Enabling User Centered Distributed Stormwater Monitoring

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***Abstract*—Stormwater management is a significant and expensive problem for cities and communities around the world. 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 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 by their owners and by municipalities. In this work, we present an open source, open hardware design and first results of a sensing system that allows user centered monitoring of stormwater flows for rain gardens.**

Keywords–Urban; Stormwater; Management; User-centered.

I. 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 [1]. Decentralized, green infrastructure, approaches can reduce the burden on existing centralized systems and delay or prevent the need for costly expansions or upgrades [2][3][4]. 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 [2]. 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 citizen-owned 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.

The management of distributed rain gardens and green roofs at the user level can provide municipalities with a granular understanding of the efficacy of these installations

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and enable them to create programs around user-centered incentives. These incentives can assume the form of credits towards already existing monthly sewage charges. In this manner, current and future owners of distributed green stormwater management infrastructure could be encouraged to install and properly maintain it and help municipalities with the mitigation of the effects of stormwater runoff.

Our work presented next starts in Section 2 with a discussion on the motivation supporting the use of distributed monitoring of stormwater flows. Thereafter, in Section 3 we visit relevant research literature in the area of green infrastructure. We then propose, in Sections 4 and 5, our design for a low-cost sensing device to monitor stormwater flows in rain gardens along an experimental design to evaluate its performance. In Section 6, we visit the the current limitations of our approach. Finally, in Section 7 we present our conclusions and discuss some viable possibilities of future work in the area.

II. 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 [5][6][7]. 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, they must be carefully maintained to ensure that plantings survive and to 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.

III. 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% are feasible [8]. A 2011 study found that a bioretention facility reduced the flow volume and rate from a parking lot by up to 99% [9]. Bioretention can also manage total suspended solids, bacteria, and temperature, if specifically designed to do so [7]. For example, average bacteria reduction for bioretention facilities with appropriate media ranges from 70 to 99% [8]. 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% [10]. 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, US 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. A field study of six bioretention cells in North Carolina, US showed the facilities reduced metal and nitrogen loads, but were less successful with phosphorous [7].

The use of green infrastructure to capture stormwater and reduce the impact of combined sewer overflows has been recently studied for the case of mega-cities [11]. A mega-city is a defined as one with over 10 million residents. In particular, in the case of New York City, different green strategies, such as bioretention facilities, rain gardens and porous pavement, have been employed to reduce the amount of stormwater runoff. This mix of strategies resulted in reductions of stormwater runoff of up to 42% for the entire watershed and up to 55% for individual cases. Similar goals for large cities have also been studied for Chinese cities under the concept of "Sponge Cities". These cities also incorporate LID green infrastructure strategies. For the particular case of Beijing the current target is to capture up to 85% of annual precipitation through the strategies. Current modeling indicates that increases in the use of rain gardens, green roofs and permeable pavement will allow the city to achieve its capture target [12].

As discussed throughout this section, the benefits of green infrastructure to capture stormwater have been studied under varied circumstances. Nevertheless, the adoption of particular strategies at the residential level face some barriers. A particular incentive strategy could be the use of green infrastructure for urban agricultural use, which empirical studies have found to be a feasible option. The yield of vegetable rain gardens has been found to be comparable to that of a control traditional vegetable garden, while still reducing stormwater runoff by 90% [13].

The location of green infrastructure installations is also of interest to municipalities. This is particularly true for distributed rain gardens in individual residences. The selection of suitable sites is a key component of a city's strategy to maximize the benefits of runoff reduction. An approach that has been shown to be effective is to quantify the suitability of locations by analyzing soil attributes, slope, land use, ground water level, available area and cost using already existing geographical information systems [14].

While the use of green infrastructure to manage stormwater is being employed in numerous locations around the U.S., the monitoring of such distributed installations is still scarce [15]. One exception is an ongoing project launched in late 2016 by City Digital a public-private initiative in Chicago [16]. In this project, precipitation amounts, humidity levels, soil moisture measurements, air pressure, and chemical absorption rates are continuously monitored for large bio-swales. 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.

IV. LOW-COST FLOW RATE SENSING DEVICE FOR RAIN GARDENS

As discussed earlier, the use of distributed green infrastructure, such as rain gardens, can achieve significant reductions of stormwater runoff. However, the distributed nature of individual rain gardens pose a monitoring challenge, especially for small cities and communities with limited resources. Therefore, a main goal of our work is to develop a low-cost distributed monitoring solution that reports data over a wireless network to a centralized site.

Distributed monitoring devices can help municipalities understand the amount of rainwater captured and potentially identify problems with the installation. Such problems may occur when individual rain gardens stop collecting stormwater due to debris on collecting gutters. Therefore, we designed a device that can be directly attached to the lower part of stormwater collecting downspouts. Our device then measures stormwater activity right before the water is diverted towards the rain garden. We are not aware of any low-cost distributed solution similar to ours as currently rain gardens are typically installed without any monitoring.

A. *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.

B. *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. We designed a sensing device that can operate continuously as energy is collected through a small solar panel and stored in a battery. The design is illustrated in Figure 1, where stormwater at the input (U-01) passes through a custom flow rate sensor (U-04/05) towards the output (U-09) and then the rain garden (U-03). The output of the sensor is the deviation angle of the floating pendulum shown on the right of Figure 1. A microcontroller based device (U-02), with onboard wireless cellular connectivity (U-08), controls the systems and collects telemetry data from the flow rate and a soil moisture sensor (U-06). The system is powered by a small 10W solar panel and battery (U-07).

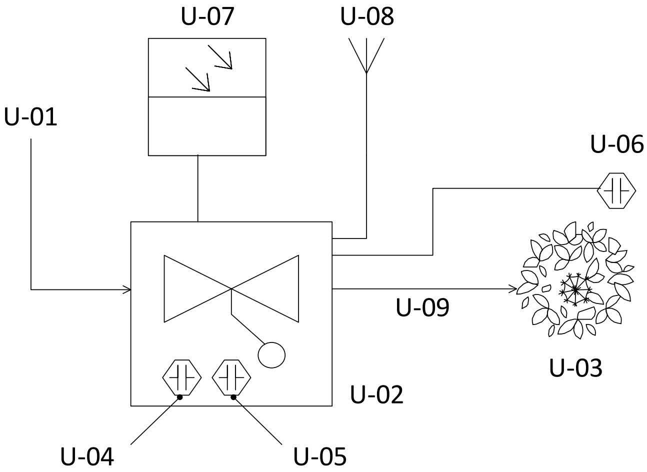

Figure 1. Architecture of the rain garden monitoring device.

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. The flow rate pendulum sensor employs an accelerometer and gyroscope board based on the MPU-6050, micro electromechanical system (MEMS), 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 in the top of Figure 3. The housing installed on a four inch plastic pipe is shown in Figure 4.

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. This method has its limitations as it is dependent on the physical characteristics of a particular setup. Different installations will have downspouts of varying heights.

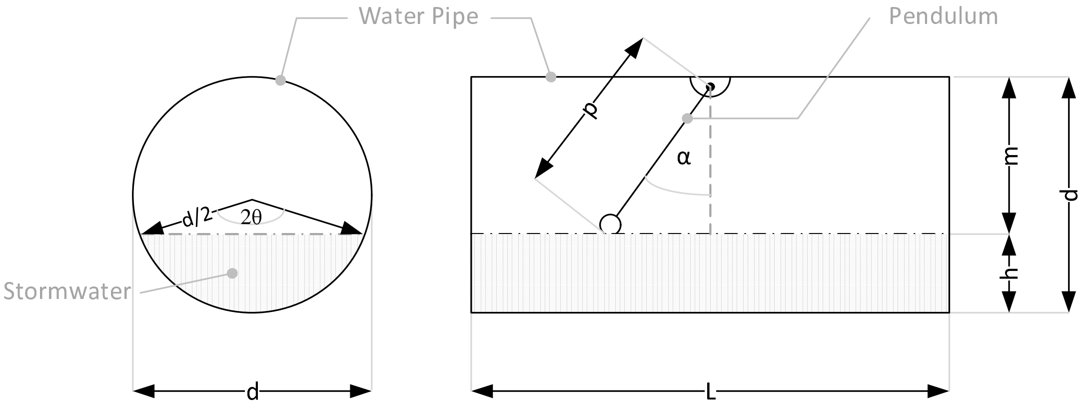

Figure 2. Flow rate sensor pendulum geometry when mounted on a 4 inch pipe (d = 4in., p = 3.2 in.) When stormwater flows through the pipe it rises to level h and deflects the pendulum an angle of α degrees. Front view (left), side view (right). Front view does not show the pendulum but just the stormwater level.

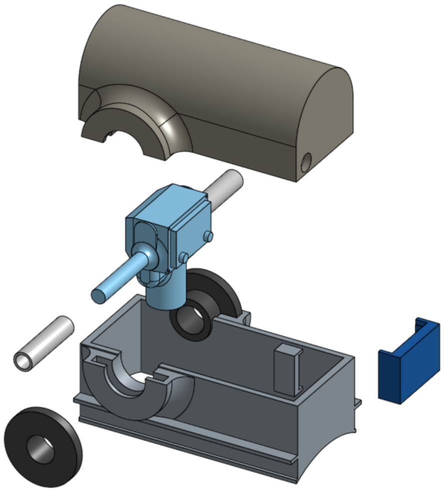

Figure 3. 3D exploded schematics of the hardware used to house the accelerometer board and the pendulum.

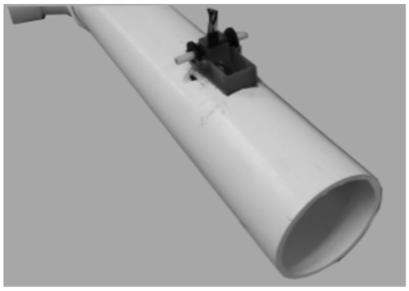

Figure 4. Hardware mounted on a 4 inch plastic pipe. The pendulum is not visible in the image as it lies inside the pipe.

However, the method can be extended to other scenarios as discussed in Section V.

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 wireless transmission of telemetry 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 power saving behavior allows us 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. It sends readings to Particle's dashboard reporting solution. Through the dashboard and custom code it also sends telemetry data to AT&T's M2X platform via the Message Queueing Telemetry Protocol (MQTT) protocol [17][18]. 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 it 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 5 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.

All of our hardware designs, developed software, documentation, installation instructions and educational material is open and can be freely obtained online [19][20]. We expect this to greatly help not only in the reproducibility of our results, but towards the adoption of our design as a low-cost management solution by citizens and municipalities around the globe.

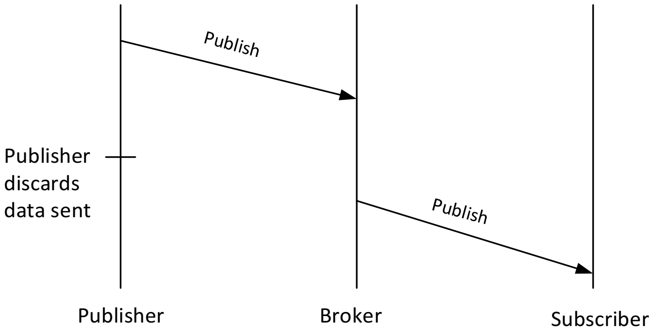

Figure 5. Sample publish of telemetry data via MQTT.

V. FLOW RATE SENSOR RESULTS

The system we constructed was first calibrated using the procedure described in Section IV-B2, using eight input volumetric flow rates ranging from 0.0681 to 0.3419 liters per second. The resulting variations over time of the pendulum's deviation angle α for three of these levels are plotted in the top of Figure 6. Their respective histogram are shown in the bottom of the figure. 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 changes of the angle, α, as a function of time plotted in the top of Figure 6 ocassionally show significant variations around its mean value. While during the tests the flow rate stays relatively constant, the sampled angle varies around a mean value as the water flow is not laminar but turbulent. The turbulent nature of the flow was increased by the characteristics of our test setup where water rushing down the downspout collides with a 90 degree elbow connector before entering the sensor housing.

Nevertheless, when these variations are studied by plotting their histogram a unimodal distribution of the sampled angles was observed. These distributions are shown in the bottom part of Figure 6. This indicates that, under the conditions tested, the mean of the sampled angles is an adequate metric that can be used to estimate the flow rate.

The effect of all eight volumetric flow rates on the pendulum's angle is shown in Figure 7. Notice that the pendulum's angle for increasing flow rates should monotonically increase with the flow rate. However, 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 evidenced by the data plotted in Figure 7. This is counterintuitive, as higher flow rate must result in larger pendulum deviations. 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 be able to estimate flow rate for any angle we constructed a linear regression from our experimental data. The regression result is shown in Figure 7. The value of the coefficient of determination, R^2, for the regression was 0.91 which suggests our dataset approximately results in a linear relationship between the measured angle and a known input flow rate. A set of summarized statistics is provided in Table I.

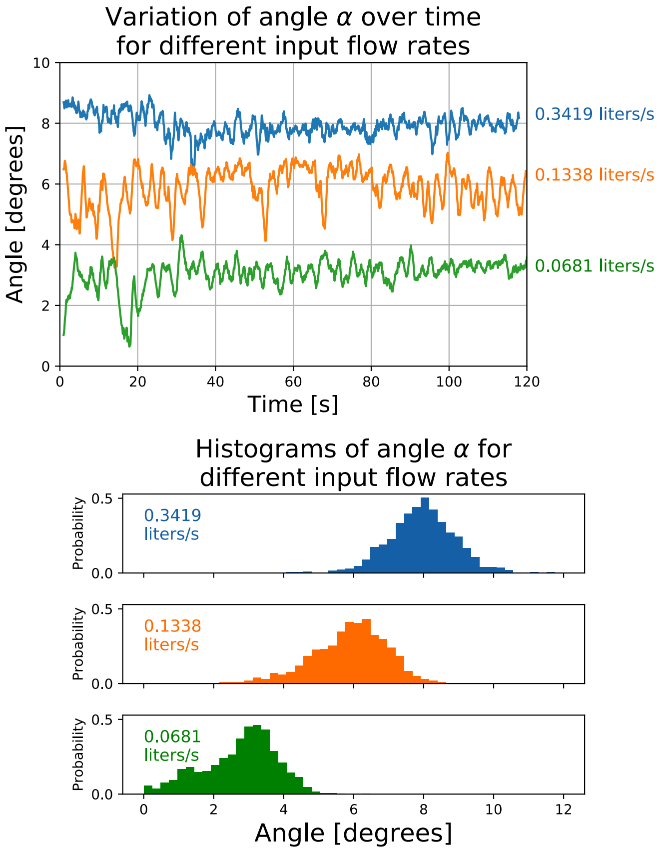

Figure 6. Variation and histogram of angle α for three different volumetric flow rates as measured by the accelerometer board.

TABLE I. SUMMARY OF EXPERIMENTAL DATA

Flow (l/s)	Mean α (degrees)	Standard deviation	Minimum (l/s)	Maximum (l/s)
0.3419	7.9440	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

VI. LIMITATIONS

It is possible to use the linear regression provided in Figure 7 to estimate the flow rate of stormwater passing through the sensor for any particular measured angle of the pendulum. However, this regression assumes the conditions the system is operating in are similar to those described in Section IV-B2. In different types of deployments, these assumptions might not hold and it may be necessary to estimate the flow velocity inside the sensor.

Given that stormwater generally flows inside a pipe following an *open channel* model where there is a pocket of air occupying part of the cross section of the pipe, estimating this velocity is not a straightforward process. Ideally our design could incorporate a flow velocity sensor; unfortunately this would increase maintenance complexity and price. Therefore,

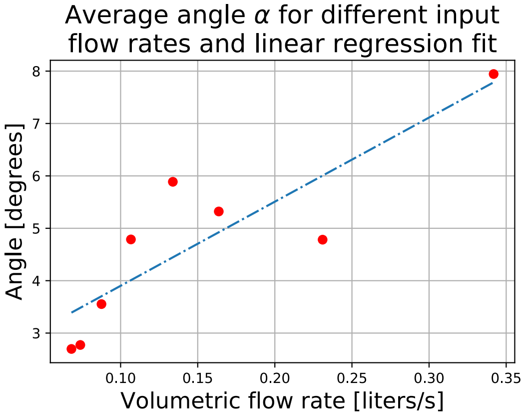

Figure 7. Variation of the average angle α for all eight input volumetric flow rates along with results from a linear regression.

we are currently using a different approach to estimate flow rate given a known deflection angle of the pendulum.

The method we use also employs a linear regression but uses as data the approximate flow rates given by the amount of rain water collected by the roof to which the sensor is attached. For any particular installation we can accurately compute the roof's surface area. The amount of rain water collected over time can be estimated by multiplying the surface area of the roof by the inches of rainfall reported in the area by weather services. The flow rate is then obtained by dividing the result by the length of the observation period. This method only provides us with approximation, but is commonly used in the sizing of residential and commercial stormwater downspouts and rain water collection systems.

While our approach is easy to implement it requires rainfall data that is only available from weather reports. On the other hand, this is a one time process. Once we have a linear regression to estimate flow rate through our device.

VII. CONCLUSION AND FUTURE WORK

The 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, such as the need for calibration at a per-site level. This can be avoided by adding an additional sensor (e.g., flow velocity sensor). However, increasing the complexity would result in a higher cost. Thus we preferred to use an approximate per-site calibration procedure.

We have carried out preliminary tests of our open solution for a period of 30 days at two different rain gardens owned by the City of Athens, OH, with encouraging results. We are currently improving the design of our solution to allow the sensor to be mounted on different types of discharge pipes as well as to be used in green roof installations where both input and output flow volumes are of interest.

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