Building Smarter Water Systems

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In the era of the self-driving car, can the same level of autonomy and "intelligence" be embedded into water systems?

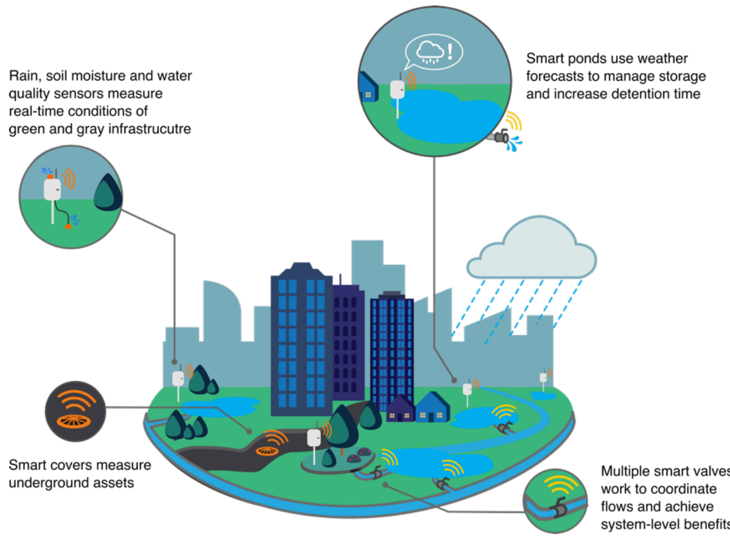

Figure 1: Toward Smart and connected stormwater. *Source*: Kerkez et al. (2016)[18].

The past decade has witnessed massive advances in sensing, computation, communications, and real-time data analysis. Many of these advances have come together under the broader umbrella of the *Internet of Things (IoT)*[1], promising to enable the cities of the future. Now, more then ever, these technologies have the potential to drastically reshape how we study and manage water systems, which presents exciting new opportunities: *by coupling the flow of water with the flow of information, modern water systems will make automated decisions based on an intimate knowledge of their overall state, permitting them to be instantly "redesigned" to adapt to changing needs and inputs.*

Water systems are included as a major component of the National Academy of Engineering's *Grand Challenge* to "*restore and improve urban infrastructure*." In this context, drinking water systems often come to mind first since they underpin much of the news in popular culture. Recent examples include droughts in the American West and lead-contaminated water supplied in the Midwestern US. Furthermore, treatment and conveyance within drinking water systems comprise nearly 2% of the US energy budget. As such, the need to better measure and respond to changes becomes imperative in maintaining safe, healthy, leak-free, and energy-efficient dirking water systems.

The role of information technology in improving drinking water systems has been illustrated by a number of studies[2–4], which include Boston's PipeNet[5] and Singapore's WaterWiSE[6], which have shown great promise to collect and analyze drinking water data in real-time. The adoption of these technologies is now being spearheaded by a number of large "smart" city companies. At the moment, it appears that utilities and municipalities are open to adopting these technologies. In part this is driven by the fact that drinking water is a revenue generating operation, which, relative to other water infrastructure, has access to larger capital to help modernized operations. The same often cannot be said for stormwater and sewer systems, which are an often-overlooked subset of the urban water infrastructure.

Floods are the leading cause of severe weather fatalities across the United States. Furthermore, large quantities of metals, nutrients, and other pollutants are washed off during storm events, making their way via streams and rivers to lakes and costal zones[7–10]. The need to manage pollutant loads in stormwater has persistently been identified as one of our greatest environmental challenges[11,12]. To contend with these concerns, most communities across the US maintain dedicated infrastructure (pipes, ponds, basins, wetlands, etc.) to convey and treat water during storm events. Many of these systems are, however, approaching the end of their design life, which is particularly troublesome considering that they are simultaneously being subjected to more intense weather[13]. In some communities, stormwater and wastewater are actually combined, meaning they share the same pipes. For these systems, large storms can often lead to combined sewer overflows, which contain viruses, bacteria, nutrients, pharmaceuticals, and other pollutants[14,15]. When coupled with population stressors, it comes as little surprise that the current sate of stormwater infrastructure has been given a near failing grade by the American Society of Civil Engineers[16].

The upsizing of pipes and other storage elements is our most common way of improving the performance of existing stormwater systems. However, even with infrastructure investments on the rise, stormwater remains the most poorly funded of all the water infrastructures[17]. As such, new construction is still limited by cost and cannot keep pace with evolving community needs and uncertain weather. As cash-strapped cities seek more resilient stormwater solutions, new and adaptive alternatives to new construction must be considered.

Stormwater adaptation via real-time sensing and control: Members of the Open-Storm team have been developing and sharing the technologies that will enable stormwater infrastructure to be retrofitted for control (Figure 2). Many of these technologies and real-time data architectures are shared in an open-source setting. The efforts include a variety of low cost controllers and actuators that can be quickly attached to existing stormwater sites. These *SmartValves* provide a reliable, secure and robust means to control the flow in pipes, ponds and green infrastructure. Once deployed, the water levels in these sites can be controlled remotely to release water based on sensor measurements or real-time weather forecasts, thus permitting system-level coordination when multiple sites are retrofitted in the same watershed.

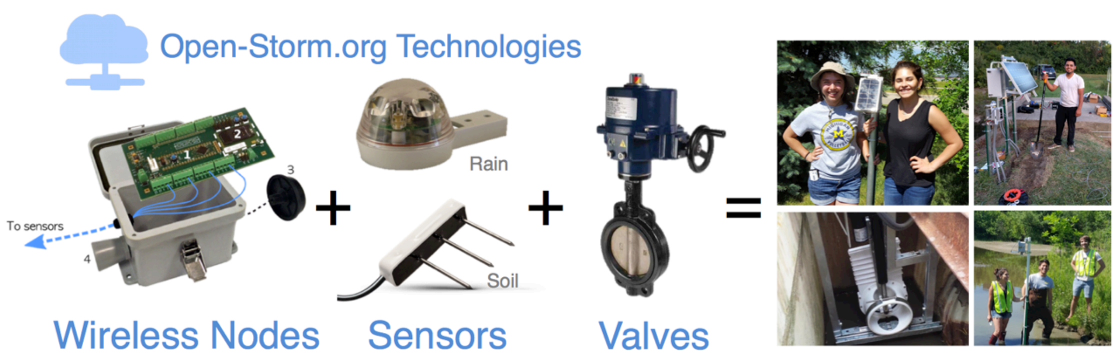

Figure 2: Open source stormwater sensing, control, and data technologies developed by the Open-storm.org team.

Case study: These technologies are presently being deployed across the Midwestern United States. The largest of these networks is located in Ann Arbor, Michigan. The sensors network spans a three square mile urban watershed, at a density of over ten sensors per square mile, measuring soil moisture, flows, rain, and water quality. The outlet of the watershed flows through a large stormwater basin (3-5 million gallons), which has been retrofitted using two wireless valves, permitting flows from the basin to be controlled in response to sensor readings and weather forecasts. Data collected by the sensors is used to create a real-time hydrologic picture of the system's state. By controlling multiple valves in real time, the risk of flooding is reduced. Storage can be allocated dynamically to ensure that all assets perform optimally and adapt to individual storm events or changing land uses. By strategically controlling how long water is held in the ponds we can fine-tune hydraulic retention time. This significantly improves the retention of solids, nutrients and other pollutants.

Figure 4: Stormwater Control Network in Ann Arbor, Michigan, with a density of nearly ten hydrologic sensors per square mile.

Our research group is also working on the next generation of algorithms that will be used to enable the city-scale control of stormwater systems (100s to 1000s of sites). These span a variety of dynamical system approaches, as well as suite of new deep-learning controllers (Figure 5). Due to the non-linearity inherent in these complex water systems, it is presently unclear which control algorithms will perform best. Furthermore, it is expected that uncertainty, in the form of weather forecasts and sensor noise will play a large role in guaranteeing the efficacy and safety of these algorithms. To that end, we have built a new simulation framework that allows large control networks to be tested using state of the art hydraulic solvers, permitting the realistic simulation of large control systems before they are deployed in the real-world (Figure 5). This will also permit researchers from other communities (e.g. Control Theory and Machine Learning) to begin applying their own algorithms to help reduce flooding and improve water quality across their communities. Those interested contributing to these efforts are encouraged to join the Open-Storm.org community.

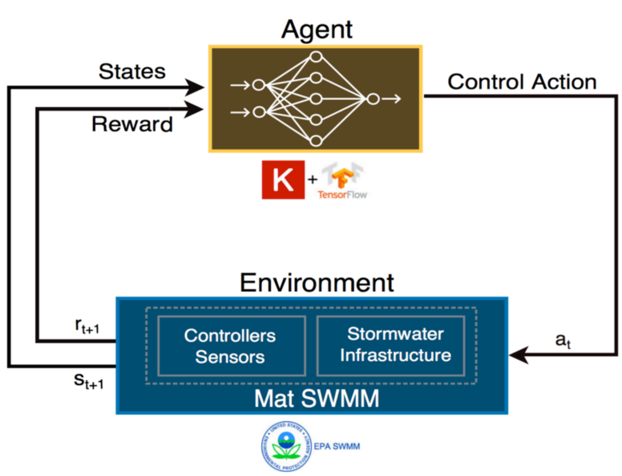

Figure 5: Reinforcement learning based control algorithms for stormwater systems. Source Mullapudi et al. (2016).

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