Flood Monitoring and Mitigation Strategies for Flood-Prone Urban Areas

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Abstract

Flooding events are expected to increase due to climate change. Because of this, cities across the country need to implement flood mitigation strategies in order to ensure the safety and health of their residents. These cities need improved modeling and sensing capabilities to determine which areas (streets, residential neighborhoods, etc.) are flooding in real-time or are vulnerable to flooding from extreme weather events. Both an objective way to monitor stormwater structures and a methodology to rank such structures in accordance to maintenance needs would be valuable. To rank storm structures by peak flow, the methodology consists of using geographic information system (GIS) data combined with Arc Hydro tools to calculate the peak flow of inlet structures grouped by diameter via the rational method. The sensing system is an optical sensor that communicates using LoRa to a The Things Network node. A virtual machine running a Python script extracts the data from The Things Network and places it in an SQLite3 database that can be used for visualization and analysis by decision-makers. Both the GIS-based stormwater infrastructure assessment methodology and flood sensor system are demonstrated using neighborhoods in the City of Charlottesville as a case study.

Keywords -- Smart City, Internet of Things, Environmental Monitoring, LoRa

Flood Monitoring and Mitigation Strategies for Flood-Prone Urban Areas

Cities across the United States are encountering increased flooding events due to the effects of climate change. Single-day extreme precipitation events have become more widespread over recent years, with the EPA reporting that nine of the top ten years of extreme single-day precipitation events have occurred since 1990 (1). Older cities have stormwater systems that may not be adequately sized for frequent extreme weather events which can result in localized flooding. Unfortunately, another effect of climate change is that weather patterns have increased variability. As such, extreme precipitation events may not be adequately captured in historical meteorology observations. Forecasting rainfall is also challenging and cities may not have enough time to mobilize to take flood measurements in real-time.

In order to determine what actions cities can take to be better equipped for extreme precipitation events, a monitoring and stormwater infrastructure assessment system has been designed. The monitoring system combines a physical sensor with The Things Network to collect and record real-time measurement data. The physical system comprises an optical sensor, a radio-enabled microcontroller, and a battery, all encased in waterproofed housing that can be mounted on the top of a culvert. The microcontroller uses LoRa to communicate the data with a The Things Network gateway. Using GIS data, the stormwater infrastructure assessment system determines storm structures at risk of overflowing by utilizing total drainage area, soil type, the grade of the slope, and peak rain intensity per inlet. The methodology can be applied across neighborhoods within cities to identify problem spots and prioritize limited flood mitigation resources.

II. Literature Review

With climate change and increased flooding affecting a growing number of US communities, scientists agree that flood mitigation needs to receive greater attention. Mitchell et al. (2013) estimate a 4.5 to 7-foot rise in sea level on the Eastern Shore of the United States by 2100, four times the global average (2). In some areas of Virginia, tidal flooding has increased by 132% since 2000 (3). The research conducted in this paper attempts to develop a system for analyzing and flagging the effectiveness of existing flood mitigation structures.

Through scientific analysis of the flooded areas, Lee et al. (2012) determined which areas around Korea were most in need of flood mitigation (4). The authors used GIS software to calculate frequency ratios for the presence of flood inducing factors. They found that flooded area susceptibility maps are very useful for engineers in choosing the most susceptible and suitable locations for the implementation of further flood mitigation. Lee's research demonstrates how GIS software can be used for flood prevention efforts; however, this paper utilizes the rational method instead of frequency ratios to determine areas and storm structures most susceptible to flooding.

Lo et al. (2015) used visual sensors to monitor urban flooding (5). The team leveraged existing passive monitoring cameras as data collection resources. Various image-processing techniques were explored to give a suite of options for decision-makers at the city level. This approach to flood monitoring made sense for Taiwan, however, given that cities in the U.S. may not have existing cameras that monitor waterways, an ultrasonic sensor that can be mounted strategically may better serve these communities.

III. Problem Statement & Objectives

This project advances prior approaches by students at the University of Virginia to measure flooding levels. In prior work, an ultrasonic sensor system was developed so that the system could be secured to a telephone or light pole and would measure water levels only directly underneath the sensor housing. While the design did allow for water levels to be measured, the stakeholders required more flexibility and a change in the deployment environment. Therefore, the housing and form factor of the system needed to be advanced.

The stakeholders asked for a system that allowed for water levels to be measured within a drainage system (i.e. inside of a pipe). The previous system was only attachable via straps that would be secured around a pole structure. This new system needed to be designed in a way that allowed for deployment without attachment to a pole structure, and one that took into account the ground-level deployment of the sensor.

In addition to the new deployment strategy, the housing needed to be reconsidered so that it could be smaller, more ruggedized, and waterproofed in order to be deployed in a drainage system. Smaller housing for all parts excluding the ultrasonic sensor was the first thing required. This also required the team to re-design the system with water-proofed electrical and computer components, as well as a water-proofed neck for the ultrasonic sensor that could extend into the drainage system. Therefore, changes had to be made to both the form-factor and the housing of the sensor itself.

Knowledge of where to place the system, that is identifying flood-prone locations in the stormwater drainage system, is needed. Therefore, a systematic analysis of Charlottesville's stormwater management system has been prototyped to understand which areas of the drainage infrastructure are most likely to flood. The analysis has determined where to deploy the aforementioned flood monitoring sensor, as the city is only made aware of overwhelmed flood structures by residents who directly alert them. The stormwater infrastructure assessment system can quickly point out potential problem areas and determine how to create new, appropriately-designed stormwater control measures.

The team used GIS data provided by the city to determine which stormwater structures are at risk of overflowing during storm events. The stormwater structures were analyzed on a neighborhood basis to see if any particular areas are less adequately designed for flood control than others. The data for the analysis had to be retrieved manually from ArcMap since there were many obstacles to automating the process that arose from using flow accumulation to determine drainage areas for inlets. Considering Charlottesville has over 11,000 storm structures, an entire city-wide analysis in this study was not feasible. Instead, the team will create a methodology that details common complications with the current analysis so that future analysis can be automated and expanded to analyze stormwater management systems on a city-wide scale.

IV. Methodology & System Design

Before redesigning the legacy system, it was replicated to gather a basic understanding of its core components and functions. From this, it was determined that the system relies on The Things Network and LoRa to communicate water level data. This form of communication met the requirement of communicating over long distances while maintaining a low power draw. As a result, it was decided to maintain this component and focus the system redesigns to accommodate this decision.

From working with stakeholders, the conclusion was drawn that improvements to the legacy systems should be centered around system flexibility. This led to the definition of the following design requirements that were the focus of the redesigns to the legacy system: (1) The system should be able to measure the water level of several types of pipes, (2) The ability to measure water level should not require any drilling into the structure of the pipe, (3) The system should not require heavy maintenance from the stakeholders (replacing a battery, rebooting the system, etc.).

In order to redesign the system to be able to measure the water level of several types of pipes, it was decided that the sensor used to measure the water level needed to be adjusted. The sensor currently previously used was the MaxBotix MB7092 ultrasonic sensor. Due to its ability to read distances within an accuracy of 1 centimeter at distances of 300 inches, it was decided to keep this sensor for the new system. However, the wiring connected to the ultrasonic sensor was extended from the central device and surrounded for waterproof tubing. The extension is approximately 5 feet in length and 1 inch in diameter allowing for the sensor placement to be adjusted. Furthermore, the extension allows the sensor to be attached using ruggedized methods to make it more accessible to pipes without drilling or mounting.

In addition to extending the sensor from the central device, it was decided that the housing of the device's microcontroller needed to be redesigned. The redesign involved making the housing smaller, more ruggedized, and waterproofed. A ruggedized redesign allowed for the customization of the housing to accommodate the other changes made. Additionally, making the housing smaller allows for the device to be more accessible for several types of pipes.

The microcontroller chosen for the system was The Things Uno. This was kept the same from the legacy system as The Things Uno interfaces well with the other components of the system such as The Things Network. In an effort to redesign the system to require less maintenance, it was discovered that, depending on the location of the tethered Things Network Gateway, the spreading factor of The Things Uno can be adjusted to save power. The spreading factor proposes a tradeoff as a higher spreading factor provides more range at the cost of more power draw. For residential areas where pipes would be located on private property, a Things Network Gateway would have to be placed further from the device, the spreading factor would have to be increased, and, from the increase in spreading factor, there would be more power draw. For a more publicly owned property, a lower spreading factor would be required and, therefore, a lower power draw.

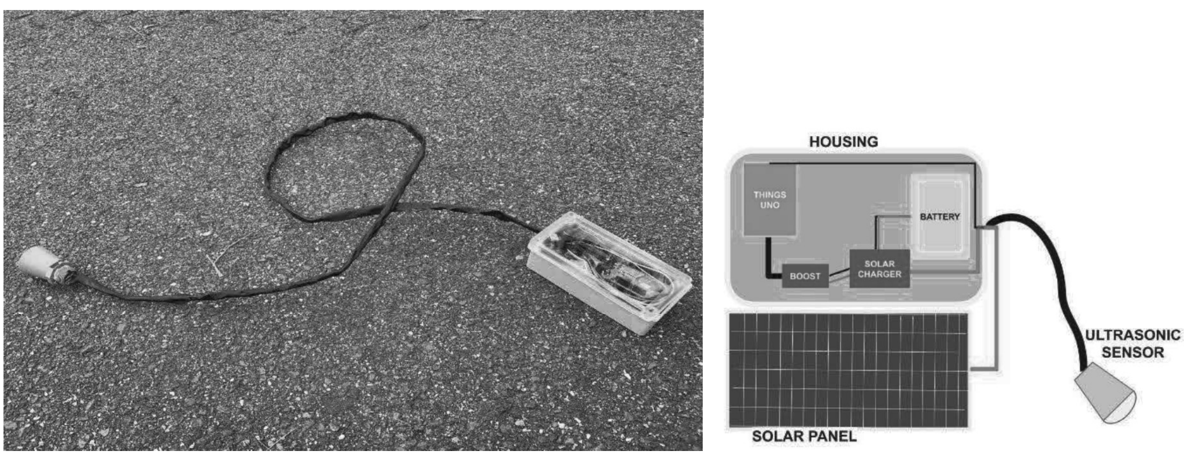

Fig. 1. (Left) Photo of the system assembled (Right) Diagram of the system

In order to record the water level data gathered by the sensor, The Things Uno communicates to a Things Network Gateway using LoRa via The Things Network. Next, a LAMP Stack hosted on an AWS EC2 instance uses a Python script to pull the data to an SQLite3 database for later visualization.

The stormwater infrastructure assessment system analysis relies heavily on the rational method and is based on data collected from two specific neighborhoods, Locust Grove and Belmont. Locust Grove was chosen for its proximity to the Rivanna River and its high concentration of waterways and streams. On the other hand, Belmont was chosen due to its contrasting characteristics compared to Locust Grove to make the data more representative of the entire Charlottesville stormwater management system.

The rational method is a technique used for estimating a discharge from a small watershed area from Equation (1) below.

$$Q = CIA \qquad (1)$$

Q = maximum rate of runoff, cfs
C = dimensionless runoff coefficient
I = design rainfall intensity, in inches per hour
A = drainage area, in acres

The end goal of the stormwater system analysis is to measure the peak flow, *Q,* heading towards an inlet structure and compare the peak flow to other inlets with similar-sized pipes. ArcMap, a GIS software, will be used to combine multiple geospatial data files to view and inspect the parameters of the rational method. Using this methodology, a correlation will be determined between the diameter of pipes and the maximum flow accumulation they can manage. Multiple steps must be done to perform this analysis:

(1) Multiple shapefiles (.shp) containing the following information need to be added as layers into an ArcMap package: the city's stormwater structures and pipes, contour elevation data and neighborhood planning areas, USGS Soils data, and the ArcMap World Topographic Map.
(2) Create a flow accumulation model in ArcMap to create a flow accumulation model, which gives the total area that drains to each cell on the map.
(3) Create a classified symbology feature in the flow accumulation layer properties to mark off flow accumulation values of 0-50, 50-100, 100-200, 200-400, 400+. To simplify the analysis, all inlets with a flow accumulation value of less than 50 will not be considered for analysis due to their low risk of overflowing.
(4) Collect values for the right-hand side of the rational method and the downstream pipe diameter
(a) For *C,* use the value provided by the rational coefficient table for the soil type and elevation grade of each inlet
(b) For *I*, use the value provided by the PDS-based precipitation table for an average recurrence interval of 10 years and a duration of 24 hours
(c) For *A*, use the maximum flow accumulation value within 20 feet of an inlet
(5) Calculate Q by multiplying *C, I*, and *A*.
(6) Create a boxplot like Figure 2 on the right for peak flow grouped by diameter size. Exclude all diameter sizes with less than ten sample points.
(7) Determine all inlet structures with peak flow that are above the 90th and 95th percentile.
(8) Manually review the outlier inlet structures in ArcMap to determine if flow accumulation value is accurate by examining the surrounding geographical area and stormwater system.

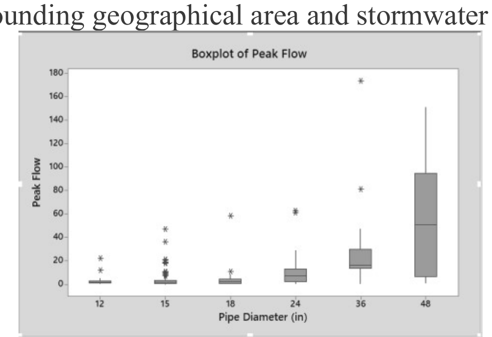

Fig. 2. Box plot displaying outliers for corresponding pipe diameters and their range of peak flow accumulations

(9) If the outlier's peak flow is deemed inaccurate, adjust the peak flow to more accurate representation and add another rule to the methodology to prevent the error from reoccurring.
(a) Otherwise, label the outlier structure as most likely to be problematic.

(10) Repeat steps 6-9 to see if any new outliers and errors appear after fixing previous inaccuracies in step 4a.

V. Results & Discussion

The sensor system analysis consisted of in-lab testing to ensure that all subsystems were working properly. The first of these lab analyses determined the battery life of the system at minimum and maximum spreading factor during normal system operation. Calculations show that the system is able to last approximately ten days without battery replacement or charging at the maximum spreading factor of 12. Additionally, the system is able to last approximately 20 days without battery replacement or charging at the minimum spreading factor of 7. This capability has positive implications for the system's use; the client requested no need for "heavy maintenance". Ensuring that the battery-life was over the span of several days was, therefore, a strong success for the system.

In addition, the system was fully powered on in-lab to ensure that all components were properly connected and the system could function as expected using its power system. The system has the ability to draw power from a battery charged either by conventional means or by an attached solar panel. The solar panel connections were added so that this additional functionality could be achieved. In this test, data flow was also checked. The sensor was able to accurately detect relative distances, and the data was received by the proper subsystems.

Lastly, the system was able to be installed on the Emmet-Ivy culvert with the help of UVA Facilities. This allowed the system to be tested in terms of usability and environmental compatibility. Inclement weather that has since occurred did not damage the system, and it was able to be installed in a way that allowed for the plastic, water-proof box housing the system to be secured to fencing above the culvert, while the neck can extend safely into the mouth of the culvert below.

Both the lab-testing of the device that ensured proper power connections and data-flow and the installation check of the device satisfied requirements set out by the client. Additional field testing was restricted due to COVID-19. The client requested that the system be able to measure the water level of (1) several types of pipes and (2) do so without any drilling into the pipe's structure. The redesign of the housing made sure that the system was deployable in a variety of positions and environments. The housing itself is water-resistant and the extendable, flexible neck allows for the sensor to reach into a pipe or culvert without putting the entire system at risk. No drilling was required to install the system; only the housing and neck must be secured. This can be done with zip-ties or other restraints. The weather-proofing ensured that the system would not require heavy maintenance, which was another client requirement.

Post-installation of the device, it was realized that the device had some issues sending data to The Things Network Gateway. It was assumed that the nearby buildings and trees were obstructing the device's ability to connect. From this, the spreading factor was increased to help with connectivity and considerations for moving The Things Network Gateway to a closer location were made. This change is justified with the addition of a solar panel to handle the increase in power draw.

The stormwater infrastructure assessment system consists of two parts: analyzing peak flows of inlets from the Belmont and Locust Grove neighborhoods and investigating shortfalls of the methodology to recommend revisions. The analysis of peak flows was done by finding upper-tail outliers for each respective pipe diameter size. While this approach does not specifically establish whether or not a pipe is undersized for the current amount of flow it is receiving, it will determine which inlets or pipes are most likely to be overflowing. After determining outliers, manual checks of the outliers were performed to validate the peak flow and to determine if the calculation was inaccurate. If the calculation seemed inaccurate or misleading, it was assumed that there was a problem with the methodology and that a revision was needed to improve the accuracy. Two revisions were made to the methodology to fix the flow accumulation values for inlet structures:

(1) If there is another series of stormwater pipes further upstream that receives part of the flow accumulation branch that drains towards the inlet of focus, subtract the flow accumulation value of the intersection of the flow accumulation branch and the nearest inlet structure in the different upstream

series of pipes from the flow accumulation value from the inlet of focus and vice versa if the inlet's flow accumulation branch is diverted to another series of pipes to get a more accurate flow accumulation value.

(2) If the inlet is within 100 feet of a defined stream and the five flow accumulation blocks upstream and downstream are also within 100 feet of the stream, then that flow accumulation branch is most likely attributable to the flow accumulation of the stream and not the inlet. To fix this, use the closest flow accumulation value in the opposite direction of the stream.

The new flow accumulation values from the revised methodology were used to determine problematic inlets. Table 1 on the next page shows an exemplary list of inlets that cities could use to prioritize the maintenance of stormwater infrastructure.

From the analysis, the Belmont neighborhood has 13 inlets that may be undersized versus Locust Grove's single potentially undersized inlet. This would seem to show that the Belmont area is more susceptible to flooding than the Locust Grove area;

TABLE I.

Inlet FID	Neighborhood	Diameter	Drainage Acres	Peak Flow	>95%?
7547	Bmont	12	8.0	11.8	No
8892	Bmont	15	5.7	9.8	No
1753	Bmont	15	6.3	10.8	No
1949	Bmont	15	6.6	8.5	No
1868	Bmont	15	8.2	10.6	No
11339	LG	18	8.5	11.0	Yes
7747	Bmont	18	6.7	8.6	No
8572	Bmont	24	41.8	61.3	Yes
1781	Bmont	24	42.9	62.9	Yes
7554	Bmont	24	18.5	21.6	No
9663	Bmont	36	69.6	81.0	No
8593	Bmont	36	118.2	173.1	Yes
1898	Bmont	48	103.1	151.1	Yes
8895	Bmont	48	92.1	119.1	No

Table of stormwater inlets identified to be potentially undersized.

however, this analysis only takes into account storm inlets overflowing. The Locust Grove area has more waterways and streams than the Belmont area, so the stormwater system in Locust Grove discharges a lot of its water into natural waterways. This analysis cannot show whether too much water is being diverted towards the waterways and streams that could cause wider floods than the floods that result from overflowing inlets. This implies that the methodology works better for areas that do not have high concentrations of waterways and streams.

The identification of these vulnerable inlets will give the City of Charlottesville a better understanding of where problem areas may occur, what similar types of situations are causing it, and how to prioritize flood mitigation resources in the future. The revised methodology will allow cities to take the stormwater infrastructure assessment system analysis and expand it to a city-wide scale by potentially automating it. There are still imperfections with the methodology; such as the flow accumulation tool not being compatible with a stormwater management system layer of pipes and inlets within ArcMap. Also, the methodology does not tell whether an inlet will actually overflow during a 10-year storm since it only points out upper-tail outliers. To improve this, more data is needed such as the slope and type of the stormwater pipes and overall depth and elevations of inlets. A new ArcMap tool that could combine the Flow Accumulation with a file type specifically designed for stormwater systems would easily allow for calculation of inlet watershed areas to expand the analysis on a city-wide scale.

VI. Conclusion & Future Discussions

This study resulted in a sensor system and GIS-based stormwater assessment tool that can be applied by cities to improve flood resilience. The sensor advanced on prior prototypes with the goal of measuring water-levels within a drainage system to provide a more accurate picture of overloaded or failing infrastructure. The system has a more flexible form factor from prior prototypes and allows for a measure of water levels in a variety of positions. The system also now provides a means to measure these infrastructures directly, as opposed to the previous system that would measure the effect of these infrastructures (i.e. street-level flooding).

For future work, the system could benefit from data visualization techniques in the user interface. This would allow for value to be added from the data collected. Another area for future work would be to significantly increase the battery life of the sensor in order to decrease dependence on the solar panel.

The stormwater infrastructure assessment system successfully located inlet structures that incur the most flow during peak rainfall intensity. The system takes pipe diameter into account and is useful for determining which pipe size to implement in specific areas. Though the stormwater infrastructure assessment system was only used to analyze two neighborhoods in this project, it can easily be expanded and applied to the entire City of Charlottesville through possible automation. Additionally, it can be used as a model for flood structure analysis in any other city as well. Seeing as increased flooding is becoming a growing problem throughout the United States, efforts to mitigate flooding must increase. Utilizing a stormwater infrastructure assessment system such as this one is an important first step in initially identifying all potential problem spots in flood-prone areas.

VII. Acknowledgements

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References

[1] US EPA. 2017. Climate Change Indicators: Heavy Precipitation | US EPA. Retrieved from https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation

[2] Mitchell, M., Hershner, C., Herman, J., Schatt, D., & Eggington, E. (2013). Recurrent Flooding Study for Tidewater Virginia. http://ccrm.vims.edu/recurrentflooding /Recurrent_ Flooding_Study_web.pdf

[3] SLR. (n.d.). Sea Level Rise. Virginia's Sea Level Is Rising. https://sealevelrise.org/states/ virginia/.

[4] M. Lee, J. Kang and S. Jeon. (2012) "Application of frequency ratio model and validation for predictive flooded area susceptibility mapping using GIS," *2012 IEEE International Geoscience and Remote Sensing Symposium*, Munich, 2012, pp. 895-898.

[5] Lo, S.-W., Wu, J.-H., Lin, F.-P., & Hsu, C.-H. (2015). Visual Sensing for Urban Flood Monitoring. *Sensors*, *15*(8), 20006–20029. MDPI AG. Retrieved from http://dx.doi.org/10.3390/s150820006