Model predictive control of retention basins enhances removal of nonpoint-source pollutants

Jeil Oh[1*], Matthew Bartos, Ph.D.[1]

[1]University of Texas at Austin, Austin, Texas

**Corresponding author email: jeoh@utexas.edu*

Highlights

- An optimal control strategy for both water quantity and quality improvement in stormwater retention basins is derived using a physically-based model.
- Dynamic actuation of an outlet valve based on nonlinear model predictive control effectively reduces peak flows and downstream TSS loads.

Introduction

Management of nonpoint-source pollutants has persistently been identified as one of the greatest challenges in stormwater engineering today. Over the last few decades, green infrastructure has been widely adopted as a countermeasure against urban runoff pollution (Li et al., 2019). However, green infrastructure suffers from maintenance challenges at scale, and may fail to adapt to changing hydrologic conditions induced by climate change (Shishegar et al., 2019).

Smart stormwater systems offer a promising alternative approach for mitigating stormwater pollution. Drawing on advances in the *Internet of Things*, these systems use dynamically-controlled sensors and actuators to reconfigure stormwater infrastructure in real-time, thereby enabling improved flood and pollutant control (Kerkez et al., 2016; Bartos et al., 2018). Real-time control enables stormwater basins to serve not only as detention basins to delay runoff but also as reactors for pollutant removal.

Despite the importance of stormwater pollution control, the majority of studies investigating real-time control of urban drainage systems have emphasized water quantity goals, such as reducing overflows and floods (Wong & Kerkez, 2018). While many studies show that water quality can be improved through real-time control, only a few studies have explicitly integrated water quality as a parameter in control strategies (Muschalla et al., 2014; Sharior et al., 2019). Existing control strategies in the literature rely on predefined rule-based approaches which require trial-and-error calibration, and are only valid for specific sites. Furthermore, due to the nonlinearity of the water quality dynamics, most studies rely either on linearized approximations, or the use of hydraulic retention time (HRT) as a proxy variable for water quality (Gaborit et al., 2016).

This paper develops an optimal valve control strategy to maximize the performance of a stormwater pond for both flow and pollution control. Control is implemented using nonlinear model predictive control (NMPC) using a mass balance and continuously stirred tank reactor (CSTR) representation. This study focuses on total suspended solids (TSS) as a pollutant of interest. The proposed optimization approach provides an adaptive solution for reducing flooding and maximizing treatment without the construction of new infrastructure.

Methodology

The hydraulic model for the stormwater pond is based on a water balance, where the change in storage is equal to the difference between inflow (q_{in}) and outflow (q_{out}). Assuming the surface area of the pond is roughly constant, the change in storage can be expressed as the change in depth (h) times the surface area of the pond (A).

$$A\frac{dh}{dt} = q_{in} - q_{out} \quad (1)$$

At the outlet of the pond, a controllable orifice is installed to regulate the outflow rate, such that $q_{out} = \theta C_d A_d \sqrt{2gh}$; where θ is the orifice opening ratio, C_d is the orifice discharge coefficient, A_d is the orifice area, and g is the gravitational acceleration.

The water quality model, formulated here for TSS, can be expressed by pollutant mass balance considering sedimentation as a first-order reaction (Krajewski et al., 2017). It is assumed that the pond itself behaves as a CSTR, which means the effluent concentration is equal to the concentration in the pond:

$$V\frac{dC}{dt} + C\frac{dV}{dt} = C_{in}q_{in} - Cq_{out} - kCV \quad (2)$$

where C is the concentration in the effluent and in the pond, and k is the first-order rate constant. Combining Equation (1) and Equation (2), the water quality dynamics are given by:

$$\frac{dC}{dt} = \frac{q_{in}}{V}(C_{in} - C) - kC \quad (3)$$

Model predictive control (MPC) is an optimization approach that has been widely adopted in many sectors as an effective tool to drive future optimal control strategies from a model of the system and forecasts of external inputs. To account for the nonlinearity of the combined hydraulic and water quality model, NMPC is used. While NMPC retains the advantages of linear MPC, such as enabling constraints on decision variables, it can also handle non-linear dynamical systems, eliminating the need for linearization which may impair the accuracy of the model. The objective function of the NMPC optimization is to minimize both peak flow and pollutant load from the pond by controlling the outlet valve. Mathematically, this objective is expressed as follows:

$$J(k) = \sum_{k=1}^{N}\left(q_{out}(k) - \frac{1}{N}\sum_{l=1}^{N} q_{out}(l)\right)^2 + \sum_{k=1}^{N}\left(C(k)q_{out}(k)\right)^2 \quad (4)$$

where $q_{out}(k) = \theta(k)C_d A_d\sqrt{2gh(k)}$. Physical constraints are imposed on both the maximum allowable water height, and the valve opening ratio:

$$0 \le h \le h_{max} \quad (5)$$

$$0 \le \theta \le 1 \quad (6)$$

Results and discussion

Compared to the uncontrolled case, dynamic control with NMPC simultaneously reduces the peak flow and TSS load, while also preventing overflow (Figure 1). About 29.6% TSS load reduction (from 0.27 kg to 0.19 kg) is achieved through active control compared to the uncontrolled case. Intuitively, NMPC enhances pollutant removal by reducing the discharge when the TSS concentration in the pond is high and increasing the discharge when the concentration is low. In addition, dynamic control shows a 61.2% reduction in the magnitude of peak flow from 3.17m^3/s to 1.23m^3/s. Through dynamic control of the outlet valve, the volume of stormwater is effectively distributed over the event duration, leading to lower concentrations of TSS in the effluent. This study also overcomes the limitations of existing rule-based control strategies, where setting a specific target concentration increases the risk of overflow, and the thresholds for both height and concentration may not necessarily lead to optimal control.

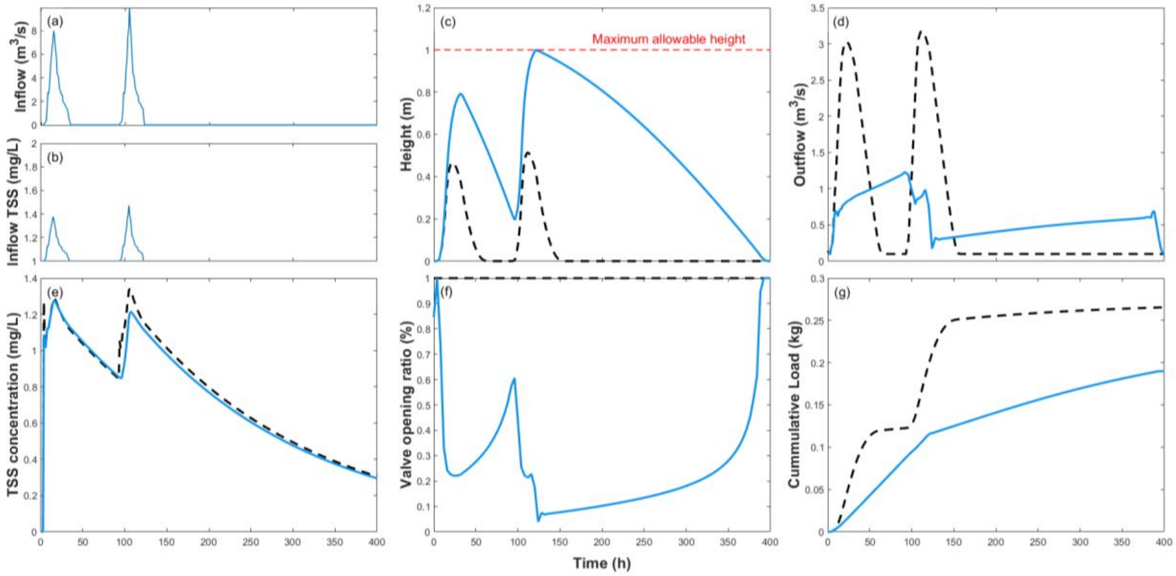

Figure 1. Simulation results of the uncontrolled (dashed lines) and controlled (solid lines) cases, showing (a) inflow, (b) inflow concentration, (c) pond water height, (d) outflow, (e) TSS concentration in the pond, (f) valve opening ratio, and (g) cumulative TSS loads exiting the pond. The input hydrograph and pollutograph are generated for simulation but can be regarded as a realistic input considering the purpose of this study.

Conclusions and future work

In this study, we propose a dynamic control strategy for stormwater ponds based on NMPC to improve both water quantity and quality. Given physical constraints, such as the maximum capacity of the pond and valve opening ratio, we develop an optimal valve control strategy for reducing downstream TSS loads and peak flows during storm events. This control strategy does not rely on specific threshold values, as is the case for rule-based approaches, and is thus adaptable to a wider range of hydrologic variability. Future work should investigate how this control strategy can be applied to other types of pollutants and expanded to networked stormwater systems.

References

Bartos, M., Wong, B., & Kerkez, B. (2018). Open storm: A complete framework for sensing and control of urban watersheds. *Environmental Science: Water Research & Technology*, *4*(3), 346–358.

Gaborit, E., Anctil, F., Pelletier, G., & Vanrolleghem, P. A. (2016). Exploring forecast-based management strategies for stormwater detention ponds. *Urban Water Journal*, *13*(8), 841–851.

Kerkez, B., Gruden, C., Lewis, M., Montestruque, L., Quigley, M., Wong, B., Bedig, A., Kertesz, R., Braun, T., Cadwalader, O., Poresky, A., & Pak, C. (2016). Smarter Stormwater Systems. *Environmental Science & Technology*, *50*(14), 7267–7273.

Krajewski, A., Sikorska, A. E., & Banasik, K. (2017). Modeling Suspended Sediment Concentration in the Stormwater Outflow from a Small Detention Pond. *Journal of Environmental Engineering*, *143*(10), 05017005.

Li, C., Peng, C., Chiang, P.-C., Cai, Y., Wang, X., & Yang, Z. (2019). Mechanisms and applications of green infrastructure practices for stormwater control: A review. *Journal of Hydrology*, *568*, 626–637.

Muschalla, D., Vallet, B., Anctil, F., Lessard, P., Pelletier, G., & Vanrolleghem, P. A. (2014). Ecohydraulic-driven real-time control of stormwater basins. *Journal of Hydrology*, *511*, 82–91.

Sharior, S., McDonald, W., & Parolari, A. J. (2019). Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. *Journal of Hydrology*, *573*, 422–431.

Shishegar, S., Duchesne, S., & Pelletier, G. (2019). An integrated optimization and rule-based approach for predictive real time control of urban stormwater management systems. *Journal of Hydrology*, *577*, 124000.

Wong, B. P., & Kerkez, B. (2018). Real-Time Control of Urban Headwater Catchments Through Linear Feedback: Performance, Analysis, and Site Selection. *Water Resources Research*, *54*(10), 7309–7330.