Pipedream: a digital twin model for stormwater networks

M. Bartos, Ph.D.[1*], B. Kerkez, Ph.D.[2]

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

[2]University of Michigan, Ann Arbor, Michigan

*Corresponding author email: mdbartos@utexas.edu

Highlights

- We present a digital twin model for stormwater networks that combines a new hydraulic solver with an online data assimilation procedure based on Kalman Filtering.
- We show that fusing sensor data into the hydraulic model improves interpolation and forecasting of water depths and flows within a real-world stormwater network.
- Our digital twin model will enable water managers to better detect floods, leaks, blockages, and other emergencies in near real-time.

Introduction

In the wake of growing urban populations, aging infrastructure, and more frequent extreme weather events, many cities are looking for new ways to monitor stormwater system performance and ensure that service targets are met. *Digital twins* address this problem by combining embedded sensing and online modelling to enable real-time supervision of stormwater system dynamics. Using digital twins of real-world stormwater networks, water managers can track system performance, detect maintenance emergencies, and optimize operations through real-time control. However, the development of digital twins for stormwater systems has been hampered by a lack of sufficient process models, and a lack of theory surrounding how data should be assimilated. New tools are needed to enable online state estimation and control in stormwater systems while at the same time ensuring that system dynamics are accurately represented.

In this study, we introduce *pipedream*—the first end-to-end software toolkit for building digital twins of stormwater networks. This toolkit consists of (i) a new online hydraulic solver based on the full one-dimensional Saint-Venant equations and (ii) a Kalman filtering approach that updates system states based on streaming sensor data. This toolkit can be executed in online mode, advancing forward in sync with the real-world stormwater system and assimilating new sensor measurements on the fly. Moreover, the toolkit provides a robust interface for executing dynamic controls through the use of adjustable orifices, weirs and pumps. Taken together, the software described in this study provides a true end-to-end framework for implementing real-time monitoring and control of stormwater networks.

Methodology

To enable real-time state estimation in urban drainage systems, we first develop a new hydraulic solver that (i) is capable of running in online mode, and (ii) facilitates data assimilation by providing a state space representation of system dynamics. We base our solver on the SUPERLINK formulation—an implicit staggered-grid scheme for solving the one-dimensional Saint-Venant equations in sewer/channel networks (Ji, 1998). In addition to its accuracy and stability, this solver enables the use of robust state estimation techniques like Kalman filtering by enabling the system dynamics to be cast in the form of a locally linear time-varying (LTV) state space model:

$$\mathbf{x}_{k+1} = A_k \mathbf{x}_k + B_k \mathbf{u}_k + \mathbf{v}_k$$
$$\mathbf{z}_k = H_k \mathbf{x}_k + \mathbf{w}_k$$

Where $\mathbf{x}_k$ is the state vector of junction heads at time k; $\mathbf{z}_k$ is the observed heads (obtained via sensor data); $\mathbf{v}_k$ is the driving noise (runoff input); $\mathbf{w}_k$ is measurement noise; A_k is the state transition matrix; and H_k is the observation matrix.

Real-time data assimilation is achieved by combining the hydraulic solver with a Kalman filter. The filter recursively updates system states by fusing sensor data with the dynamical state-space model. At each time step (k), the updated state estimate and estimate covariance are given by the recursive formulation:

$$\hat{\mathbf{x}}_{k+1} = A_k \hat{\mathbf{x}}_k + B_k \mathbf{u}_k + L_{k+1} \cdot [\mathbf{z}_{k+1} - H_{k+1} \cdot (A_k \hat{\mathbf{x}}_k + B_k \mathbf{u}_k)]$$

$$L_k = P_k H_k^T \left(H_k P_k H_k^T + W_k \right)^{-1}$$

$$P_{k+1} = A_k \cdot \left(P_k - P_k H_k^T \cdot \left(H_k P_k H_k^T + W_k \right)^{-1} \cdot H_k P_k \right) \cdot A_k^T + V_k$$

Where $\hat{\mathbf{x}}_{k+1}$ is the updated state estimate; P_{k+1} is the updated estimate covariance, V_k is the covariance of the driving noise; and W_k is the covariance of the measurement noise. The Kalman filter provides the optimal linear estimator of system states for the case in which (i) the process model is accurate, and (ii) the noise is uncorrelated and Gaussian with known covariance.

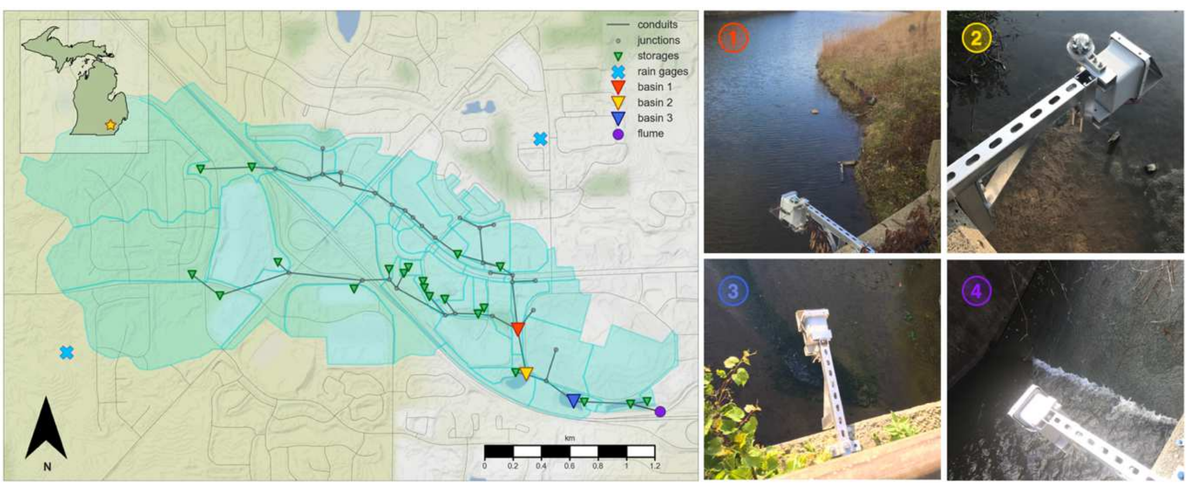

Figure 1. Study area with sensors placed at four sites on the stormwater system mainstem.

To evaluate the *pipedream* digital twin toolkit, we apply our data assimilation methodology to a real-world stormwater network, and evaluate the extent to which the Kalman filter improves the accuracy of interpolated and forecasted system states. First, a real-world catchment is selected, and real-time depth data is collected at four sites (see Figure 1). We then construct a model of the catchment using known channel/storage geometries and hydrologic parameters. Next, we force the model with rainfall from a real-world storm event, and use a holdout cross-validation approach to measure the degree to which fusing sensor data at selected sites reduces error at the holdout sites. We also evaluate the ability of the Kalman filter to forecast system states by fusing sensor measurements at one-hour intervals and quantifying the reduction in error over the remainder of each hour.

Results and discussion

Using a holdout cross-validation assessment, we find that the data assimilation toolkit accurately interpolates hydraulic states within the network. Figure 2 shows the result of the holdout cross-validation analysis. For this experiment, the filter is applied to sensor sites 1 and 3, and the output of the updated model is compared with sensor measurements at sites 2 and 4. While the model performs well on its own, the Kalman filter reduces the mean absolute error (MAE) at site 2 by 55% and at site 4 by 55%. Because the filter improves model accuracy even at locations where it is not directly applied, the holdout assessment suggests that the Kalman filter pushes the system closer to its actual state rather than simply "overfitting" individual sites to measured data. By moving the system closer to its true state, the Kalman filter also significantly improves forecasts of depths and flows throughout the network.

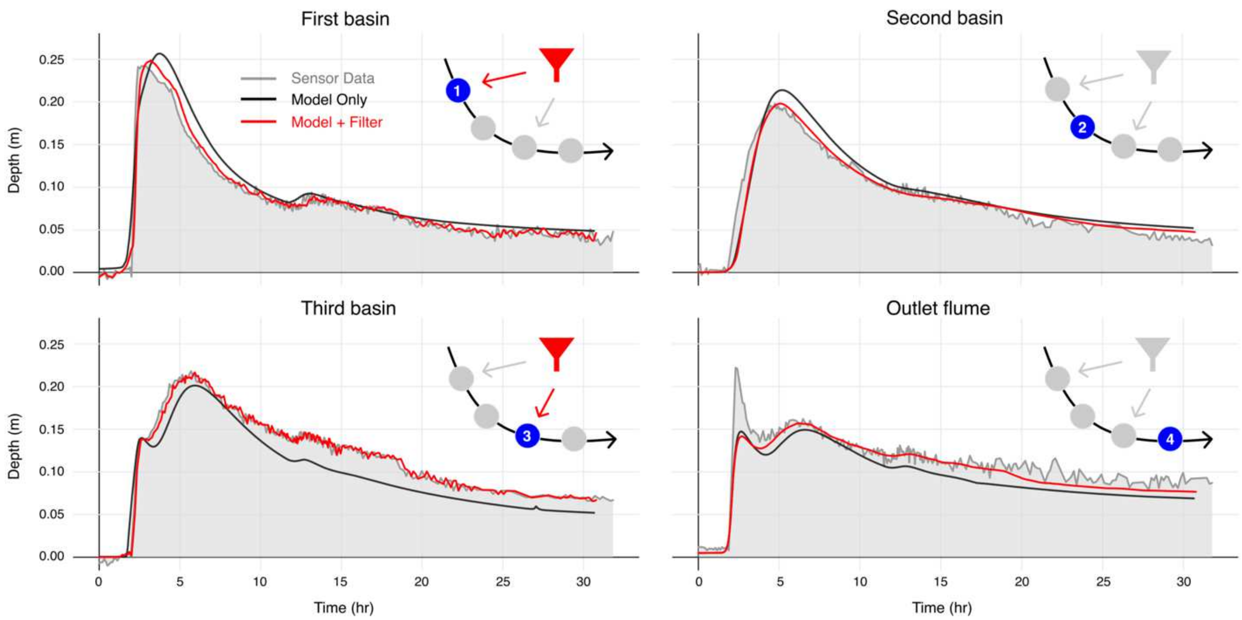

Figure 2. Validation of Kalman filter using a holdout assessment. (Left): Depth hydrographs at sites 1 and 3, where the Kalman filter is applied. (Right): Depth hydrographs at locations where Kalman filter was not applied. The Kalman filter reduces error at both holdout sites.

Conclusions and future work

In this study, we introduce the first end-to-end toolkit for building real-time digital twins of urban stormwater systems. This toolkit consists of a new hydraulic solver based on the full one-dimensional Saint-Venant equations along with an implicit Kalman filtering methodology that facilitates assimilation of real-time sensor data. Drawing on sensor data from a real-world stormwater network, we find that the implicit Kalman filter is effective at both interpolating system states within the network, and forecasting future states based on current measurements. By providing a physically-based methodology for state estimation in stormwater networks, this toolkit will enable system operators to pre-emptively detect and repair blockages, leaks and other maintenance emergencies. Moreover, by improving interpolation and forecasting of system states, our toolkit will provide a strong foundation for model-based real-time control schemes that will reconfigure stormwater infrastructure in real-time to better meet operational objectives such as mitigation of combined sewer overflows.

References

Ji, Z. (1998). General Hydrodynamic Model for Sewer/Channel Network Systems, Journal of Hydraulic Engineering 124(3) 307–315.