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Smarter Stormwater Systems

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ABSTRACT: Existing stormwater systems require significant investments to meet challenges imposed by climate change, rapid urbanization, and evolving regulations. There is an unprecedented opportunity to improve urban water quality by equipping stormwater systems with low-cost sensors and controllers. This will transform their operation from static to adaptive, permitting them to be instantly "redesigned" to respond to individual storms and evolving land uses.

■ INTRODUCTION

The design of stormwater and sewer systems is based on historical observations of precipitation and land use. These systems require significant investments to meet challenges imposed by rapid urbanization, evolving regulations and an uncertain climate. As a result, runoff from urban environments is threatening environmental health by lowering the quality of receiving waters, including fisheries, recreational sites and sources of drinking water. There is an unprecedented opportunity, however, to improve urban water flow and quality by equipping existing stormwater systems with low-cost sensors and controllers. This will enable a new generation of *intelligent* green and gray stormwater networks, which will adapt their operation to maximize water quality benefits in response to individual storm events and changing landscapes.

■ STATIC SOLUTIONS TO A DYNAMIC PROBLEM

The vast majority of the world's population resides in or near urban centers, underscoring the need to sustainably manage anthropogenic environmental impacts. Urbanization and land development are disruptive to the hydrologic cycle since they result in an altered, more impervious landscape, which promotes increased runoff at the expense of infiltration and evapotranspiration.[1,2] While most cities maintain a dedicated stormwater infrastructure, ecosystems near many postindustrial cities in the U.S. are adversely impacted by exfiltration and overflows from combined sewers.[3−5] These overflows have increased due to leaks in aging infrastructure and shrinking municipal budgets.

The increase in the volume, velocity and contaminants in stormwater runoff has caused a crisis in receiving water bodies.[6−9] Harmful algal blooms, associated with anthropogenic inputs of nutrients, have resulted in unsafe drinking water, impaired fisheries and damage to recreational waters.[10−14] As such, managing pollutant loadings from urban stormwater has become one of our most pressing environmental challenges.[15,16]

Expansion and upsizing of *gray* infrastructure are perhaps the most common solutions to coping with increased runoff resulting from changing weather and land use.[17] Aggressive climate adaptation via traditional tools may lead to overdesigned gray infrastructure, which conveys water too quickly to streams, leading to floodplain encroachment, increases in runoff volumes, and stream erosion. To preserve stream stability and ecological function, advances in stormwater science are calling for traditional peak attenuation designs to be replaced with those that reduce stream erosion during smaller, more frequent storms.[18] As communities seek more

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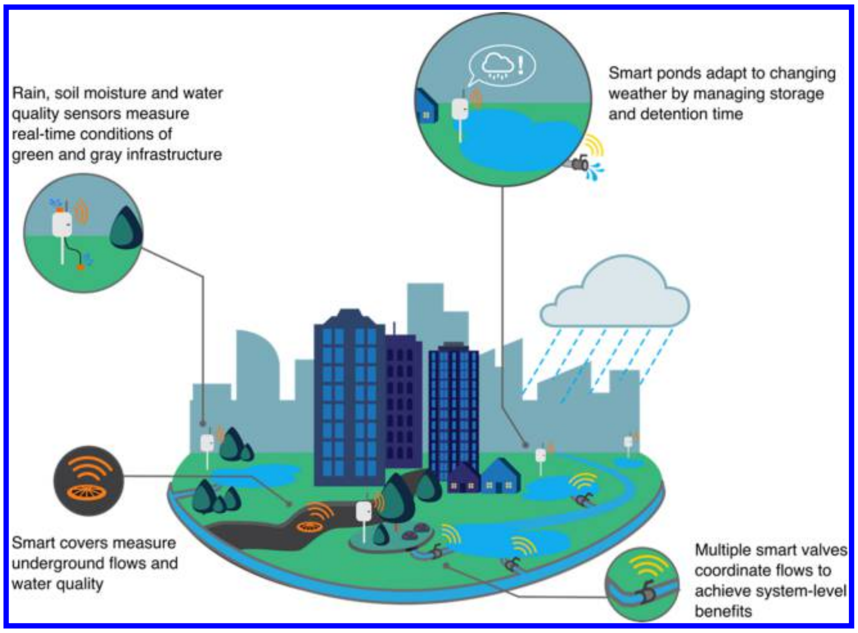

Figure 1. System-level stormwater measurement and control.

resilient and adaptive stormwater solutions, novel and non-traditional alternatives to new construction must be considered.

One such alternative is provided by *green infrastructure (GI)*, which augments impervious urban areas with pervious solutions such as bioswales, green roofs and rain gardens.[19−21] GI is designed to restore some ecosystem functions to preurbanization levels by capturing runoff and contaminants before they enter the stormwater system. These solutions have experienced a significant rise in popularity due to their promise to offer a low impact alternative toward buffering flows and improving runoff water quality.[22] Much research remains to be conducted, however, to test the efficacy and scalability of GI as an alternative to gray infrastructure. To that end, more cost-effective sensing solutions are required to assess the in situ performance and improve the maintenance of GI.[23,24]

While stormwater systems do change (albeit slowly), their design performance is often regarded as static due to limited ability to adapt to changing climate and land uses. More importantly, stormwater solutions are engineered on a site-by-site basis, with little consideration given to ensuring that local benefits are actually adding up to achieve a collective outcome.[25] Rather than offering an alternative, a new solution promises to augment, rather than replace, green and gray infrastructure. This approach relies heavily on sensor and information technology to make existing stormwater systems more adaptive by embedding them with connectivity and *intelligence*.

■ REAL-TIME ADAPTIVE MANAGEMENT

The past decade has witnessed significant advances and reduction in the cost of novel sensors, wireless communications and data platforms. In large, much of this development has accompanied the recent boom on the *Internet of Things (IoT)*, a technological movement that promises to build the next generation of interconnected and *smart* buildings and cities.[26] The stormwater sector has been slow in its adoption of these technologies, especially in the context of high-resolution and real-time decision-making. Present uses of sensors range from regulatory compliance[27,28] to performance studies of individual stormwater facilities.[29] These technological advances have the potential to become highly transformative, however, by enabling stormwater infrastructure to evolve from static to highly adaptive (Figure 1). By coupling the flow of water with the flow of information, modern stormwater infrastructure will adapt itself in real-time to changing storms and land uses, while simultaneously providing a highly cost-effective solution for cities that are otherwise forced to spend billions on stormwater reconstruction.[30]

Given advances of modern sensors and data acquisition systems, it is now feasible to monitor green and gray infrastructure projects pre- and postconstruction to provide in situ performance metrics. This is afforded by a significant reduction in the cost of sensors and cloud-hosted real-time data systems. Many commercial and open-source platforms, specifically geared toward demands imposed by storm and sewer applications, are now available and promising to lower the cost of wireless sensor deployments. Water flow, stage, precipitation and soil-moisture can now be measured seamlessly and continuously. The development of robust and affordable in situ water quality sensors for nutrients, metals or bacteria is still evolving.

While new measurements will provide significant insight into the study and management of stormwater systems, it is the ability to directly and proactively control these systems that presents the biggest potential impact to water quality. Low-cost, reliable and secure actuators (e.g., valves, gates, pumps) can now be attached to existing stormwater systems to control the flow of water in pipes, ponds and green infrastructure. Examples include inflatable pillows that can be used to take advantage of underused inline storage,[31] or *smart* outlet structures that control water levels in response to real-time data and weather forecasts (Figure 2).

While real-time process control in water and wastewater treatment has been studied extensively and continues to be a fruitful area of research,[33] there is now the opportunity to distribute these treatment ideas to the watershed scale. This presents an exciting new paradigm: *retrofitting existing stormwater infrastructure through cost-effective sensors and actuators will*

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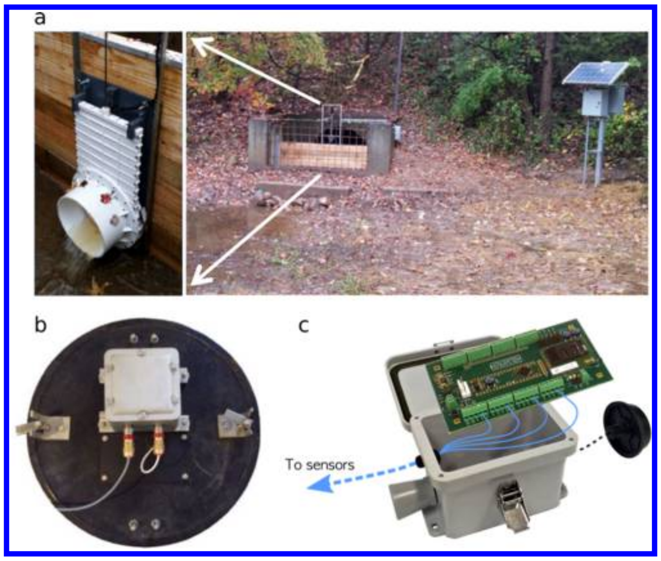

Figure 2. Example sensing and control devices (a) Remote valve for basin control, (b) smart sensing manhole cover, and (c) an open-source sensor node for distributed measurement and control.[32]

transform its operation from static to adaptive, permitting it to be instantly "redesigned" to respond to changing conditions. There is an inherent complexity associated with control of city-scale systems, however, as they are comprised of a variety of gray and green solutions and driven by complex storm patterns, hydrologic phenomena, and water quality dynamics. The number of studies addressing real-time water quality control is limited but promising, ranging from local- to city-scale control.

■ REAL-TIME CONTROL OF INDIVIDUAL STORMWATER FACILITIES

Many existing studies focus on the real-time control of stormwater basins and ponds, which are some of the most common elements in a stormwater system.[34−36] Pollutant removal in basins comprises a complex interaction between a number of mechanisms, including sedimentation, flotation, infiltration, biological conversion, and degradation.[37] Traditionally, these facilities are designed as compromises between flood control (detention) and water quality control (retention), with limited ability to adapt functionality to individual storm events. Retrofitting an existing site with a real-time control valve permits it to serve both as a detention and retention basin, as well as a spectrum of in-between configurations. One control rule, for example, opens a valve to drain a pond if a storm is forecasted, which creates additional storage for incoming runoff. Similarly, runoff can be strategically retained after a storm to improve settling and biological uptake. It has been shown, for example, that by temporarily converting a detention basin to a retention basin, the removal efficiency of total suspended solids (TSS) increased from 39% (189 120 g inflow vs 98 269 g outflow) to 90% (e.g., 59 807 g inflow vs 8055 g outflow) and ammonia-nitrogen increased from 10% (101.1 g inflow vs 79.2 g outflow) to nearly 90% (e.g., 163.5 g inflow vs 7.8 g outflow).[37,38] Using data from these studied, Mushalla et al.[39] simulated that retaining water using real-time controls may result in up to a 60% improvement in small particle removal compared to a traditional design.

Some studies are also beginning to show that real-time control can play a significant role in removing biological, metal and dissoved contaminants. A controlled basin in Pflugerville, Texas, achieved 6-fold reduction in nitrate plus nitrite-nitrogen compared to the same preretrofit dry basin (0.66 mg/L to 0.11 mg/L) by extending detention time and releasing water before a storm to create additional storage.[40] While biological uptake likely contributed to nitrogen removal, reliable and affordable in situ sensors for many dissolved pollutants are still needed to fully understand the impacts of control to dissoved pollutant removal in natural treatment systems.

Real-time control of a retrofitted detention pond showed that the removal of *Escherichia coli* was improved by strategically retaining water for 24 h after a storm rather than allowing the water to flow though the pond as originally designed.[41] For the controlled basin the outlet concentrations were an order of magnitude lower than inlet concentrations (1940 MPN/100 mL in vs 187 MPN/100 mL out; and 3410 MPN/100 mL in vs 768 MPN/100 mL out), whereas the uncontrolled basin showed limited removal and even increased *E. coli* at the outlet (4350 MPN/100 mL in vs 8860 MPN/100 mL out; 10800 MPN/100 mL in vs 11000 MPN/100 mL out). Since streambed concentrations of *E. coli* were three times higher than in the streamwater, the primary mechanisms for removal were attributed to sedimentation and increased exposure to sunlight. This example also speaks to the need to be cognizant of flow releases from controlled basins, as high outflows can resuspend pollutants. As such, real-time control can be used to modulate the flow rate from storage facilities to reduce downstream erosion and pollutant loads. Such strategies begin to place real-time control into a much broader systems context, whereby each individual stormwater facility not only generates local benefits, but can also be used to improve flow and water quality at the city-scale.

Flow modulation for stream protection was demonstrated at two pilot sites owned by Clean Water Services (CWS) in Washington County, Oregon. In one system (sized to retain 0.2 in. of rainfall), the addition of real-time control to an existing wet pond reduced the volume and duration of channel forming discharges by approximately 25%. In a second facility (a dry detention pond), the use of real-time control was used to minimize release rates in smaller, more frequent storm events while maintaining the ability to match predevelopment peak flows during larger storms. This enhancement was modeled to reduce the volume of erosive flows by nearly 60% and the volume of wet weather discharges by nearly 70% compared to a passive basin (Figure 3). Additionally, the use of real-time control increased the average residence time of this facility from 1 to 19 h. In a simulation case study real-time control reduced

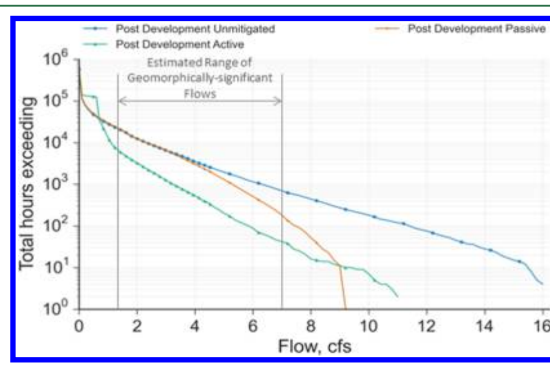

Figure 3. Improvement achieved by retrofitting an existing basin to reduce erosive flows.

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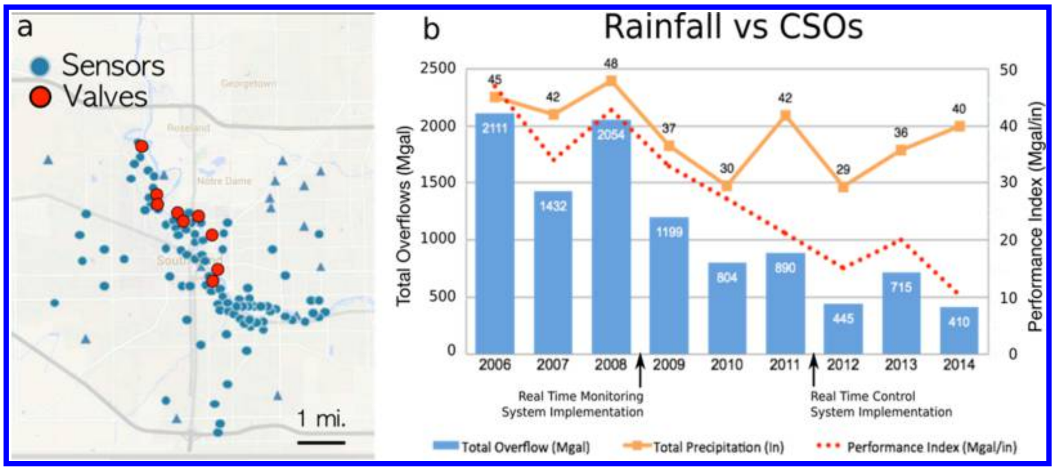

Figure 4. Comparison of combined sewer overflows (CSOs) before and after commissioning of real-time sensing and control system in South Bend, IN.

the required pond volume by 30–50%, compared to a passive facility, while achieving the same level of flow-duration control performance. Finally, based on whole lifecycle cost estimates, it was determined that a real-time control retrofit of an existing stormwater detention facility would be approximately three times lower in lifecycle cost than the equivalent passive alternative.[42]

■ SCALING UP

An insight into the scalability of real-time control is provided by a large-scale control network that is presently deployed in South Bend, Indiana.[43] The network encompasses 100 km^2 and is comprised of 120 real-time flow and water depth sensors (Figure 4), which share information every 5 min. The system has been retrofitted with control valves located at nine CSO regulators to modulate flow into the city's interceptor line. The control valves allow more water to enter the interceptor line when conveyance capacity is available, while avoiding surcharging the interceptor, which may cause surface flooding or structural damage. The system operates by taking advantage of excess conveyance capacity within the interceptor line, which is driven dynamically by spatial or temporal features of specific storms.

The distributed control strategy uses an agent-based control scheme to optimize the water collection system, whereby each infrastructure component trades its own storage or conveyance capacity to other upstream assets, similar to traders in a stock market.[44] Even before the system was controlled, benefits were achieved by means of monitoring alone. By isolating maintenance issues in its first year of operation (2008), the system helped the utility eliminate critical dry weather sewer overflows, which were occurring an average of 27 times per year. Overall, the control system reduced total sewer overflow volumes from 2100 MGal to 400 MGal from 2006–2014 (Figure 4). Even after adjusting for total annual rainfall, a near 5-fold performance improvement (ratio of overflows to precipitation) was achieved. While a reduction in *E. coli* concentrations (443 cfu/100 mL to 234 cfu/100 mL) in the downstream sewer locations was also observed, a more comprehensive ecological study is warranted to study the impacts of real-time control to *E. coli* removal mechanisms. It is estimated that over one billion gallons of untreated sewer flows were blocked from flowing into the river, suggesting that real-time control played a role in improving water quality.

■ KNOWLEDGE GAPS

Systems Thinking. While nascent, research on real-time stormwater control is not limited by technology, but rather by a much more fundamental need to understand the complex spatiotemporal dynamics that govern water flow and quality across large urban areas. One of the largest challenges with existing stormwater solutions relates to their design as single entities. This means that benefits achieved at a local scale may often be masked or eliminated at the city scale if the performance of an individual element is not designed in a broader systems context.[25,45] Perhaps the biggest benefit of control relates to the ability to leverage real-time interconnection to guide the behavior of individual elements to achieve city-scale benefits.

There is a need to build upon prior and ongoing research efforts on best management practices (BMPs)[20,29,46,47] to understand how individual green and gray stormwater solutions perform when stressed by varying climate, storms, and runoff dynamics. Many studies focus on hydrologic control and removal of solids and bacteria, but much work still remains to be done to determine the impacts of these solutions to the treatment of metals, nutrients and emerging contaminants. This will require the expanded development of cheap and reliable sensors for these pollutants. Furthermore, there is an urgent need to fill a knowledge and measurement gap on the interconnectedness of BMPs across various scales and runoff dynamics (e.g., first flush vs peak flow). By improving the understanding of stormwater networks as a function of scale, it will then be possible to posit how very large systems (ten to a hundred ponds, for example) should be controlled or tuned in real-time to achieve a collective outcome.

Uncertainty. The role of uncertainty is rarely acknowledged in the design of traditional stormwater systems, since it is assumed that many transient system behaviors will average out into a cumulative performance over time. The benefits of real-time control, however, are highly underpinned by uncertainties related to weather forecasts, models, control algorithms, and sensor measurements. Some elements of the system will always remain unmeasured or not understood. Furthermore, many control decisions will continue to be based on hydraulic parameters, such as flow or residence time. Until reliable and low-cost water quality sensors become available, water quality control decisions will rely on statistical correlations or physical

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models. It will be important to quantify the role of the resulting "error bars" on the performance of real-time control.

As with many controlled systems, there may be an inherent risk to infrastructure, private property, or even human life due to poorly designed control algorithms. Since risk relates directly to uncertainty, reliable and consistent real-time operations can only be achieved by exhaustively quantifying the role of uncertainty in control operations. Furthermore, even the best controllers and sensors may only achieve marginal benefits if storms cannot be predicted adequately, thus calling for the need to begin investigating the value of weather forecasts in control operations. Many other examples can be given, but studies exploring the role of uncertainty have yet to be conducted.

■ OUTLOOK AND BROADER ADOPTION

Real-time control promises to revolutionize the management of urban water quality by providing the ability to significantly improve the operation of existing stormwater assets. As the community of researchers grows, there will be a need to develop baseline performance metrics, study sites, measurement platforms, and data sets. Research on stormwater capture and direct use (reuse) has recently increased[48] due to the potential of reclaimed stormwater to serve arid regions. In drought-prone regions of the U.S., where stormwater direct use is becoming one of the few viable water recovery options, sensing and real-time control will improve stormwater extraction compared to static or natural treatment options. Controlling the timing and magnitude of flows and improving removal of contaminants before they reach the plant will also result in a reduction in resources required for treatment in combined sewer systems.

Outfitting stormwater infrastructure with sensors and digital control systems introduces new opportunities for efficiency and new risks of failure. Responsible use of these systems extends beyond deployment, requiring ongoing effort to maintain trust in the data produced and the integrity with which control actions are followed. As with all Best Management Practices,[20] standards will be required to facilitate broader adoption of real-time control and to assess the risks introduced by the use of information sourced from these embedded systems. Future standards may focus around data formats, sensor requirements or actuator specifications, and will need to ensure interoperability between various sites. Failure to recognize, plan for, and manage the ongoing cyber security risks introduced by the distributed installation of sensors and actuators in stormwater infrastructure will result in new risks to public health and safety, which may undermine trust in broader efforts to deliver the potential benefits of these technologies.

There will be a need to address regulatory compliance, ownership, governance, and operational jurisdictions relating to real-time controlled systems. Unlike existing deployments of sensor and control systems in wastewater treatment, digital stormwater infrastructure is deployed across a watershed, outside of buildings staffed by an operations team. A key tension relates to jurisdiction, both in terms of who owns the infrastructure being controlled and which software system provides this dynamic capacity. Many cities may only wish to try retrofitting some sites, with the plan to augment their systems over time as they see benefits. This raises the possibility that many software systems may operate simultaneously and interfere with a global goal. If control systems are deployed by a spectrum of public and private stakeholders, they should nonetheless interoperate to provide capacity for watershed-scale control and maintenance. Governance models must be explored to facilitate cooperation and liability concerns. While solutions to these concerns can build on successful models used for ownership and operation of passive controls, they may require further thought in their translation to real-time controlled systems.

Beyond technical challenges, the ecosystem of municipalities and engineering firms must adapt to accommodate real-time control within a large umbrella of green and gray infrastructure solutions. Broader community engagement is necessary to facilitate dissemination and adoption of real-time stormwater control. Compliance regulators, such as state and federal environmental protection agencies, must be highlighted as members of this community, since many cities are wary of innovation because of perceptions that regulators will reject nontraditional solutions. Environmental consulting firms, municipalities, and researchers will need to acquire nontraditional skillsets, which span electrical engineering and computer science. To help with this effort, a major initiative is presently underway to organize an open-source consortium and share reference implementations on real-time stormwater control (http://open-storm.org). While open-source options for sensing and control are alluring due to their perceived cost, examples of holistic open-source approaches, which integrate environmental science, technology and engineering design, have yet to be developed. To that end, this consortium will serve as a hub for reference applications, standards, architectures, sensors, hardware and algorithms, to show that it is well within the abilities of most academic groups, municipalities and engineering firms to begin instrumenting and controlling stormwater infrastructure.

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Notes

The authors declare no competing financial interest.

Biography

Branko Kerkez (Assistant Professor) and Brandon Wong (Graduate Student) are part of the *Real-time Water System Lab* in the Department of Civil and Environmental Engineering at the University of Michigan. Cyndee Gruden is an Associate Professor at the University of Toledo, Department of Civil Engineering. Dr. Matt Lewis is the CTO of *Michigan Aerospace*, in Ann Arbor, Michigan. Dr. Luis Montestruque (CTO), Ruben Kertesz and Tim Braun are employed at *EmNet* in South Bend Indiana. Marcus Quigley (CEO), Alex Bedig and Owen Cadwalader are employed at *OptiRTC*, while Aaron Poresky works with *GeoSyntec*. Carrie Pak works at *Clean Water Services* in Hillsboro, Oregon.

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