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STATISTICAL LEARNING APPROACHES FOR THE CONTROL OF STORMWATER SYSTEMS

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Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

ABSTRACT

Our existing stormwater systems are unable to keep pace with the evolving weather events and rapid urbanization. Smart Stormwater systems are an effective solution for operating such systems so they can tackle the storms events. In this dissertation, scientific knowledge and tools for developing control algorithms for stormwater systems. Also tools being developed for making this accisible to the wider research community.

PUBLICATIONS

Publications from this thesis.

[1] **Mullapudi, Abhiram**, Brandon P. Wong, and Branko Kerkez. "Emerging investigators series: building a theory for smart stormwater systems." In: *Environmental Science: Water Research & Technology* 3.1 (2017), pp. 66–77. ISSN: 2053-1419. DOI: 10.1039/c6ew00211k. URL: http://dx.doi.org/10.1039/C6EW00211K.

[2] **Mullapudi, Abhiram**, Matthew D. Bartos, Brandon P. Wong, and Branko Kerkez. "Shaping Streamflow Using a Real-Time Stormwater Control Network." In: *Sensors* 18.7 (2018), p. 2259. ISSN: 1424-8220. DOI: 10.3390/s18072259. URL: http://dx.doi.org/10.3390/s18072259.

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

ACKNOWLEDGMENTS

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ACRONYMS

1 INTRODUCTION

As the cities grow larger and they alter the landscape of the watersheds. As the watershed shape changes, it alters the how the water flows on the watershed. This altered water flow can be dangerous and can be harmful to the people in the system. Hence, we need to infrastructure in place to move this water away from the urban environment. This is where, stormwater infrastructure comes in. This infrastructure moves water accumulated in cities away from them into downstream water bodies.

Stormwater systems though designed to handle the runoff, are not able to handle the rising demands in the urban environments. Redesigning and retrofitting these systems to handle the rising demands, such an approach might not work always. Given the dynamic nature of the systems, such a static solution might not always be the best way to tackle these challenges. Furthermore, given the these systems have to achieve multiple objectives, having them as static systems might not be the best solutions. Also these systems are designed as localized systems, with the intent that localized solutions will eventually scale up and improve the performance of the system as a whole. But Maryland et al have demonstrated that might not always be the case. Hence, we need a more system scale approach that takes into account all the moving parts and treats the entire network as a single entity.

These rising demands can be addressed by rebuilding the infrastructure with larger capacities to handle the increasing inflows. Though adding capacity to the existing system, can help us handle the incoming flows, it is an expensive process and it is not sure that it will work. Alternatively, by retrofitting the existing system with sensors and controllers, we can monitor the state of the stormwater network in real-time and control its response to achieve system scale objectives. This enables us to dynamically control the stormwater network to fully utilize the existing potential in the stormwater network to handle the incoming stormevents. Dynamics of stormwater networks are inherently complex and given the scale and the impact they can have on general public, we need good algorithms for controlling them. Over the past decade, there has been a lot of interest on developing algorithms for the control of stormwater systems.

1.1 CONTROL OF STORMWATER SYSTEMS

The state-of-the-art in stormwater control can be broadly classified under two categories, based on how they identify control actions:

- Control algorithms reliant on parametrized models (e.g. Model Predictive Control) for identifying control actions.
- Search based algorithms (e.g. evolutionary approaches like Genetic Algorithms) that exhaustively simulate models for identifying control actions.
- Heuristic based approaches that identify the control actions solely based on the state of the system. (e.g. Fuzzy logic controllers).

Though these control algorithms have been applied for localized control in stormwater systems[1], their investigation in the context of coordinated control has been limited. To fully realize the potential of the stormwater infrastructure and to safeguard our water bodies, we need to synthesize control algorithms that are able to coordinate the response of many distributed control assets in the network, while simultaneously achieving a diverse set of water quality and flow objectives. Technologically, we are at a point where we can monitor and control these assets in real-time, but the development of control algorithms is hampered by a number of fundamental knowledge gaps.

MPC in stormwater control literature is broadly. In this dissertation, MPC is the explicit use of process based dynamical models for control.

Our existing stormwater infrastructure systems are unable to keep pace with rapidly evolving storm events and changing landscapes. These infrastructure systems — designed for an "average" event — are still proving to be inefficient in tackling dynamic weather conditions and achieving diverse urban sustainability objectives[2]. While existing stormwater systems could be rebuilt to reduce flooding and improve water quality, such an undertaking is often not financially viable, nor guaranteed to work. In lieu of new construction, one alternative would be to retrofit existing stormwater systems with sensors and controllers, so that these systems can be dynamically controlled in real-time to achieve the desired objectives. The goal of my dissertation is to make fundamental discoveries that will inform the control of smart stormwater systems, specifically focusing on statistical learning approaches that can be used to generate safe and reliable control algorithms.

1 e.g. maintaining constant water levels and flows in individual basins.
2 e.g. improving water quality and minimizing erosion

1.2 STATISTICAL METHODS

Knowledge Gaps

1. We do not know how to design control algorithms that can target pollutants in stormwater runoff, nor do we have the simulation tools necessary for such studies.
2. We do not know to how to characterize the controllability of an urban watershed, especially in the context of water quality.
3. We do yet know how to synthesize control algorithms for distributed storm-water assets without making explicit dynamical assumptions (e.g. linearity).
4. We do not know how to quantify the uncertainty of algorithms used in the real-time control of stormwater systems.
5. We do not know how to explicitly incorporate and account for hydraulic travel time within a real-time controlled system.
6. We do not have open platforms for the systematic evaluation and comparison of different control algorithms.

1.3 DISSERTATION OUTLINE

My dissertation addresses these knowledge gaps, leveraging statistical approaches, to develop tools and algorithms for enabling control of stormwater systems. The first chapter of this dissertation focuses on the development of a theoretical framework and the necessary tools for simulating control in stormwater systems. The second chapter demonstrates how a real-world wireless sensor network can be used for shaping the flow response of an entire urban watershed. In the next three chapters, various control algorithms are proposed, and their performance is evaluated across diverse scenarios to quantify the strengths and limitations. In the final chapter, I introduce a python-based simulation sandbox, which is being developed specifically for the systematic evaluation and comparison of stormwater control algorithms.

2 BUILDING A THEORY FOR SMART STORMWATER SYSTEMS

Rapid advances in sensing, computation, and wireless communications are promising to merge the physical with the virtual. Calls to build the "smart" city of the future are being embraced by decision makers. While the onset of self-driving cars provides a good example that this vision is becoming a reality, the role of information technology in the water sector has yet to be fleshed out. These technologies stand to enable a leap in innovation in the distributed treatment of urban runoff, one of ourlargest environmental challenges.

Retrofitting stormwater systems with sensors and controllers will allow the city to be controlled in real-time as a distributed treatment plant. Unlike static infrastructure, which cannot adapt its operation to individual storms or changing land uses, "smart" stormwater systems will use system-level coordination to reduce flooding and maximize watershed pollutant removal. Given the sheer number of storm water control measures in United States, even a small improvement to their performance could lead to a substantial reduction in pollutant loads. Intriguingly, such a vision is not limited by technology, which has matured to the point at which it can be ubiquitously deployed. Rather, the challenge is much more fundamental and rooted in a system-level understanding of environmental science. Once stormwater systems become highly instrumented and controlled, how should they actually be operated to achieve desired watershed outcomes? The answer to this question demands the development of a theoretical framework for smart stormwater systems. In this paper we lay out the requirements for such a theory. Acknowledging that the broad adoption these systems may still be years away, we also present and evaluate a modeling framework to allow for the simulation of smart stormwater systems before they become common place.

Recent urban floods[13], many of which are driven by flashy events and inadequately sized infrastructure, are all too common example that aging stormwater infrastructure is struggling to keep pace with a dynamic and changing climate. While flood control often emerges as one of the most promising application areas, to illustrate the flexibility of smart stormwater systems this paper will focus on the impacts to urban water quality.

2.1 DO BEST LOCAL PRACTICES ACHIEVE THE BEST GLOBAL OUTCOMES?

Pollutants in runoff are threatening the health of downstream ecosystems, as evinced by harmful algal blooms, such as those on Lake Erie[22] and the Chesapeake Bay[4, 29]. Simultaneously, "dry" regions of the country are struggling to find new and clean sources of water. By some estimates, the capture of stormwater in Los Angeles[17] and San Francisco[16] could offset the water used by these cities. This, however, requires at least some level of treatment to ensure that captured stormwater is safe for direct use or aquifer injection. In the face of these challenges, novel solutions for stormwater management are needed.

Reductions in hydraulic or pollutant loads are commonly achieved via a set of distributed stormwater solutions[5, 19], such as ponds or treatment wetlands. Our body of knowledge on the treatment potential of these systems is extensive, showing that significant water quality and hydraulic benefits can be achieved at the level of individual sites[6, 33]. Most recently, an exciting and growing research area has formed around smaller-scale and more distributed Green Infrastructure (GI) solutions, such as green roofs or bioswales[3]. Most of these solutions are grouped under the broader umbrella of Best Management Practices[35] (BMPs) or Storm Water Control Measures (SCMs)[9].

Given the aggressive adoption of these stormwater practices, rarely is the question asked: Does doing the "best" at a local scale translate to doing the best at the watershed scale? Research on this question is limited[27, 28, 30], but paints a cautionary picture. Unless designed as part of a coordinated, city-scale solution, a system of SCMs may actually worsen watershed-scale outcomes. For example, unless coordinated at design-time, hydrographs from individual SCMs may add up to cause larger downstream flows compared to the same watershed without these SCMs[11]. This, in turn, can lead to increased stream erosion and re-suspension of sediment-bound pollutants. More examples can be given, but there is an urgent need to investigate the scalability of SCMs and to ensure that their functionality is tuned in the context of the broader stormwater system.

Even if system-level optimization is used to determine the placement of SCMs[8, 36], it is difficult to guarantee that the overall system will perform as designed. The sheer variability in rainfall[7], seasonal pollutant loadings[26], and broader land use changes[18] will always push stormwater systems beyond their intended design or the "average" storm[10]. As such, it becomes imperative to find a way to adapt to these uncertain disturbances. One solution relies on real-time sensing and control. By equipping stormwater elements with control valves, which can be operated in real-time based on sensor readings, the overall performance of the entire system can be adapted to achieve watershed-scale benefits (Figure.2.1a).

2.1.1 Existing studies on real-time control

The bulk of existing literature on real-time control of stormwater SCMs focuses on water quality and hydraulic impacts at individual sites, particularly ponds and basins. These studies assume that the outlet of a BMP has been retrofitted with a remotely controllable gate or valve. By strategically controlling outflows before or during storm events, internal volumes can be modified and hydraulic retention time (HRT) can be increased. Jacopin et al.[20] demonstrated that detention basins, designed for flood control, can reduce sediment-based pollutant loading (57% decrease) in downstream water bodies by simply opening and closing a valve. Middleton et al.[23] analyzed the water quality response of a controlled detention basin, observing up to a 90% improvement in TSS and ammonia-nitrate removal. Recent studies[14, 15, 25] in Quebec, Canada, proposed a rule-based control logic for a pond, based on rainfall forecasts, to maximize retention time and reduce hydraulic shocks to the downstream water bodies. The authors observed a 90% improvement in TSS retention. A comprehensive review of these and other studies is summarized in Kerkez et al.[21], along with additional information on how these solutions are deployed in the field. While these studies demonstrate significant potential to improve water quality at the scale of individual sites, the mechanisms behind the removal of pollutants in controlled SCMs remain a research challenge. This is particularly true in the removal of dissolved pollutants, such as ammonia and nitrate. Furthermore, the scalability of real-time control must be evaluated to ensure that local benefits do not overshadow watershed-scale benefits.

Since the 2000 European Union's Water Framework Directive [34] there has been an increasing emphasis on integrated, system-level control of sewer water distribution systems. The resulting control strategies vary in complexity[2, 12, 31] and have since been implemented in a number of urban water networks[24]. Applying these methods to distributed stormwater solutions introduces a new set of challenges, however. Unlike in well-maintained sewer networks, the exposed and distributed nature of stormwater systems introduces complexities associated with the urban hydrologic cycle, such as infiltration, evaporation, soil moisture and groundwater dynamics. Furthermore, one major function of stormwater systems relates to the distributed control of a large variety of solid, dissolved and emerging pollutants. Control of sewer networks is often targeted at volume control to mitigate sewer overflows or overloading treatment plants. As such, much work remains to be conducted on investigating how these methods can be applied to the distributed control of SCMs.

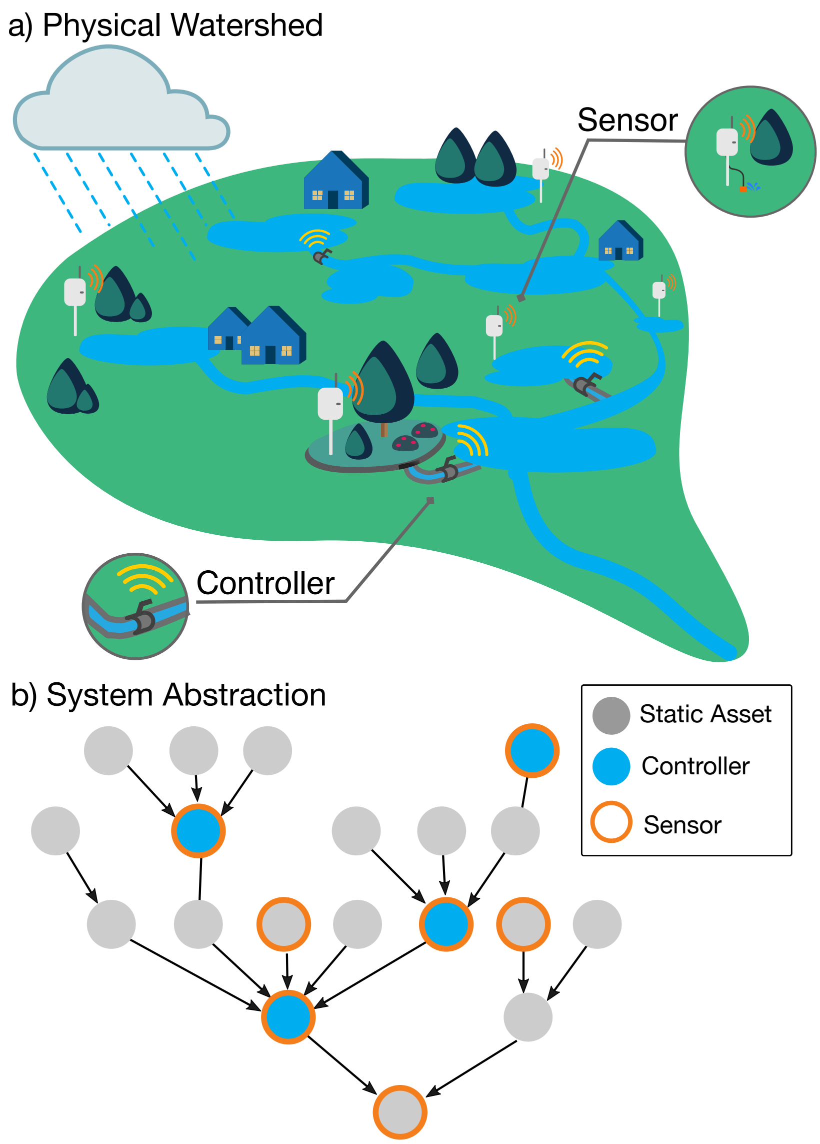

Figure 2.1: Application of control and optimization methods to the real-time operation of stormwater systems will be made possible by abstracting physical models to system-theoretic representations.

2.2 TOWARD A FRAMEWORK FOR SMART STORMWATER SYSTEMS

Many methods have been developed by the operational research and control theory communities to optimize the operation of networked systems[1, 32]. Given their inherent non-linearity and complexity, existing stormwater models are not compatible with these tools. To that end, our knowledge of treatment processes and the physical nature of stormwater systems must first be embedded in a system-theoretic framework (Figure.2.1b). Such a formal and mathematical approach will be crucial toward developing a system-level understanding of stormwater. Not only will this framework help to control future stormwater systems, but it will also create a foundation upon which to answer critical questions, such as: How many controllers are needed and where should they be placed to achieve best system-level benefits? Consequently, how many sensors are needed and where should they be placed to help the control system achieve these objectives?

Until sensors and controllers become ubiquitously deployed across stormwater systems, which may take years to accomplish, there is enough domain knowledge embedded in existing models to begin answering these questions through simulation.

3 SHAPING THE RESPONSE IN WATERSHEDS USING A SENSOR NETWORK

Rapid advances in sensing, computation, and wireless communications are promising to merge the physical with the virtual. Calls to build the "smart" city of the future are being embraced by decision makers. While the onset of self-driving cars provides a good example that this vision is becoming a reality, the role of information technology in the water sector has yet to be fleshed out. These technologies stand to enable a leap in innovation in the distributed treatment of urban runoff, one of our largest environmental challenges.

Retrofitting stormwater systems with sensors and controllers will allow the city to be controlled in real-time as a distributed treatment plant. Unlike static infrastructure, which cannot adapt its operation to individual storms or changing land uses, "smart" stormwater systems will use system-level coordination to reduce flooding and maximize watershed pollutant removal. Given the sheer number of stormwater control measures in United States, even a small improvement to their performance could lead to a substantial reduction in pollutant loads. Intriguingly, such a vision is not limited by technology, which has matured to the point at which it can be ubiquitously deployed. Rather, the challenge is much more fundamental and rooted in a system-level understanding of environmental science. Once stormwater systems become highly instrumented and controlled, how should they actually be operated to achieve desired watershed outcomes? The answer to this question demands the development of a theoretical framework for smart stormwater systems. In this paper we lay out the requirements for such a theory. Acknowledging that the broad adoption these systems may still be years away, we also present and evaluate a modeling framework to allow for the simulation of smart stormwater systems before they become common place.

4 DEEP REINFORCEMENT LEARNING FOR THE CONTROL OF STORMWATER NETWORKS

Rapid advances in sensing, computation, and wireless communications are promising to merge the physical with the virtual. Calls to build the "smart" city of the future are being embraced by decision makers. While the onset of self-driving cars provides a good example that this vision is becoming a reality, the role of information technology in the water sector has yet to be fleshed out. These technologies stand to enable a leap in innovation in the distributed treatment of urban runoff, one of our largest environmental challenges.

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5 BAYESIAN OPTIMIZATION FOR SHAPING THE RESPONSE OF THE STORMWATER SYSTEMS

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6 A SIMULATION SANDBOX FOR THE DEVELOPMENT AND EVALUATION OF STORMWATER CONTROL ALGORITHMS

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7 CONCLUSION

Part I

APPENDIX

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DECLARATION

Put your declaration here.

Ann Arbor, June 2020

Abhiram Mullapudi

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst's seminal book on typography "*The Elements of Typographic Style*". `classicthesis` is available for both LaTeX and LyX:

https://bitbucket.org/amiede/classicthesis/

Happy users of `classicthesis` usually send a real postcard to the author, a collection of postcards received so far is featured here:

http://postcards.miede.de/

Thank you very much for your feedback and contribution.