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The Use of Smart Wireless Technology for the Effective Management of Combined Sewer Overflows in Richmond, Virginia

Trevor Smith
Old Dominion University
Norfolk, Virginia

Junyong Ahn, Ph.D.
Florida Institute of Technology
Melbourne, Florida

Younghan Jung, Ph.D., LEED AP BD+C
Old Dominion University
Norfolk, Virginia

Due to Environmental Protection Agency (EPA) regulations, over 750 cities with combined sewers, including Richmond, Virginia, have had to present Long-term Control Plans (LTCP) and consent to lowering combined sewer overflows (CSO) to safe levels. Storm Water Management Modeling (SWMM) software is used to determine which measures to take in controlling combined sewer overflows. Many cities use a combination of sewer separation, green infrastructure improvements, and grey infrastructure improvements in their plan. Richmond, Virginia and South Bend, Indiana have had very similar problems including average rainfall, average overflows, and treatment plant capacity. South Bend is taking a more modern approach using inexpensive wireless sensor technology to enhance modeling efforts, increase capacity in the existing structures, and better prepare for storm events. Richmond is focused on traditional methods using mostly grey and green infrastructure improvements, along with monitoring and modeling. Research suggests that by combining current efforts with wireless sensor technology, Richmond can better meet its LTCP goals to prevent CSOs by inexpensively enhancing monitoring, dynamically controlling stormwater flow, and making more informed decisions on infrastructure improvements.

Keywords: Combined Sewer Overflow (CSO), Long-Term Control Plan, Wireless Sensor Technology, Stormwater Management, Storm Water Management Modeling (SWMM)

Introduction

Richmond, Virginia has used many methods to control combined sewer overflows (CSOs) as part of their Long-Term Control Plan (LTCP) to fulfill a commitment to the Environmental Protection Agency (EPA) to lessen the amount of wastewater that ends up in rivers and streams. The conventional methods accepted by the EPA are separation, green infrastructure, and grey infrastructure. New research along with the declining costs in wireless sensor technology has allowed for a fourth solution using wireless flow and level sensors to monitor and manipulate stormwater flow. The benefits and shortcomings of each method are shown using information gained from EPA reports and local public works sources. Much of this data including annual overflow and effectiveness of systems were obtained by the cities' use of EPA's Storm Water Management Modeling (SWMM) software. The objective of this research is to use available SWMM data to determine the best path forward for Richmond, VA using current methods along with the use of wireless sensor technology.

Combined sewer systems were designed over 150 years ago to convey wastewater and stormwater directly into waterways. Figure 1 shows a typical combined sewer system compared to a separate sewer system. These systems have since been augmented to direct these flows to a Wastewater Treatment Plant (WWTP). Due to blockages or high stormwater flow wastewater is oftentimes still directed to the original body of water. This is called a combined sewer overflow or CSO. CSOs have hazardous consequences to surface waters, both health related and economic. This causes high levels of E. Coli bacteria which can lead to harmful algal blooms and between 3500 – 5500 gastrointestinal illnesses per year (EPA, 2004). This can also have high economic impacts when recreational areas have to be shut down or avoided. This problem is wide-ranging. Over 850 billion gallons of CSOs happen annually from over 750 cities with combined sewers (EPA, 2012a). Due to the extreme costs of preventing these overflows, many cities did not confront these problems until the late 20th century. In 1994, brought on by violations of the

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Clean Water Act, the Environmental Protection Agency issued the CSO Control Policy. Through the use of the National Pollutant Discharge Elimination System (NPDES) permitting program, cities were mandated to immediately reduce and plan to eliminate CSOs or face major fines. As a result, cities had to present a Long-Term Control Plan (LTCP) for prevention of CSOs.

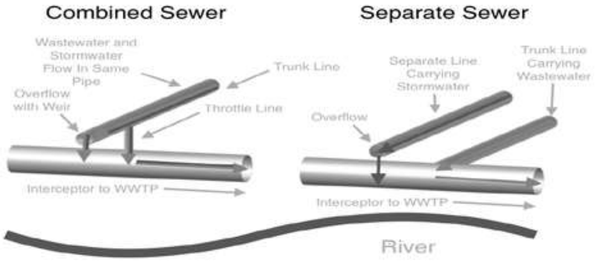

Figure 1: Typical Combined Sewer System Compared to a Separate Sewer System

Current Methods

A city's CSO prevention goal is to successfully divert most of the stormwater and wastewater to the WWTP during the highest points of wastewater daily use cycles and annual stormwater cycles. In an effort to understand these complex systems, cities use standardized modeling systems such as SWMM to understand how much stormwater and wastewater are coming into the system. These models allow the city to ascertain how much water can be treated versus how much water will overflow. SWMM uses geographical and sewer system data to determine the effects that storm events will have or have had on the system. SWMM data suggests that the solution to preventing CSOs is creating or allowing for more capacity within the system or lowering the flow of stormwater that enters the system. SWMM has allowed for the research of three major categories for controlling CSOs, total separation of the wastewater system, green infrastructure, and grey infrastructure. Figure 2 shows a graph developed by the EPA using various SWMM data to show how various combinations of increased grey infrastructure storage capacity and green methods impact CSOs. (EPA, 2014b). From the results of Figure 2, the city might determine that adding 1.6 million gallons in underground storage along with a robust green infrastructure plan is a more cost effective than simply adding 3 million gallons of underground storage with the same results.

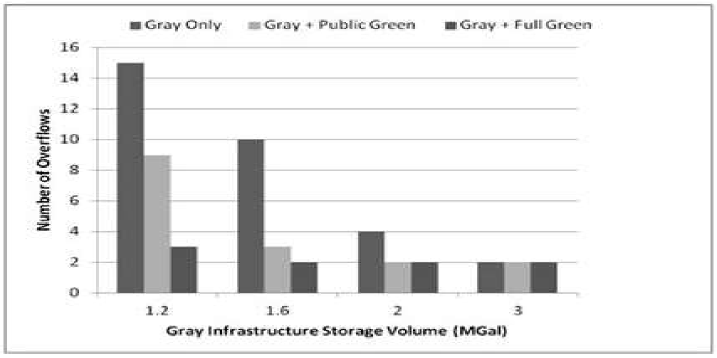

Figure 2: SWMM data of CSOs with Feasibility (EPA, 2014b)

The method used for total prevention of CSOs is complete separation of the sewer system. This is the method Grand Rapids eventually used to solve their CSO problem. Grand Rapids with a population of just under 200,000 (US Census Bureau, 2015), finished converting its combined sewers to separate sewers in 2015. They went from spending $2.7 million a year on wastewater treatment in 1991 to $1.9 million a year in 2015 (Grand Rapids DPW, 2018). They have lowered CSOs from 12 billion gallons in the 1970s to zero CSO events from 2014. The separation started in 1991 and cost the city $400 million (Grand Rapids DPW, 2018). The greatest hurdle for separation is the financial means to construct such a system with limited financial sources. Many of the over 700 cites effected by CSOs have populations of less than 10,000 people (EPA, 2004). For these small cities and cities like Detroit with larger populations and decreasing budgets, the costs associated with separation projects are overwhelming and unfeasible.

According to the EPA, green methods which can be an inexpensive solution should be included in any CSO reduction plan. Drainage of stormwater is achieved through pervious roads and parking lots, creating green spaces, rain gardens, and bio swales. Retention can be achieved with green roofs, retention ponds, flood plains, and planter trenches. Municipalities using this method often make a call to action in their communities to enact green methods around homes and businesses. They also typically incentivize businesses to use green site plans by creating award programs, lowering permitting fees, taxes, and stormwater fees, and offering grants (EPA, 2012). Green infrastructure comes with the added value of improving communities by adding green space and beautifying public areas, which is not the case for most grey infrastructure improvements. These low costs and added benefits are the reason the city of Philadelphia is focusing 70 percent of its LTCP efforts to curtail CSOs with a 1.7-billion-dollar green infrastructure initiative including all of these methods (Philadelphia PWD, 2011). SWMM data suggests a limiting control of CSOs and that green infrastructure cannot be the only method used (EPA 2014). In most cities, green infrastructure is a secondary or tertiary part of the LTCP.

Grey infrastructure improvements are often the preferred method. The objective of grey infrastructure is to create more storage in the system on the way to the WWTP or to increase the capacity of the treatment plant. Due to the age of combined sewer systems, CSOs are exacerbated by cracked, damaged and improperly fitted pipes. The inflow of water at bad connections or infiltration into pipes through cracks can substantially add to flow during a storm event. Another concern with old pipes is the internal smoothness changes over time with scouring and scale buildup. These pipes can be replaced or lined with a smoother material that lessens the diameter but increases flow. Through the repairs and maintenance of deteriorated pipes, the capacity of the sewer system can be improved. Further capacity can be gained by increasing the sizes of pipes, especially the interceptors that run perpendicular to CSO outfalls. Adding capacity can also be achieved by adding retention basins or underground storage. One example is the highly ambitious $3.8 billion Tunnel and Reservoir Plan (TARP) project in Chicago now in its second phase. As of today, huge underground tunnels have added 2.3 billion gallons of extra capacity in the system. This has lowered the days that CSOs occur in a year from 100 days to 50 days. In the second phase, three reservoirs are being built that can hold over 18 billion gallons of waste water before treatment in hopes of bringing CSOs close to net zero (Landis, 2017). Many cities are adding similar elements on a smaller scale. SWMM data has shown that grey infrastructure can be a stand-alone method or work in conjunction with green infrastructure (EPA, 2014a).

Smart Control

An emerging control method may be able to control CSOs as situations change within the system. Wireless enabled sensors that control strategically placed weirs, gates, pumps, and valves may be able to move wastewater around the system to make the most use out of the available capacity. During a storm event only a part or parts of the system are overwhelmed, so only a number of outfalls have CSOs. This shows that the areas where no overflow is occurring have the capacity to spare. This technology attempts to solve the problem by moving the flow from pipes reaching capacity by increasing the flow in other pipes. This technology may help to streamline combined sewer systems and allow for more advanced real-time monitoring.

The technology consists of sensors that collect and relay information, repeaters that fill distant gaps across the grid, and gateways that share information to a database and process information. The wireless sensors are designed to be placed under manholes. The sensors are made up of a mote, a tiny, low cost computer about the size of a quarter, a time keeping chip, an 8-megabyte storage chip, a battery pack, a radio with an inverted antenna, and up to four sensor probes. The two probes measure water level and flow rate. The repeaters are similar to the sensors but are hard wired and contain no sensor probes. The gateways are wired and sit above street level. They contain a small Linux based computer, a cellular modem, 900 MHz radio, and an interface to control parts of the sewer. The gateway uses a Cloud Based Network to transmit all information to a control center where it can be monitored by public works. The information is also shared between the gateways and is used to control the actuators to best use the capacity in the system. The wired actuators operate the weirs, gates, pumps, and valves. The gateways operate under multiple control algorithms. One control uses a switching algorithm that opens and closes a valve as capacity is reached. Another algorithm allows sensors to begin to compute for capacity in which the pipes with the lowest capacity are able to collect more wastewater. If one or more pipes have more flow capacity, valves will be activated to shut which allows time for fuller pipes to drain while others fill close to capacity. With another algorithm using weather forecasting schemes, the amount of runoff that will need to be collected is anticipated, and the system makes room early on in the process (Montestruque, 2015).

Case Study of South Bend, Indiana

South Bend, Indiana currently has 36 outfalls and treats 48 to 77 million gallons a day (City of South Bend DPW, 2017). South Bend has an average yearly rainfall of 38 inches (US Climate Data, 2017). In the years between 1990 and 2004, South Bend had an average of 2 billion gallons of CSOs and spent $87 million on CSO infrastructure. In 2004 South Bend submitted its LTCP to the EPA which included a plan to separate a few CSO outfalls, make updates to the WWTP, and add nine underground storage tanks throughout the city. In 2008 the city began the CSOnet project and with early success revised their long-term control plan to include the CSOnet project. CSOnet is a real time decision support system that empowers the City of South Bend with understanding, control, and optimization of its sewer system. CSOnet minimizes sewer overflows to the river and maximizes the capacity of the existing infrastructure (New Deal, n.d.). Phase I of South Bend's LTCP was finished in 2017 that included separating a number of sewers, adding throttle valves between a number of outfalls, and integrating 150 sensors and 12 actuators that control nine pumps and three weirs (Montestruque, 2015). Phase I costs exceeded $150 million, but the CSOnet improvements cost only $6 million.

The city has benefited from CSOnet in three major ways, through real time monitoring of the combined sewer systems network, through optimizing water flow in CSO outfalls, and preemptively dumping clean storage basins and retention bodies before a high stormwater event. Data is collected from the 150 sensors, is sent to the 17 gateways, and then sent to a database using cloud-based technology where the data is collected and shared in real time. Using IBM's Intelligent Operations Center software along with Supervisory Control and Data Acquisition (SCADA) information and the city's geographic information system (GIS) an interface can be created in which public works can view the network of pipes in real time. In the geospatial representation, the public works department can view current pipe levels, retention basin levels, storage capacity left in basins, and CSOs as they are occurring.

Many improvements can be made from these observations. Many dry weather CSOs and backups arise as a result of blockages in a pipe. Blockages can occur due to invasive tree roots or buildup of debris. Dry CSOs can be very costly as they are considered unpermitted and carry big fines. Backup and damage to personal property can also cost a city millions of dollars each year. Overtime data that is collected can help create an understanding of expected flow from all the pipes at normal and peak times. If a pipe exceeds normal levels, workers can go out and clear the blockage. This can create a system of preventative maintenance rather than fixing pipes after overflows and backups occur. The ability to do this helped South Bend go from an average of 27 to 0 dry CSOs in the first year of operation (Kerkez, 2016). Another key advantage is controlling inflow and infiltration (I/I). I/I can be determined by higher than normal flow during a storm event. The last advantage is the data can be used in SWMM or similar modeling software to further understand the system and deficiencies in capacity. This can help the city effectively make decisions on where to invest in expensive grey infrastructure.

South Bend uses the network of sensors to try to stop CSOs at outfalls along the St. Joseph River. At these outfalls, a weir blocks the wastewater from entering the river. Wastewater is then diverted into a throttle line that is connected to an interceptor that heads to the wastewater treatment plant. During medium sized rainfalls it was noticed that some outfalls were overflowing, and others were not. This meant that the interceptor had not reached its full capacity. If the flow of stormwater could be stopped at the trunk lines of non-overflowing outfalls, it would create more volume in the interceptor allowing overflowing trunk lines to drain faster. Based on this premise valves were added to each throttle line between the trunk line and the interceptor and controlled with a competing algorithm that allows them to open and close. During a storm event, the trunk lines reaching full capacity are allowed to drain into the interceptor through the open throttle valves controlled by CSOnet. The other throttle valves would stay closed until each trunk line reached a set parameter for the valve to open and "compete" for usage of the interceptor. Figure 3 shows how the algorithm would operate during a storm event.

Figure 3: The Competing Algorithm in Action

The last major benefit from CSOnet is creating storage for stormwater before a storm event happens. With weather prediction algorithms, a high stormwater flow event can be anticipated. This can trigger CSOnet to dynamically activate pumps to drain retention basins into the river before the storm occurs. By allowing more space for stormwater to go, less stormwater gets into the sewer system.

Since the implementation of CSOnet in 2008 along with the other Phase I CSO infrastructure improvements, CSOs have dropped from 2.1 billion gallons in 2008 to 458 million gallons in 2014. SWMM data suggests that CSOnet was responsible for preventing 25 percent of all the overflows or 312 million gallons (Montestruque, 2015).

Case Study of Richmond, Virginia

Richmond, Virginia has faced huge challenges with combined overflows. Richmond is a city with a population of over 220,000 and an area of 62.5 square miles (US Census Bureau, 2015). Richmond gets an average of 44 inches of rain a year (US Climate Data, 2017). Richmond has 26 CSO outfalls that until the 1990s contributed to over 3 billion gallons of CSOs per year in the James River (EPA, 2001). Richmond has spent over $242 million on CSO infrastructure and has needs of $500 million more (ASCE, 2015). Richmond has implemented green infrastructure, grey infrastructure, and separation of pipes in efforts to control CSOs. In Richmond's LTCP, the prioritized controls have been to invest in grey infrastructure to add more storage and more treatment capacity, to continue to monitor water quality and CSO events, and to continue adding green infrastructure to affected areas (EPA, 2001).

According to Richmond's 2017: RVA Clean Water Plan, grey and green infrastructure and monitoring and modeling have led to many successes. In 1983 the city completed the 44-million-gallon retention basin, named the Shockoe Basin. This large basin is connected to the main combined sewer line, and water can be diverted by weirs to the basin just before the WWTP. Two 7 feet diameter interceptor pipes were added to connect a number of CSO outfalls to the Shockoe basin and WWTP. This has contributed to minimal overflow at 10 CSO outfalls. The other major storage improvement implementation was adding an underground storage tunnel deep within an underlying granite layer. The Hampton-McCloy Tunnel, at the cost of $50 M, stores 7 million gallons. It has helped significantly lower CSOs in 3 outfalls near an important recreational area. The WWTP has been increased to treat 45 million dry flow gallons per day or 75 million gallons of storm flow per day (Richmond DPU 2017a).

Richmond has placed an importance on monitoring and modeling of the sewer and stormwater systems. These methods include mapping the CSO areas, reviewing documents to show pipe lengths, material, and diameter, taking water samples, and monitoring CSO flow. The green infrastructure methods Richmond has used include creating flood zones, adding green space, tree boxes, supplying rain barrels, clearly marking drains that are part of the combined sewer, and public outreach (Richmond, DPU 2017b). Richmond's CSO improvements have lowered CSOs from 3 billion gallons a year to an average of 1.67 billion gallons a year, a 44% drop (ASCE, 2015)

In the LTCP plan to the EPA, Richmond mapped out a three-phase plan. As of today, phases I and II are complete including the Shockoe Basin and the Hampton-McCloy tunnel. In phase III many implementations are planned. The CSO infrastructure improvement plan includes increasing wet weather treatment capacity to 300 million gallons per day, disconnecting two outfalls, increasing the interceptor line in the lower Gillies Area, replacement of a regulator and adding a million gallons of storage at a problematic outfall, adding 15 million gallons of storage to the Shockoe basin, and chlorine disinfection at another problematic outfall. Phase III green infrastructure plans include creating 18 acres of impervious surfaces. This can be done by improving 6 acres of public utility property, 2 acres of city owned vacant properties, 2 acres of public parks, and adding 24 tree boxes in the Combined Sewer System area (Richmond, DPU 2017a). Data collected from SWMM shows a ten-million-gallon annual drop in CSOs from all the green infrastructure implementations and a drop from 1.67 billion gallons to 228 million gallons from the grey infrastructure improvements. That is a total estimated drop of 86% (ASCE, 2015).

Cost Comparison of Methods

SWMM data can show how many gallons of CSOs can be prevented using the different methods. By dividing these numbers from estimated costs, a cost per million gallons of annual CSOs can be ascertained. Table 1 shows a substantially lower cost for South Bend's wireless Sensor method compared to Richmond's grey and green methods and Grand Rapid's total separation.

Table 1: A Comparison of the costs associated with different control methods based on SWMM

City	CSO Control Method	Cost	Drop in CSOs	Cost Per Million-Gallon Annual Drop in CSOs
Richmond, VA	Phase III - Grey Infrastructure	$375 M	1.44 billion gallons	$260,000
Richmond, VA	Phase III - Green Infrastructure	$2.6 M	10 million gallons	$260,000
Grand Rapids, MI	Sewer Improvement Project - Total Separation	$400 M	629 million gallons	$636,000
South Bend, IN	CSOnet - Wireless Sensor Technology and Throttle Line	$6 M	312 million gallons	$19,200

Benefit of Using Wireless Technology in Richmond, VA

Richmond's combined sewer overflows prevention strategies attempt to control the maelstrom of people's activities, rain events, snow melts, inflow and infiltration, pipe blockages, flooding, river flows, and changing climates. After hundreds of million dollars are spent on green infrastructure, sewer maintenance, and repairs, updating treatment facilities, and adding massive underground storage tanks the city is left with a static solution. This is a system in which all the components are set in place to control dynamic forces. On most days the system works, but on many days millions of gallons of CSOs occur. Richmond's CSOs only happen an average of 53 days a year to add up to 1.67 billion gallons (Richmond DPU 2017). Designers of the static system have to overcompensate to allow the system to handle the higher peaks of the SWMM hydrographs. An example is shown in a cost versus benefit study to determine the value of increasing the interceptor size in Richmond's Gillies Creek area. It was determined through SWMM that it would cost $300 million for storage that would only be at full capacity once every five years based on 5-year storm models (City of Richmond 2010). Preparedness for a five-year storm is not even in the scope of an EPA control policy. At this level of grey infrastructure costs go up exponentially for small percentage gains. In static systems, 100 percent control is almost impossible to achieve. Richmond's LTCP only plans for a 92% reduction in CSOs (Richmond DPU, 2017a).

Richmond can benefit from wireless sensors by integrating them into their LTCP. A flagship of Richmond's effort to control CSOs has been monitoring, data collection, and modeling. These goals can be better achieved with real time monitoring using Richmond's existing SCADA and GIS capabilities along with this technology. Monitoring can help decrease I/I, blockages, and dry weather CSOs. Crucial capacity can be added by streamlining the system and making sure stormwater is only entering through drains. Data collection may help the city gain insight on which pipes should be lined or replaced. Richmond has many CSO locations that can improve from controlling flow and creating more capacity. Wireless sensors along with pumps could redirect flow from deficient CSO outfalls to the nearby two, 7 feet diameter interceptors. The majority of CSOs are occurring at the outfalls that drain to smaller interceptors. These areas can improve with the addition of actuated valves and an added throttle line similar to South

Bend. Using data from SWMM of CSOs from Richmond's CSO Monthly Reports between July 2017 to June 2018, it can be shown that Richmond has a similar situation to South Bend in which CSOs are happening at some trunk line outfalls sharing an interceptor, but not at others. This can be seen in figure 4. Only the outfall "CSO40" at the end of the interceptor has CSOs during rainfalls of less than 2 inches. It is also possible that controlling flow in Gillies Creek area can help Richmond lower the cost of the $300 interceptor as part of Phase III of the LTCP.

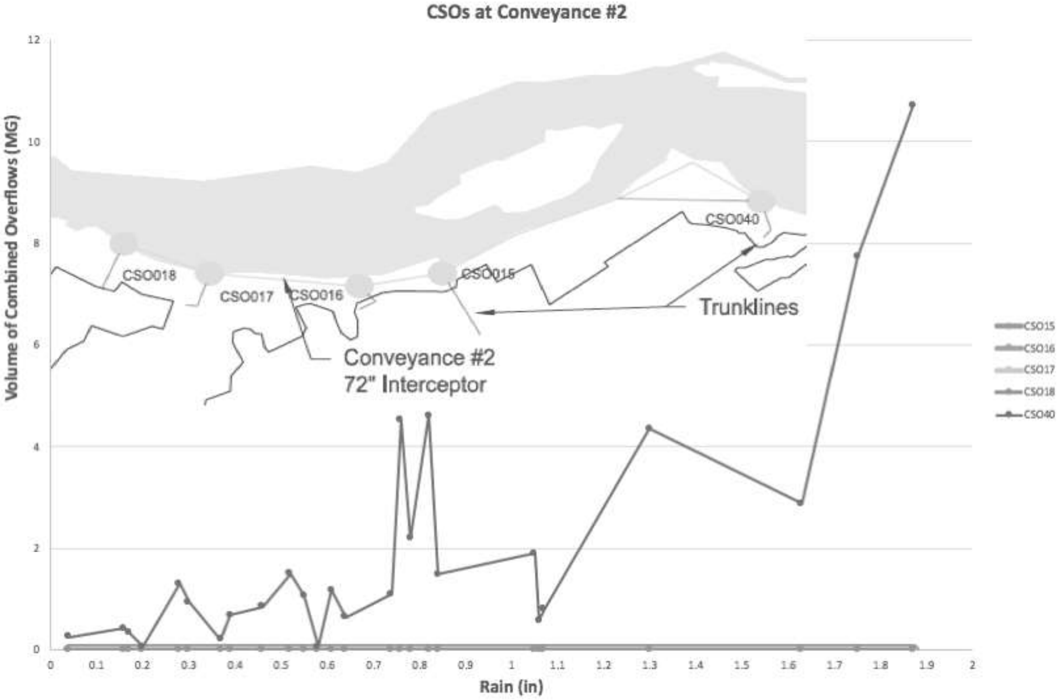

Figure 4: Overflow Activity at an Interceptor called Conveyance Number 2, Shown as the Line that Connects the Circles Representing the 5 Outfalls

Conclusion

Many cities are meeting the EPA's CSO control requirements in various ways and striving to lower CSOs to an acceptable level. Separation has shown to be the most successful method of controlling CSOs, but due to cost constraints, it is not a feasible option for many cities. Most cities have to control CSOs by adding to or manipulating the current infrastructure. Current methods have depended highly on SWMM by using a baseline stormwater flow to predict a change in CSOs. This informs the city on how and where implementations should be made. The result is a static system that can support stormwater and wastewater flow in higher peak flow events. Heavily implementing grey infrastructure along with green infrastructure has shown a moderate success. With these methods, costs increase significantly as larger percentage gains are desired. Using wireless technology, cities can combat these complex and chaotic systems with a more dynamic solution. The ability to monitor in real time can allow for seamless data collection and the creation of more accurate models. These models lead to more informed decisions on future projects. Real-time modeling has been very effective in stopping illegal dry CSOs and quickly identifying deficiencies in the system. Wireless sensor technology has stopped CSOs using current infrastructure at a fraction of the cost of the other methods. South Bend has shown that this technology could be an inexpensive and valuable tool for controlling CSOs, but it is not an effective control on its own. The best achievements in CSO reduction can be made by integrating wireless technology with other control methods. Richmond is a similar city that could benefit from this technology. They have a lot of potential shared capacity in their current infrastructure and have a strong commitment and foundation for continued data collection. They can harness the power of real time monitoring to produce better models and make more sophisticated decisions on how to proceed with grey and green infrastructure improvements. Richmond has made a good faith effort to control CSOs and are almost halfway to their goal. As Richmond continues Phase III of the LTCP, SWMM data suggests that CSOs can be better controlled using wireless sensor technology.

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