Using Embedded Sensor Networks to Monitor, Control, and Reduce CSO Events: A Pilot Study

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Keywords: Combined sewer overflow, CSO, real-time control, CSONet, embedded sensor networks

Abstract

Each year in the United States, combined sewer overflow (CSO) events result in the release of 850 billion gallons of untreated wastewater into lakes and rivers, causing drinking water contamination, human illness, animal and fish kills, and eutrophication. This paper examines the ability of an embedded sensor network to reduce the frequency and severity of CSO events by maximizing the existing storage capacity in the combined sewer system (CSS). This novel network system is called Combined Sewer Overflow Network (CSONet). CSONet uses data gathered from a distributed network of sensors to provide decentralized, distributed, real-time control of the CSS's storage capacity using automated valves called Smart Valves. One pilot CSONet was deployed in South Bend, IN during the summer of 2005. It controlled the storage of stormwater runoff in a large retention basin using level data from sensors within the basin and at the CSO outfall, 3.2 miles away. Once there was no longer a threat of a CSO event, CSONet automatically released the stored water into the CSS and prepared for the next storm. Before the CSONet was in place, the basin was very ineffective during small and medium storm events. The basin can now store all of the water that enters during most storm events, preventing it from overflowing into the St. Joseph River. Further work is being done to expand CSONet to handle in-line storage, Smart Valves in series, and predictive control.

Key Words Combined sewer overflow, CSO, real-time control, CSONet, embedded sensor networks

Introduction

During the first half of the 20th century, construction of sewer systems to transport wastewater in urbanizing areas increased dramatically. To minimize construction costs, these wastewater systems were built to accept both sanitary wastewater and storm water runoff. During times of dry weather, these systems adequately carried wastewater flows to wastewater treatment plants. In wet weather, the additional volumes from rainfall runoff would surcharge the systems. To relieve the systems, overflow points were built at numerous locations within the systems to allow for the discharge of these excess volumes into the local water bodies. As communities grew and sprawled outward, they began to separate the sewer and storm lines with new construction. The result was a distribution system that resembled a donut, with the inner circle (i.e., the donut hole) being the historic combined sewer systems (CSSs) and the outer circle (i.e., the donut) consisting of the separate systems. Such engineering and construction practices were most common in the nation's northeast and mid-west urban areas. Following passage of the Clean Water Act in the early 1970s, federal regulators were charged with cleaning up the waters of the nation. The goal was that all rivers and lakes would support aquatic life and safe recreational uses, which meant the problem of point discharges to the nation’s waters had to be addressed. During the 1970s and 1980s, regulatory emphasis was on industrial and publicly owned treatment plant discharges. Following significant improvements to water quality from these regulations, emphasis shifted in the 1990s to the control of discharges from the nation’s CSSs.

Because the diverted wastewater from CSO events is untreated, it has adverse effects on water quality and poses a significant public health threat. The United States Center for Disease Control states that thousands of waterborne illnesses result from CSO events each year (USEPA 2004). The fecal matter from domestic wastewater and animal waste found in storm water runoff leads to fecal coliform concentrations up to 200,000 times higher in combined wastewater than in treated wastewater (USEPA 2004) and *E. coli* concentrations in the combined wastewater up to 1,000-2,000 times the maximum permissible concentrations in river systems (Greeley and Hanson 1994, Thackson et al. 1999). CSO events are estimated to be responsible for 76% of the fecal coliform that enters receiving waters (USEPA 2004) and cause one third of the pollution loading to urban streams and watercourses, even though they only account for 4% of the input flow (Thomas et al. 2004). This was clearly demonstrated in the Hudson-Raritan Estuary in New York. CSO events there were responsible for 89% of the total fecal coliform and 19% of the Biochemical Oxygen Demand (BOD) that entered the New York Harbor, yet they only accounted for 1% of the harbor’s freshwater input (USEPA 2000). Pathogens found in wastewater can cause severe gastroenteritis and even Typhoid fever. The microbial degradation of the fecal matter and other organics that enter the water system during CSO events depletes dissolved oxygen in the water and can lead to eutrophication.

As the United States Environmental Protection Agency (USEPA) moves forward in achieving water quality objectives for the nation as outlined in the Clean Water Act, the issue of water quality degradation due to discharges from CSOs is a major focus. The USEPA reported that the average individual CSO outfall discharges 50 to 80 times per year, resulting in the conveyance of approximately 850 billion gallons of raw wastewater and storm water runoff into receiving waters each year (USEPA 2004). The American

Society of Civil Engineers considers combined sewer overflow control the greatest wastewater infrastructure need in the United States and estimates that it may cost up to $45 billion to solve (ASCE 2001). The USEPA estimates that it will cost $50.6 billion to reduce the annual number of CSO events in the United States by 85% (USEPA 2004).

Due to high construction costs, it may not be possible to entirely eliminate CSO events. Complete elimination of CSO events would require the construction of sewer systems that could handle even the most severe storms and associated flows, which is not economically feasible. Instead, most municipalities are redesigning their system with the understanding that some CSO events will still occur. The key is to reduce the adverse effects of these overflows. Solutions to controlling CSO events range from public policy arena involving revisions to water quality standards rules and regulations, to those based in direct technology. On the technology front, conventional approaches such as sewer separation, transport-and-treat, and off-line storage are at the heart of many community plans. In most cases, they are cost-prohibitive and can negatively impact the environment in other ways, such as destroying terrestrial ecosystems (USEPA 1999b). Other communities are looking at green technology, such as open channel streams and green roofs, as a solution to the CSO problem, but are having difficulty gathering public support (Villarreal et al. 2004). More advanced technological solutions involving applications of sophisticated dynamic models to design and operate controls in real time are just now entering center stage (Bagstad 1997, Field and O'Connor 1997, Kopecny et al. 1999, Sugita et al. 2001, Wiese et al. 2002). These networks function within the collection systems and at the wastewater treatment plants, but they are still localized and somewhat passive systems. A more advanced approach to CSO control is the use of real time control systems to continually modify the setpoints of all of the regulators and valves to meet the changing conditions within the system. While many agree that this system is the most effective way to maximize the existing CSS storage capacity (Jørgensen et al. 1995, Weinreich et al. 1997, USEPA 1999a, Meirlaen et al. 2002, Schütze et al. 2002, Schütze et al. 2003, Duchesne et al. 2004, Thomas et al. 2004), few such networks exist today.

One such system is the Quebec Urban Community System. This network uses 5 moveable in-line gates controlled by Programmable Logic Controllers (PLCs) to direct the combined wastewater in real time to two underground storage tunnels with a combined storage volume of 3,960,000 gal. It controls the system using data from 17 flow monitoring and weather stations. This real-time control network reduced the overflow volume by 70% in 2000, and only cost US$2.6 million. The estimated cost for the same volume reduction using conventional storage techniques was US$15.5 million. The network is currently being expanded to 30 moveable gates and 70 measurement locations (Schütze et al. 2002). The Northeast Ohio Regional Sewer District has also implemented a large scale, global, real-time, control system to maximize inline storage and reduce the total overflow volume. The entire system is operated by a central computer, and uses data collected from 25 rain gauges, 24 remote level monitors, 56 remote flow monitors, and local level monitors to adjust 29 automated regulators using PLCs. This network prevents over 700 million gallons of combined wastewater from overflowing into the receiving waters each year (USEPA 1999a). These systems are very cost efficient, when compared to more conventional methods of CSO volume reduction, yet still achieve high levels of environmental benefit. These systems both require centralized control and the use of large and expensive PLCs in order to operate. They tend to be very reliable, but are susceptible to problems when power outages occur.

A decentralized control scheme using a distributed network of small, low cost, low power nodes may be able to create a less expensive, more robust, and faster reacting control system. Unlike PLCs, these nodes do not need an outside power supply or any particular infrastructure, so they can be deployed anywhere with ease. Because the nodes are significantly less expensive than PLCs, more nodes can be deployed throughout the CSS. This provides a measure a redundancy, which allows the network to function if one or two nodes fail, and also gives a clearer picture of what is happening within the CSS at all times.

This project addressed the CSO problem through the use of a novel embedded sensor network called Combined Sewer Overflow Network (CSONet). CSONet consists of sensors that are controlled by embedded micro-processors. The micro-processors exchange information over a wireless communication network. CSONet allows for real-time in-situ monitoring and control of environmental systems at a spatial and temporal resolution unknown in existing water quality monitoring systems. While a few embedded sensor networks have been built for environmental monitoring (Steere et al. 2000, Sukhatme et al. 2000, Cerpa et al. 2001, Mainwaring et al. 2002), this particular project represents the first large-scale embedded network used for monitoring and controlling water quality over a large geographic area. To do this, CSONet becomes an intelligent sensor, a distributed memory, and ultimately a distributed database system that users can access interactively to study the system being monitored and make real-time decisions concerning control. CSONet can control the wastewater flow by using "Smart Valves," which are automated valves that CSONet controls based on data from the embedded sensor nodes. CSONet adjusts the Smart Valves at the in-line and off-line storage locations in real-time in order to minimize or prevent CSO events. The aim of this project was to develop, deploy, and test a pilot distributed in-situ intelligent and interactive embedded sensor and communication network to monitor and control CSO events in the South Bend Clyde Creek Watershed, which drains into the St. Joseph River.

Experimental Protocols

CSONet Concept

The purpose of CSONet is to maximize the existing storage capacity in the CSS in order to minimize the amount of combined wastewater that enters the receiving waters. Figure 1 shows a section of CSONet in which there are three Smart Valves in series. If each Smart Valve worked independently of the others, water would be released or held locally without any knowledge of what was happening up or down gradient. This could result in flooding and inefficient use of available storage within the system. However, if the control nodes could communicate with each other, then the middle Smart Valves would know that water was about to be released upgradient and that storage capacity still existed further downgradient. The Smart Valve could in turn release some of its own water to the downgradient storage area in preparation for the additional flow that would come from the upgradient release. With this scheme, no flooding or backup of water occurs, and each one of the storage areas is used efficiently. The CSONet system allows control nodes to communicate with each other and determine among themselves how to best handle the changing weather conditions.

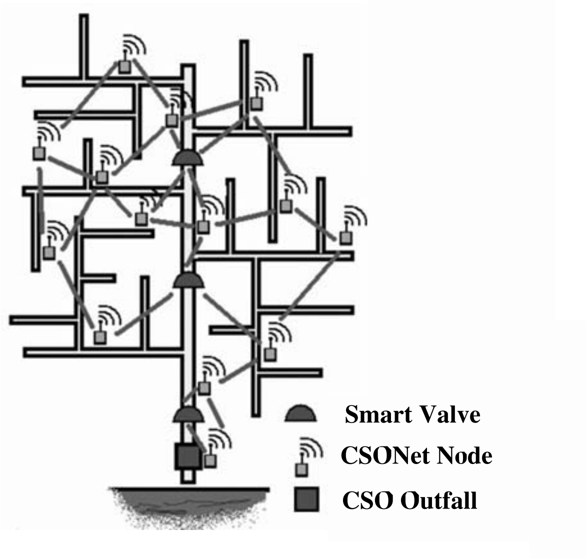


Figure 1. CSONet controlling three Smart Valves in series.

Decentralized control enables more effective control of the network because each impacted node is able to process independently how it should adjust the Smart Valve in order to best respond to real-time events. This results in much more diverse and creative control decisions that optimize local and global storage in the CSS. This control improves overall storage capacity by allowing each section to maximize its capabilities, while minimizing the risk of overflow or flooding.

One of the additional strengths of CSONet is that it can be implemented into existing distribution systems with only minor infrastructure modifications. The nodes communicate with each other wirelessly. No fiber optic network or Supervisory Control and Data Acquisition (SCADA) systems are required. If such networks already exist, the nodes can easily access them. There is no need for PLC construction or maintenance, nor the erection of antenna towers. Some roadwork and sewerwork is required for the placement of Smart Valves into the sewerlines and retention basins, but this localized work can be done with minimal inconvenience to the public. Smart Valves do require electricity, but battery or solar-powered options are possible. Municipalities have the resources needed to implement CSONet, no matter what the size and location.

A citywide CSONet is not required in order for the benefits of the network to be seen. Once the first Smart Valve and its corresponding nodes are implemented, the storage ability of the CSS immediately is increased. As more Smart Valves and nodes are phased in, implementation becomes easier because some of the previously deployed nodes can be used for multiple new Smart Valves and control nodes. Once CSONet is full implemented, the storage capacity of the CSS can be optimized. Also, the network of wireless nodes provides another layer of communication infrastructure for the municipality, which can be used for other tasks as well.

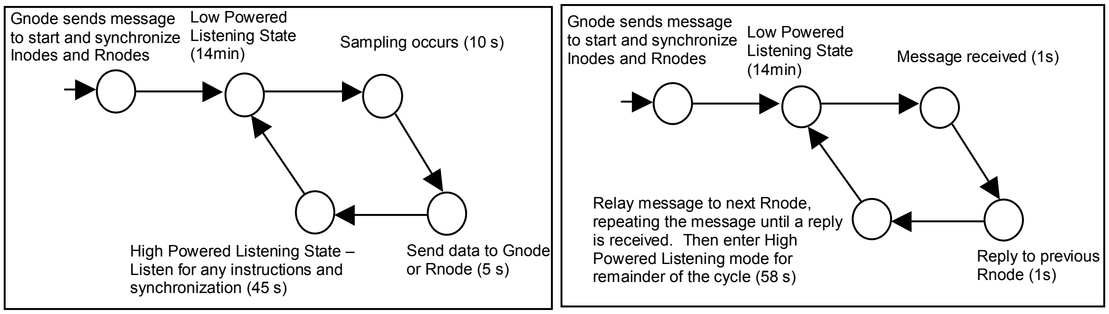
Once implemented, CSONet is very robust because of the large number of sensors distributed throughout the CSS, each reporting data to the control nodes. A single detection may indicate a change in system capacity, or it may be a sensor error. CSONet distinguishes between these two cases by comparing node measurements with neighboring sensor nodes. By comparing the measurements of adjacent nodes, it is possible to accurately distinguish between actual events and temporary variations in a single node's sensor measurements. The local wireless communication between nodes allows this exchange of information to take place, thereby improving network detection, sensitivity, and estimation accuracy to levels that were not previously possible.

The network provides real-time in-situ measurements that can be used to: (1) increase the efficiency of the current in-line storage in main trunk-lines, (2) allow for increased storage by making use of the smaller in-line distribution lines, above ground basins, and upgradient basins not fully utilized, (3) convert the existing CSO planning models into real-time control and operations models, (4) improve land management by pin-pointing when/where to drain streets and place down spouts; (5) develop a real-time CSO public notification plan; (6) expedite required and preventive maintenance through real-time identification of problem areas as indicated by reduced flow and increased pressure; and (7) revise and improve the overall CSO strategy plan.

CSONet Components

There are three main types of nodes in CSONet: the gateway node (Gnode), the instrument node (Inode), and the routing node (Rnode). Each node contains a microprocessor, a radio, and a power supply. Gnodes are the main control nodes in CSONet. They have powerful microprocessors and cost less than $2,000 apiece. These nodes collect data from Inodes and Rnodes and then use that data to adjust Smart Valves to meet changing conditions. In addition to controlling Smart Valves, Gnodes are responsible for keeping all of the nodes in CSONet synchronized. Synchronization ensures that all of the nodes are awake and operating at the same time, allowing for real-time communication. Gnodes' microprocessors also contain a cellular card and connect to the internet via a wireless cellular connection to exchange information. The wireless connection allows the Gnodes to post current conditions of the system and the Smart Valves on the Internet for the wastewater treatment plant (WWTP). These functions require considerable power, which requires the Gnodes to be linked into the AC power supply for the Smart Valves. Each Gnode contains a small emergency battery, which allows it to function for a brief time should a power outage occur. That way, if the outage is short, the CSONet never stops functioning. Because they have a continual source of power, Gnodes do not undergo a power conservation cycle. There is also a wire connection between the Smart Valves and Gnodes, which is why Gnodes must be placed close to Smart Valves and the rest of CSONet must be built around these fixed points.

Inodes and the Rnodes are similar to each other in construction. Both have the same radio and microprocessor. Inodes and Rnodes are powered by 4D batteries and cost less than $1000 each (plus the cost of the Inode's sensors). Although their hardware is similar to each other, their functions are very different. Inodes act primarily as data gathering devices. Each Inode is connected to a single or multiple off-the-shelf sensors. Once the sensor readings are recorded, Inodes send this data to Gnodes. If the distance between the corresponding Gnode and Inode is greater than the Inode's radio's range (about 1000-2500 feet, depending on the line of sight), then the data is relayed to the Gnode via Rnodes. The Rnodes enable the data to be sent over many hops, covering great distances. Since the Rnodes and Inodes are powered by batteries, they minimize their power consumption as much as possible by undergoing a power conservation cycle. They alternate between a low-powered mode (14 minutes) and a full-power mode (1 minute). When in the full power mode, they collect and send data (see Figure 2). With this power scheme, the nodes' batteries have a life of about 4-6 months, highly efficient when compared to similar nodes used for other projects (Yang et al. 2002). Modifications to the software and hardware are currently underway to improve battery life to over a year, or to make the nodes solar-powered.



(a) (b)

Figure 2 (a). The energy conservation cycle for Inodes (b). The energy conservation for Rnodes

The nodes are encased in waterproof PVC casings with screw-off bottoms. The casings are strapped to stoplight poles or utility poles, approximately 20 feet above the ground. With this arrangement, the nodes can be easily accessed and serviced using lift trucks.

Communication Scheme

CSONet communication system operates in an efficient and controlled manner and does not interfere with other wireless communications that may be present. Each node contains an XStream radio that broadcasts at a frequency between 902 and 928 MHz with a transmit power of 100 mW. This frequency bandwidth falls into the bandwidth allocated for cellular communications. To avoid interference with the cellular signals, each radio contains a frequency-hopping, wide band FM modulator, which distributes the signal broadcast over a wide range of frequencies. This transmission scheme prevents the signals from being jammed and accidentally or purposefully intercepted. The receiving node accepts all of the signal packets, reforms them into the initial signal, and then transmits again, if necessary.

To disseminate the data, advanced routing algorithms are used. In particular, a scheme called Persistent Stateless Gradient-Based Routing is used. This algorithms enables the network to maintain connectivity in spite of poor node-to-node reception (between 60% and 80%) while requiring low computational power. The result is robust data communication over the network with more than 99% end-to-end data arrival success rate.

Rnodes are spaced as far apart as possible to minimize costs. Because there is not always perfect connectivity, some signal packets may be lost during transmission. Rather than having this transmission error propagate as the signal moves downgradient, the transmitting node keeps repeating the signal until the receiving node signals it has received all of the packets (see Figure 2). The receiving node then starts broadcasting the signal to the next node. This broadcasting scheme makes CSONet very robust, because it allows for the original message to be sent in the harshest conditions. Also, if one node in the network stops working, then the signal is just repeated until the next node in line receives the full message and relays it on. In such circumstances, the network can still work until appropriate repairs can be made.

CSONet Goals

The goals of CSONet are to:

- Maximize the existing storage capacity (e.g., retention basins and in-line storage) of the CSS before allowing a CSO event to occur.
- Maximize the amount of stored water that is sent to the wastewater treatment plant.
- Empty the storage capacity as quickly as possible in anticipation of the next storm event.
- Reduce the peak flood in the CSS during storm events.
- Minimize the risk of street and basement flooding.
- Provide a system where network deployment and maintenance can be implemented by any municipality.
- Provide data that can improve existing CSO planning models.

The Ireland-Miami Pilot CSONet

Pilot Site Background

The first pilot CSONet was implemented in the CSO 22 service area in South Bend, IN during the summer of 2005. South Bend is the fifth largest city in Indiana, with a population of 107,789 people. The city contains about 13,100 acres of combined sewers, which overflow at 36 CSO locations into the St. Joseph River (Greeley and Hansen 2003). South Bend receives an average of 36.11 inches of rainfall each year from an average of 122 storms per year. Most of these storms are small storms that result from the climatic impact of nearby Lake Michigan. The South Bend wastewater treatment plant receives an average of 41.6 million gallons per day (MPG) and has a capacity of 70 MGD (Greeley and Hansen 1994).

The CSO 22 service area spans 3,758 acres and contributes to 17% of the city's total CSO discharge volume (Greeley and Hansen 1994). An overflow will occur at the CSO 22 control structure if it rains more than 0.10 inches in 7 hours or less. Despite the large size of the service area, the trunkline can only handle 15.5 cfs before an overflow occurs (Greeley and Hansen 2003). The diameter of the pipe at the outfall is 90 inches, but an overflow will occur if the flow depth exceeds 56 inches. The CSONet focused primarily on the Ireland-Miami basin, which lies in the western side of the service area. This basin consists of three interconnected sub-basins with a combined capacity of 12,560,000 gallons. Approximately 270 acres of separated storm sewer (65% commercial and 35% residential) empty into this basin, which discharges into the CSS

(Lawson-Fisher Associates 2003). This basin is located primarily in a commercial area surrounded by parking lots and business offices. Before CSONet, the flow from the basin to the CSS was controlled manually by a valve and by the flow capacity of a 10" diameter outlet pipe. The valve was only effective during storms that were long enough in duration for a worker to travel to the basin to close the valve and allow for storage. In most cases, the water would stay in the retention basin for several days until the valve was opened. This delayed storage created anoxic conditions in the basin, leading to odor and potential health problems (USEPA 1999b). It also reduced the basin's capacity to absorb the impact of following storms, providing little or no flood protection for the surrounding area. As it was, the valve was inoperable and had been for an unknown length of time. Hence, the only factor controlling the retention in this basin was the size of the outlet pipe. The basin only retained water during short, intense storms, when the capacity of the outlet pipe was exceeded. Although only a few large storms hit South Bend each year, the number of small storms is significant, each causing a CSO event. The City of South Bend recently replaced this valve with an actuated gate valve, which serves as the Smart Valve for CSONet.

CSONet Components

The Ireland-Miami CSONet is the first pilot test of the CSONet concept. It consists of 1 Gnode, 7 Rnodes, and 3 Inodes. The Gnode is attached about 20 ft above the ground to an existing antenna pole at the edge of the basin. From here, the Gnode can easily access the internet and receive signals from the appropriate Inodes and Rnodes. The Gnode has two sets of wires, one for power and the other to control the Smart Valve. The Gnode controls the Smart Valve via an analog signal sent through the control wire and then reports on how open the valve is via the Internet.

Two Inodes are connected to pressure sensors deployed in the basin. One of the Inodes is free-floating on the surface of the basin water, and the other is attached to an existing concrete structure (see Figure 3). In both cases, sensors are anchored to the bottom of the basin using cement blocks, at depths not impacted by freezing during winter. These deployment techniques were also chosen because they were deemed to be very secure while demonstrating the versatility of the nodes for deployment in any basin. Both Inodes are close enough to the Gnode for direct communication as they report the depth in the basin every 15 minutes. Should the two depth readings ever differ beyond a given threshold, the higher reading is used and the CSONet administrator is notified.

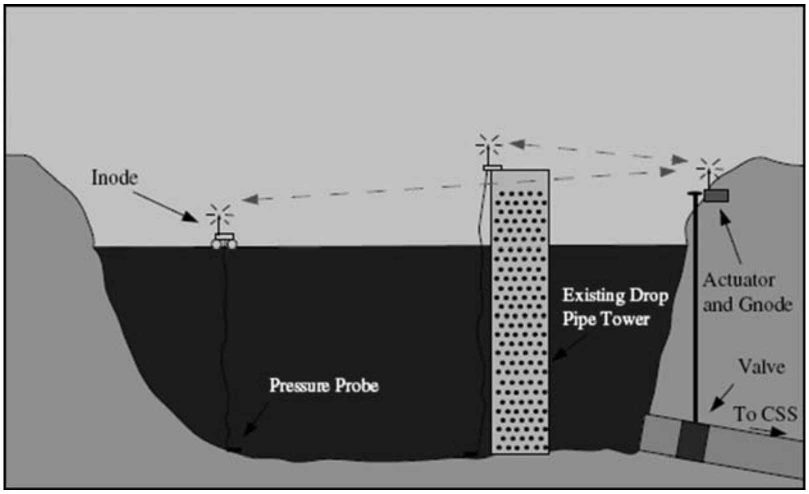


Figure 3. A schematic of the CSONet components in the Ireland-Miami basin.

The third Inode is deployed at the CSO 22 outfall, approximately 3.2 miles away from the basin. This Inode communicates with an existing level sensor at the outfall and then transmits that data back to the Gnode via a series of Rnodes (see Figure 4). Rnodes are deployed along two major roads and attached to stoplight poles approximately 20 feet above the ground. Deploying Rnodes along major roads assures clear lines of sight and the presence of ample stoplight poles. These roads are also the first to be plowed in winter, an important consideration should emergency repairs be required. Rnodes are deployed as far above the ground as the city-owned lift trucks could reach in order to provide a measure of security, while still allowing for maintenance access. When the outfall Inode sends a signal, it is carried downgradient by the Inodes until it reaches the Gnode. The Rnodes are deployed in such a way that the signal is able to make two hops at one time should one Rnode stop working. For example, about three months after deployment, one of Rnodes ran out of batteries before the others did, but the signal still made its final destination.

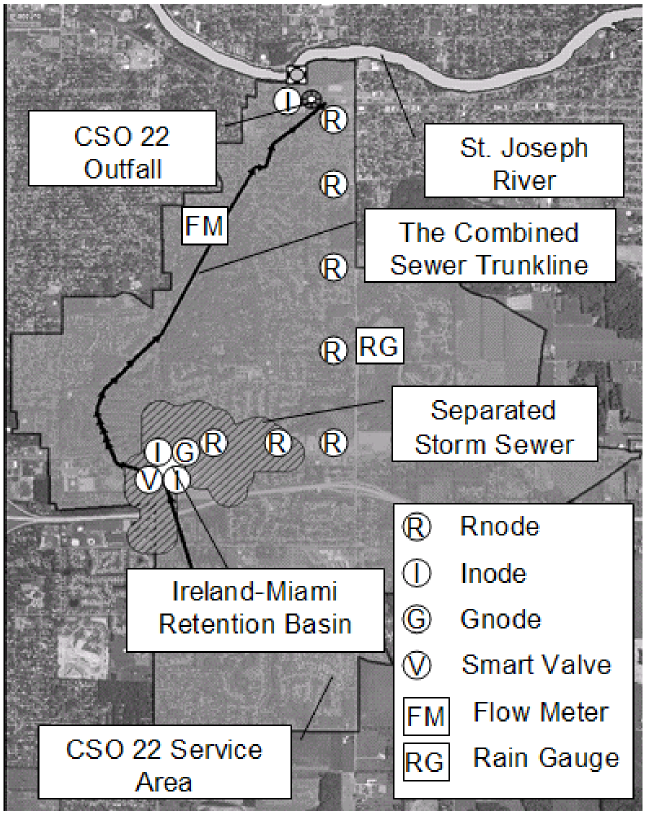


Figure 4. Deployment of CSONet in the CSO 22 service area.

Control Scheme

The overall goal of the Ireland-Miami CSONet was to automatically retain as much water as possible in the basin during wet weather events without flooding the surrounding area and then empty the basin as quickly as possible in anticipation of the next storm event. During dry weather, the Smart Valve remains closed. When a storm event occurs, the basin filled with stormwater runoff, and the basin Inodes sent the depth data to the Gnode. The Gnode kept the gate closed during the storm unless the basin depth exceeded a predetermined limit, indicating the possibility of future flooding. If this were to happen, the Gnode would release some of the retained water into the CSS, even though this may cause a CSO event. A licensed CSO event was determined to be preferable to flooding or property damage around the basin. The unsafe depth was set initially at a very conservative six feet, but was increased as CSONet demonstrated its reliability.

The Gnode released the stored water as soon as there was no further threat of a CSO event. Once the Inode at the outfall reported that the flow depth was below 30 inches (26 inches below the overflow depth) at the outfall, the Gnode opened the gate and released the water at a constant 2 cfs. A constant, controlled, discharge rate minimizes the impact of the additional flow on the CSS and downstream structures (USEPA 1999b) while the Gnode predicts how additional flow will impact the flow depth at the outfall. In order to keep this rate constant, the Gnode used the data from the basin Inodes to open the valve more as the hydraulic head behind the valve decreased. If the flow depth at the outfall exceeded 40 inches, the Gnode automatically closed the valve until the flow depth dropped below 30 inches. This phenomenon often happens when another storm event occurs while the basin is emptying. Once the basin is emptied, the Gnode closes the gate and waits for another storm event.

Each morning, if there is no threat of a CSO event, the Gnode completely opens and closes the Smart Valve in order to release any dry weather flow that may have accumulated during the previous day and to test the valve. This way, any problems with the valve are detected before the next storm event occurs.

Results and Discussion

The Ireland-Miami CSONet was completed in the summer of 2005 and provided local control of the basin based on in-line conditions in the CSO service area. The total cost of CSONet, including the new valve and its installation, was approximately 55% less (US$26,000 compared to US$58,000) than the estimated cost of replacing and automating the valve at the basin using a conventional PLC. The long term cost of CSONet vs. more conventional technology cannot be determined at this time because the network has not been in place long enough to determine this. It is predicted that the CSONet maintenance cost will be only slightly higher than that of PLC's.

Since its deployment, CSONet has functioned during several storm events. Each time, water was stored and discharged at the appropriate time in a controlled manner. Figure 5 demonstrates how CSONet functioned during a typical storm on September 22, 2005. During the September 22, 2005 storm event, 500,000 gallons of water was stored in the basin, the maximum volume that could be retained for this storm event. However, the difference between the CSONet-controlled system and a passively controlled system was most clearly demonstrated during a November 1, 2005 storm. During this event, 0.79 inches of rain fell over a 9.5 h period. The depth in the basin reached 4.53 ft (see Figure 6), with 1.59 million gallons of water being stored by CSONet, with essentially no outflow during the storm. Once the threat of a CSO event passed, the water was released into the CSS. The same storm was simulated using a computer model of the basin without CSONet, where the basin outflow was controlled by the size of the outlet pipe. The depth in that basin only reached 2.52 ft, for a total storage of 758,000 gallons. This means that while a CSO event was occurring downstream, the basin discharged 836,000 gallons of stormwater runoff into the CSS. CSONet increased the storage ability of the basin during the storm by an additional 110% or 836,000 gallons. The CSO outfall started overflowing 2.5 h into the storm, and any water that entered the CSS after this time would cause the same volume of combined wastewater to overflow. This means the release of the 836,000 gallons of stormwater into the CSS due to passive control resulted in the overflow of 808,000 gallons of combined wastewater in the St. Joseph River. CSONet prevented this release. The City of South Bend estimates long-term storage potential is worth approximately US$3/gallon. CSONet's improved storage capacity for the basin clearly provides substantial cost savings.

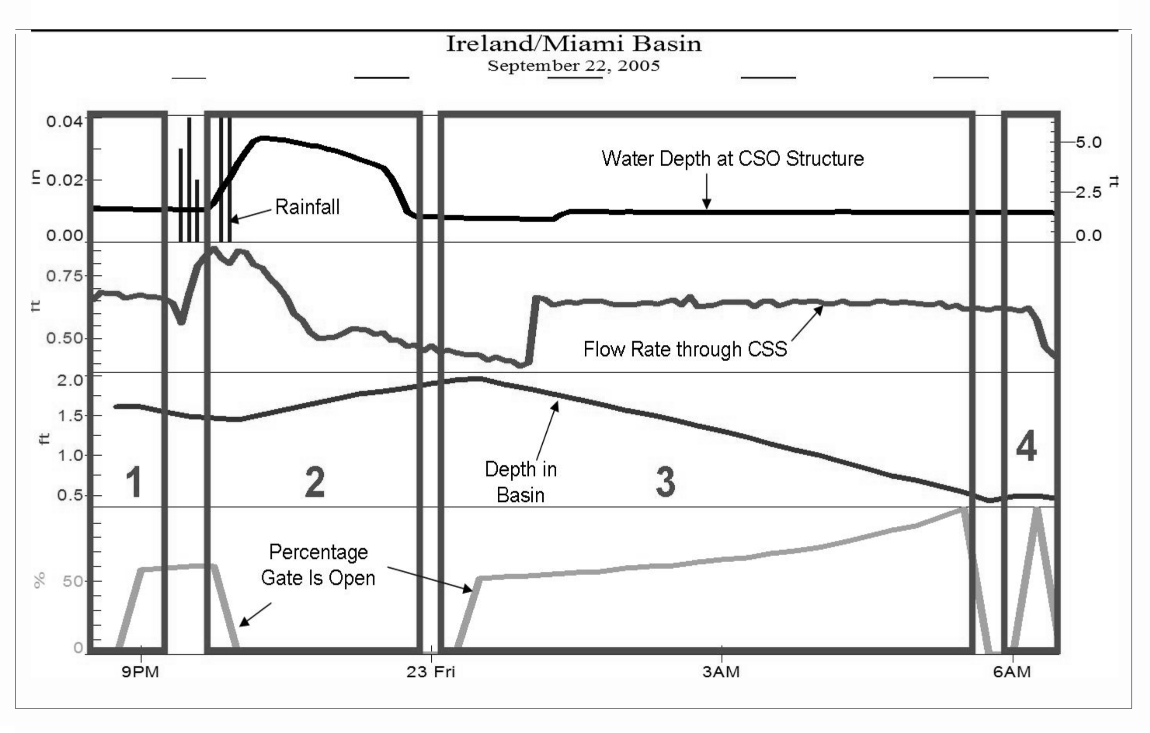


Figure 5. Results from a typical storm event in the CSO 22 service area. Following a small storm, the outfall Inode signaled that the outfall flow depth was below 30 inches, and the Gnode opened the valve to discharge (Box 1). While the basin was emptying, another storm event began. It then proceeded to rain 0.16 inches in one hour, which was enough for a CSO event to occur. The outfall Inode signaled that the flow depth was above 40 inches, and the Gnode immediately closed the Smart Valve (Box 2). When the storm event ended, the flow depth soon returned to less than 30 inches. The Gnode once again began to release the stored water. As the water depth in the basin decreased, the valve opened further to ensure a constant discharge rate. During the discharge, flow in the CSS increased by 2 cfs, the water depth in the basin decreased constantly, and the outfall flow depth increased by 0.6 ft. Once the basin returned to its dry weather depth, the Gnode closed the valve (Box 3). After a few minutes, the Gnode performed its daily task of completely opening and closing the valve to release any dry weather flow that accumulated during the day and to test the Smart Valve (Box 4).

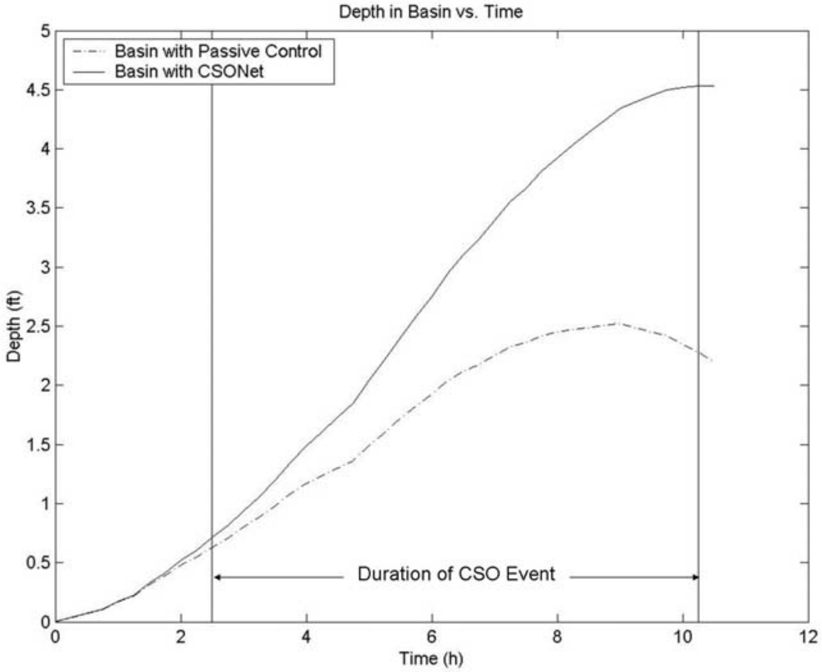


Figure 6. Comparison of basin depth vs. time for a CSONet controlled basin and passively controlled basin.

CSONet allowed for optimal storage to be achieved, regardless of storm size, storm duration, or storm frequency. South Bend, like many CSO communities receives many, small storms each year, often resulting in CSO events. Passive control systems (such as using pipe capacity or weirs) do not result in effective storage during these storm events. Instead, a more active approach is necessary for the optimal storage of stormwater runoff and combined wastewater. CSONet provides this active control in a cost-effective, efficient, and robust manner.

The next step in this project is to create a CSONet that controls in-line storage within a sewerline. This will require precise control because the risk of backup flooding is much higher than with the above-ground basins. A second Smart Valve will be installed in this CSONet in series. With this arrangement, a decentralized distributed control scheme will be implemented and tested. For this control scheme, a software optimization package such as Expert System (Nielsen et al. 1993) or Neural Net (Cohen et al. 2003) may be implemented to determine the proper Smart Valve setpoints. Programs such as these are "learning" programs, meaning that they use data from each prior storm event to better optimize the whole system. The eventual goal is for South Bend's entire CSS to be controlled by CSONet, to include the integration of the WWTP. This system will allow the WWTP to run at full capacity during wet weather events while CSONet determines how much stored water to empty without exceeding the WWTP's capacity.

CSONet is currently a reactive system, responding to changing conditions in the CSS; however, its ability to store water could be enhanced to make it a predictive system. Several authors have noted that the integration of rain forecasting into the control scheme can improve a network's storage capacity by up to 50%, as compared to locally controlled networks (Pfister and Cassar 1998, Harremoës and Rauch 1999, Sugita et al. 2001, Duchesne et al. 2004, Marinaki and Papageorgiou 2004). With the predictive rainfall data, the network knows where the rain will fall and how much to expect. By integrating rain gauges into CSONet, the lag time between when the storm event begins and when CSONet can respond can be reduced or eliminated.

Summaries

This project examined the ability of CSONet to reduce the frequency and severity of CSO events by improving the storage potential within a CSS. CSONet provided real-time control by gathering data about the current conditions in the CSS from a distributed network of sensors and controlling the upgradient storage with Smart Valves. This network is novel because it is capable of decentralized, distributed, robust, real-time control of a CSS at minimal cost. The first pilot CSONet was deployed during the summer of 2005 and automated a large retention basin in South Bend, IN. The Gnode used level readings from within the basin and the CSO outfall to maximize the basin's storage capacity, reducing the volume of combined wastewater that discharges into the St. Joseph River. Before CSONet was installed, the basin had only minimal storage capacity during small and medium storm events. Because of CSONet, the basin now retains all of the wet weather inflow without any risk of flooding. The stored water is only released when there is no threat of the additional flow causing a CSO event. The network accomplished this task while costing 55% less than the more conventional PLC controlled scheme. Work is currently underway to integrate in-line storage and multiple Smart Valves in series into CSONet. As CSONet expands, it will prevent more and more wastewater from entering the environment and save the City of South Bend millions of dollars in infrastructure improvements.

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