ABHIRAM MULLAPUDI

STATISTICAL LEARNING APPROACHES FOR THE CONTROL OF STORMWATER SYSTEMS

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ABHIRAM MULLAPUDI

Doctor of Philosophy
Department of Civil and Environmental Engineering
University of Michigan

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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

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LISTINGS

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.

Such an wholistic approach requires us to

1.1 CONTROL OF STORMWATER SYSTEMS

The state-of-the-art in stormwater control can be broadly classified under two categories: (1) Control algorithms reliant on parametrized models (e.g. model predictive control) for identifying control actions. (2) Search based algorithms (e.g. genetic algorithms) that exhaustively simulate physical models for identifying control actions. Though these control algorithms have been applied for localized control in stormwater systems[1], their investigation in the context of coordinated control and targeted removal of pollutants has been limited. To fully realize the potential of the stormwater infrastructure and to safeguard our water

1 e.g. maintaining constant water levels and flows in individual basins.

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.

Over the years several control algorithms have been proposed for controlling urban water networks. Exisiting stormwater control algorithms can be classifed under three overarching catagories,

- Parametrized Approches
- Evolutionary Algorithms
- Model Predictive Control

MPC in stormwater control literature is referred as the use of any model of making control decisions. 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.

1.2 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.

2 e.g. improving water quality and minimizing erosion

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 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.

Part I

APPENDIX

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:

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