) the monitoring of such distributed installations is still scarce. One exception is an ongoing project launched in late 2016 by City Digital a public-private initiative in Chicago (UI Labs, 2016). In this project precipitation amounts, humidity levels, soil moisture measurements, air pressure, and chemical absorption rates are continuously monitored for large bioswales. Then real-time data is collected available for management purposes. However, from the published details it is unclear what kind of sensing devices are employed or their cost.

4. Networked, Low-Cost Flow Rate Sensing Device For Rain Gardens

4.1 Variable Selection

The performance level of a rain garden is a function of how well it can operate as a pervious system. There are two variables of interest we consider describe the overall performance of such a system. It is first necessary to understand how much water is flowing into the soil in the garden, thus it is vital to count with data that describes stormwater flow rate over time. Additionally, it is relevant to understand the humidity levels of the garden's soil. Under normal operation, the vegetation and the soil in the garden should regularly absorb the incoming stormwater. However, should the soil become saturated, normal operation is hindered and stormwater might overflow the garden.

4.2 System Architecture

The architecture of the system for monitoring the performance of a rain garden encompasses two main sensors, a flow rate sensor and a soil moisture sensor. In this work we focus on the flow rate sensor, as affordable soil humidity sensors are readily available in the market. The system can operate continuously as energy is collected through a small solar panel and battery. The design is illustrated in Figure 1 where stormwater at the input (U-01) passes through a custom flow rate sensor towards the rain garden (U-08), where a set of humidity sensors is placed (U-05). A microcontroller device with onboard wireless cellular connectivity controls the systems and collects telemetry data from both sensors. The development of this architecture is funded in part by a grant from Ohio's Environmental Protection Agency Environmental Education Fund. Once the system is ready for deployment we have an agreement with the City of Athens for the deployment of the solution in at least two sites.

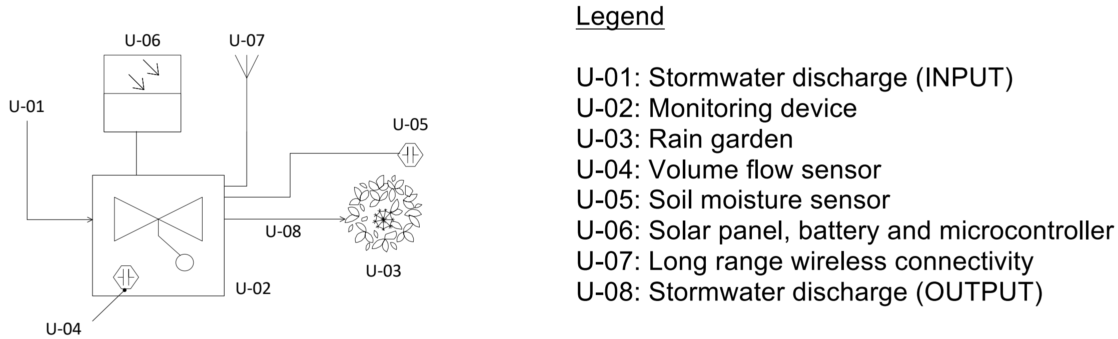

Figure 1. Architecture of a rain garden networked monitoring device

4.2.1 VOLUMETRIC FLOW RATE SENSOR DESIGN

While there are numerous commercial and industrial grade flow rate sensors these are typically suited for measurements in clean water scenarios. These sensors are not suitable for stormwater measurements as they are prone to malfunction due to large contaminants or objects likely to be present in stormwater flows. Furthermore, these sensors are generally very expensive hindering the goal of constructing a low-cost device.

Using a simple approach based on a floating pendulum and low-cost fabrication methods we designed a first version of the flow-rate sensor. When stormwater flows through a pipe of inner diameter d the sensor constantly measures the angle α between the pendulum axis and the vertical axis of the discharge pipe using an accelerometer. Figure 2 illustrates the geometry of the system.

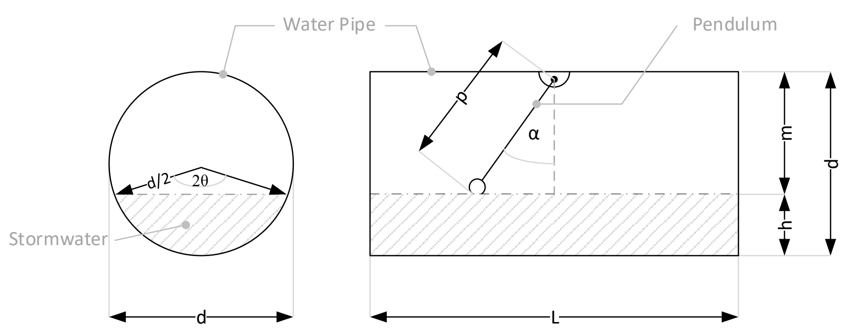

Figure 2. Flow rate sensor pendulum geometry when mounted on a pipe (d = 4 in., p = 3.2 in.) Front view (left), side view (right)

The flow rate pendulum sensor employs an accelerometer and gyroscope board based on the MPU-6050 MEMS (micro electromechanical system) manufactured by Invensense and available in small quantities for approximately 5 USD. When a stormwater flow is detected this sensing board supplies the microcontroller with the angle α necessary to compute the flow rate. The board is installed in a custom designed, water sealed 3D printed housing that incorporates the floating pendulum. An exploded view of the housing and pendulum mechanism is shown on the left of Figure 3. The housing installed on a four inch PVC pipe is shown on the right of the figure.

Figure 3. 3D exploded schematics of the sensor housing (left) and photograph of the sensor mounted on a 4 inch PVC pipe (right).

4.2.2 Sensor Calibration And Experimental Design

To estimate the volumetric water flow, Q, as a function of the angle α we calibrated the system using a typical setup consisting of a 2.5 meter tall downspout attached to a standard gutter. A known water flow rate was fed into the system and data was collected for eight different flow rates with three iterations of 2 minutes each. We heuristically set the data to be collected every 50 ms. While this method has its limitations as it is dependent on the physical characteristics of a particular setup it can be extended to other scenarios as discussed in Section 5.

4.2.3 Microcontroller And Wireless Connectivity

The design incorporates a microcontroller board to communicate with the MPU-6050, store real-time data, and provide cellular wireless connectivity. The Electron ARM based microcontroller board manufactured by Particle was chosen as it is a low cost (65 USD) solution that incorporates 3G cellular connectivity as well. This microcontroller board requires very low power to operate drawing less the 1mA when no telemetry data is acquired, an average of 20 mA when the system is acquiring data and 800 mA during a two-minute duration batch wireless transmission. During the wireless transmission 15 minutes of previously recorded data is transmitted. The state of the pendulum (e.g. detecting water flow or not) dictates if data needs to be continuously collected every 50 ms or if the microcontroller should go to a low power state. This behavior allows us to employ to provide continuous 24 hour monitoring with a small 10 Watt solar panel.

The microcontroller board is currently configured to send information to two cloud-based data management platforms. First the board sends reading to Particle's Dashboard reporting solution. It also sends data to an open MQTT (MQTT Organization, 2017) test server from Eclipse foundation [(Eclipse Foundation, 2017). MQTT is a basic machine-to-machine lightweight telemetry reporting protocol. In the near future the system will also report telemetry data to AT&T's M2X platform via the MQTT protocol (M2X 2017). The cloud solution provided by AT&T allows data storage and real-time visualizations of the status of the system. It also enables data to be analyzed offline to carry out further studies of the results.

We selected MQTT as being a tested telemetry protocol, software implementations are available for different platforms and programming languages. In MQTT a broker receives published telemetry values from a client. Clients publish their data to a category referred to as topic. MQTT brokers can accept requests from other clients asking for this telemetry data to be shared. The simplest MQTT exchange is illustrated in Figure 4 where a client publishes data to the broker which in turn publishes it to an already subscribed client. MQTT provides for other types of exchanges that provide different guarantee levels to the messages being published.

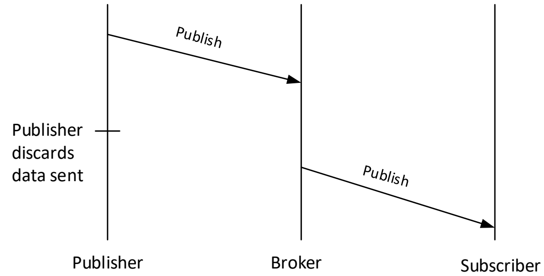

Figure 4. Sample publish of telemetry data via MQTT

5. Flow Rate Sensor Results

The system was tested with eight input volumetric flow rates ranging from 0.0681to 0.3419 liters per second. The resulting variations over time of the pendulum's angle for three of these levels are plotted in Figure 5 along with their histogram. The plotted variations over time are the result of applying a 20 sample average moving window (which corresponds to one second of samples collected every 50 ms).

The time variations in the figure sometimes show significant variations around the mean. During the tests the flow rate stays relatively constant, but the read angle varies around a mean value as the water flow is not laminar but turbulent. The turbulent nature of the flow is increased by the characteristics of the system where water rushing down the downspout collides with the elbow connector before entering the sensor housing. Nevertheless, the long-term effect of the constant input flow rate does result in a unimodal distribution of the angle as shown in the sample histograms.

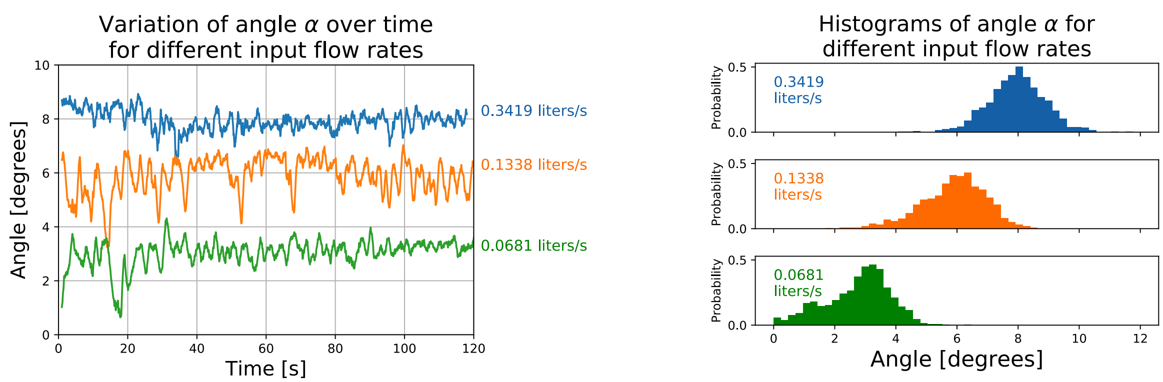

Figure 5. Variation and histogram of angle α for three different volumetric flow ratesas measured by the accelerometer board

The effect of all eight volumetric flow rates on the pendulum's angle is shown in Figure 5. Notice that the pendulum's angle for increasing volumetric flow rates should monotonically increase with the volumetric flow rate. During the experiments some increases in input flow rate resulted in decreasing values of the average angle (e.g. 0.1637 and 0.2310 liters per second) as shown in Figure 5. This is counterintuitive, as higher flow rate must result in larger angle readings. After some investigation, we traced back this issue to random deviations of the actual input flow rate due to imperfections of the water pumping mechanism. To further visualize the relationship between the angle and the flow rate, a linear regression is included along all the summarized statics in Table 1.

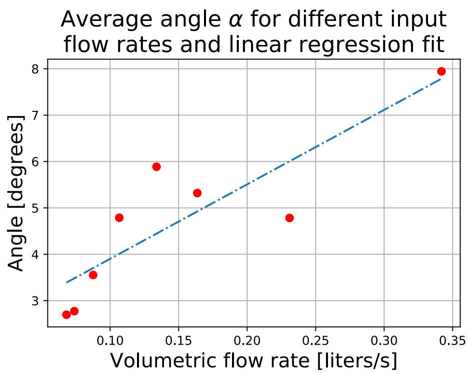

Figure 6. Variation of the average angle α for all eight input volumetric flow rates

Table 1. Experimental data summary
(All data sets employ 2400 samples data points)

Flow [liters/s]	Mean α [degrees]	Std. Deviation	Min. [liters/s]	Max. [liters/s]
0.3419	7.944	0.9767	0.2259	11.7575
0.2310	4.7825	1.4651	0.5081	11.7580
0.1637	5.3209	0.9885	0.4581	8.4047
0.1338	5.8872	1.0612	1.7901	8.6158
0.1067	4.7872	1.0666	1.2105	8.4521
0.0876	3.5529	0.8082	1.1049	8.2843
0.0739	2.7729	0.6936	0.7093	6.2919
0.0681	2.6969	1.1247	0.7101	6.2919

5. Closing Remarks

This first version of our Internet connected stormwater management device offers a robust solution at a low-cost. We estimate that in low quantities it is possible to construct the device for less than 120 USD. The current version does have limitations that need to be addressed. First, the device needs to be calibrated for each particular installation. This is due to the fact that all rain garden installations will have different input geometries, with downspouts varying in height and a varying number of elbow connections. This results in different input velocities into the system and thus the need to translate site by site the resulting pendulum's angle into the corresponding volumetric flow. There are two steps that can be taken to overcome this limitation. First, it is possible to generate an approximation curve that estimates the input velocity into the system and program this curve into the microcontroller. Second, it is possible to incorporate a low-cost flow velocity sensor in the pendulum thus avoiding the need for site-by-site calibration.

We are currently improving the design of our solution to allow the sensor to be mounted on different types of discharge pipes. Once the system is ready for deployment we will be installing it in two publicly owned sites in the City of Athens and making the real-time data publicly available.

6. Acknowledgements

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