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## Advances in system-scale state estimation and control of urban drainage networks using the PipeDream hydraulic solver

### Avancées dans l'estimation de l'état à l'échelle du système et le contrôle des réseaux de drainage urbain à l'aide du solveur hydraulique PipeDream

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#### RÉSUMÉ

Au cours des dernières décennies, les gestionnaires de l'eau ont de plus en plus reconnu le potentiel de l'estimation et du contrôle de l'état en temps réel pour relever les défis du drainage urbain tels que les inondations et les débordements d'égouts unitaires. Cependant, les implémentations à l'échelle du système ont été entravées par un manque de modèles de processus appropriés, ce qui a conduit à s'appuyer sur des modèles de substitution qui ne capturent pas la dynamique physique complète des systèmes de drainage urbain. Cette étude traite des progrès récents dans l'estimation de l'état à l'échelle du système et le contrôle des réseaux de drainage urbain rendus possibles par le nouveau solveur hydraulique PipeDream. Conçu pour les applications en temps réel, ce solveur simule les équations de Saint-Venant pour un écoulement instationnaire à l'aide d'un schéma implicite stable et exprime la dynamique du système sous forme d'espace d'état, permettant l'application directe du filtrage de Kalman étendu (EKF) pour l'assimilation des données des capteurs, et Model-Predictive Control (MPC) pour la détermination des stratégies optimales de contrôle du réservoir. Cette étude démontre deux cas de test d'estimation et de contrôle d'état à l'échelle du système. Tout d'abord, il est démontré que la fusion des données des capteurs dans un modèle de drainage urbain à l'aide de l'EKF améliore les estimations de la profondeur et du débit à un emplacement non jaugé. Ensuite, il est montré que le MPC peut être utilisé pour éviter les débordements dans un réseau de réservoirs, en tenant compte des effets de remous et des temps de parcours à travers le réseau. Sur la base de ces résultats, on s'attend à ce que le solveur PipeDream fournisse une plate-forme importante pour l'estimation et le contrôle de l'état à l'échelle du système pour les applications de recherche et de l'industrie.

#### ABSTRACT

In recent decades, water managers have increasingly recognized the potential for real-time state estimation and control to address urban drainage challenges like flooding and combined sewer overflows. However, implementations at the system scale have been hindered by a lack of suitable process models, leading to a reliance on surrogate models that do not capture the full physical dynamics of urban drainage systems. This study discusses recent advances in system-scale state estimation and control of urban drainage networks enabled by the new PipeDream hydraulic solver. Designed for real-time applications, this solver simulates the Saint-Venant equations for unsteady flow using a stable implicit scheme and expresses system dynamics in state-space form, allowing for direct application of Extended Kalman Filtering (EKF) for sensor data assimilation, and Model-Predictive Control (MPC) for determination of optimal reservoir control strategies. This study demonstrates two test cases of state estimation and control at the system scale. First, it is shown that fusing sensor data into an urban drainage model using EKF improves estimates of depth and discharge at an ungaged location. Next, it is shown that MPC can be used to avert overflows in a network of reservoirs, accounting for backwater effects and travel times through the network. Based on these results, it is expected that the PipeDream solver will provide an important platform for system-scale state estimation and control for both research and industry applications.

#### KEYWORDS

Data assimilation, Digital twins, Hydraulic modeling, Real-time control, State estimation

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## 1 INTRODUCTION

In recent decades, water managers have increasingly recognized the potential for real-time monitoring and control systems to address stormwater challenges like flooding and combined sewer overflows. Real-time data assimilation allows water managers to continuously monitor urban drainage systems for hazards like flooding, blockages, and combined sewer overflows (CSOs). Real-time control goes one step further, enabling water managers to halt flooding and CSOs before they occur using actuated valves and gates.

Despite the transformative potential of these technologies, state estimation and control of urban drainage networks at the system scale remains an open problem (Webber et al., 2022). A major limiting factor is the lack of modelling software built for real-time applications. Existing studies largely rely on surrogate models, which often fail to account for the full physical dynamics of urban drainage systems, including backwater effects and travel times that can significantly influence the optimality of control strategies.

This study demonstrates applications of real-time state estimation and control in urban drainage networks using the new PipeDream model—a hydraulic solver based on the full Saint-Venant equations for unsteady flow that is specifically designed for real-time modelling (Bartos and Kerkez, 2021). Regarding state estimation, we first demonstrate that fusing sensor data into the PipeDream hydraulic solver improves estimates of heads and discharges at ungaged locations in a drainage network. With respect to control, we show that the solver efficiently computes optimal reservoir operation strategies to reduce flooding using a model-predictive control approach. Unlike previous approaches that rely on surrogate models, the pipedream model determines optimal estimation and control strategies using the full Saint-Venant equations for unsteady flow, thereby accounting for backwater effects and surcharged pipe conditions that are characteristic of urban drainage networks.

## 2 NEW HYDRAULIC SOLVER

The pipedream solver implements an implicit scheme to simulate the Saint-Venant equations for fully unsteady flow in networks consisting of pipes and open channels (links) connected by storage elements (junctions). These equations consist of a continuity equation (mass balance) and a momentum equation (force balance):

Continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{in}$$

Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial Qu}{\partial x} + gA \left( \frac{\partial h}{\partial x} - S_o + S_f + S_L \right) = 0$$

Where  $A$  is the channel cross-sectional area,  $Q$  is the discharge,  $q_{in}$  is the exogenous runoff input,  $u$  is the velocity of flow,  $h$  is the depth of flow,  $S_o$  is the channel bottom slope,  $S_f$  is the friction slope,  $S_L$  is the local loss slope. The PipeDream model solves these equations for networks of interconnected links and junctions using the SUPERLINK numerical scheme (Ji, 1998). Crucially, the SUPERLINK scheme enables the dynamical equations to be expressed in state-space form, which facilitates the use of optimal state estimation and control algorithms, as described in the following two sections.

## 3 STATE ESTIMATION BY EXTENDED KALMAN FILTERING (EKF)

PipeDream enables real-time sensor data assimilation in urban drainage networks via an Extended Kalman Filter (EKF), facilitating better estimates of depths and discharges at ungaged locations. Briefly, Kalman Filtering is an optimal state estimation technique that combines a process model with real-time sensor data to deliver improved estimates of system states. From the discretization scheme introduced by the PipeDream solver, the discretized Saint-Venant equations may be expressed in state-space form (Bartos and Kerkez, 2021):

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

$$\mathbf{z}_k = H_k \mathbf{x}_k + \mathbf{w}_k$$

Where  $\mathbf{x}_k$  is the state vector of junction heads at time  $k$ ;  $\mathbf{z}_k$  is the observed heads (obtained from 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. The Kalman recursion may be applied to this system to produce the optimal linear estimator of system states at the next time step,  $\hat{\mathbf{x}}_{k+1}$ :

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

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

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

Where  $\hat{\mathbf{x}}_{k+1}$  is the optimal posterior state estimate;  $P_{k+1}$  is the posterior estimate covariance,  $V_k$  is the covariance of the driving noise; and  $W_k$  is the covariance of the measurement noise.

To demonstrate the utility of system-scale state estimation in urban drainage networks, a holdout assessment is performed to verify that data assimilation improves estimates of depths and discharges at ungaged locations. This assessment concerns a semi-urbanized catchment in Central Texas that is monitored by three gages collecting real-time depth and discharge measurements (Fig. 1, left). Here, a hydraulic model is constructed using known channel geometry data. A storm event is then selected and the model is forced with lateral runoff and subsurface recharge from the National Water Model (NWM), generating a model-only estimate of depths and discharges in the network. Next, sensor data is fused into the dynamical model via EKF at the two upstream sites, yielding updated estimates of depth and discharges throughout the network. The updated posterior estimates of depth and discharge are then compared with the measured sensor data at the downstream site to determine the extent to which EKF improves depth and discharge estimates at ungaged locations.

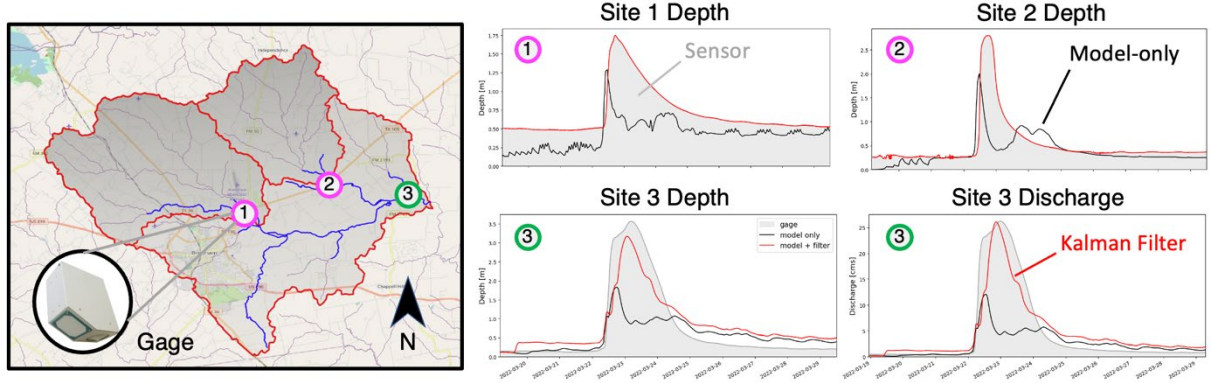


Fig. 1: Application of data assimilation via Extended Kalman Filtering (EKF). Fusing sensor data at upstream sites (1) and (2) improves depth and discharge estimates at downstream site (3).

From Fig. 1 (right), it is observed that EKF improves estimates of both depth and discharge at the downstream holdout site. Briefly, these plots show the sensor data, the model-only estimate, and the EKF result for the two upstream sites (top, middle) and the downstream holdout site (bottom). From this plot, it can be seen that assimilating data at the two upstream sites improves both depth and discharge estimates at the downstream site. Crucially, by using a fully physically-based dynamical model in the data assimilation scheme, it is possible to accurately estimate both the discharge and depth even when only fusing depth measurements.

#### 4 OPTIMIZING RESERVOIR OPERATIONS WITH MODEL-PREDICTIVE CONTROL (MPC)

The PipeDREAM solver enables optimal model-predictive control (MPC) strategies to be efficiently computed for urban drainage networks of arbitrary size and complexity, facilitating improved flood and CSO mitigation. MPC is a widely-used technique for control of dynamical systems that recursively computes the optimal schedule of control actions (e.g. valve operations) over a moving horizon, using predictions of the system state (e.g. pressure heads and flows) informed by forecasts of future inputs to the system (e.g. rainfall). MPC is particularly suitable for control of urban drainage systems, which suffer from constraints on actuator authority—meaning that valves and gates can only release a limited amount of water at a time and reservoirs may take a long time to empty completely. Thus, to achieve effective flood control or CSO mitigation, optimal control actions must be scheduled ahead of time based on predictions of future runoff inputs.

Consider the problem of determining the optimal valve opening strategy needed to maintain the water level in a set of reservoirs at constant set-points. In terms of our state-space model, this problem can be expressed using the constrained optimization routine:

Objective function:

$$\min \sum_{k=0}^N (\mathbf{x}_k - \bar{\mathbf{x}}_k)^2$$

Constraints:

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

$$\mathbf{u}_k \geq 0$$

$$\mathbf{u}_k \leq CA_o \sqrt{2gh}$$

Where  $\bar{\mathbf{x}}_k$  is a vector of the desired heads, and  $\mathbf{u}_k$  is the vector of control inputs representing the outlet discharge

from each controlled storage element. Because the actuators are valves,  $\mathbf{u}_k$  is physically constrained by the orifice equation. This quadratic program may be solved efficiently over each forecast horizon using the Goldfarb/Ilnani dual algorithm to determine the optimal schedule of valve opening positions needed to maintain the water level setpoint.

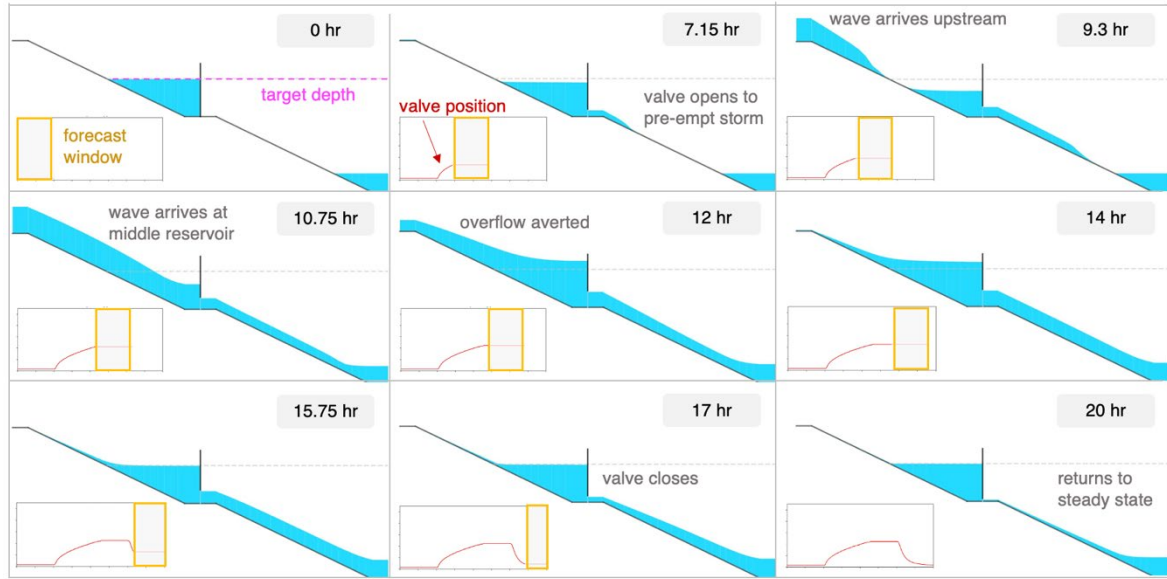


Fig. 2: Application of model-predictive control (MPC) to maintain a target depth in a three-reservoir channel network.

Fig. 2 demonstrates the results of MPC for a network consisting of three reservoirs in series connected by open channels. In this test case, the upstream reservoir is forced with a sudden runoff input, and the objective is to keep the water level in the middle reservoir as close as possible to its initial elevation. As shown in Fig. 2, the MPC strategy successfully keeps the water level in the middle reservoir near the desired setpoint. Using a forecast of the incoming hydrograph, the valve on the middle reservoir opens approximately two hours before the inflow hydrograph arrives at the reservoir upstream. This anticipatory control action allows the reservoir to empty sufficiently such that the incoming wave does not overwhelm the middle reservoir and cause it to overflow. After the incoming wave subsides, the valve closes to ensure that the water level remains at the desired setpoint. It should be noted that by incorporating the full Saint-Venant equations, the MPC strategy accounts for the travel time of the wave, as well as the effects of the backwater on the optimization routine. Although a linear network of junctions is presented here for demonstration purposes, the PipeDream solver allows the MPC implementation to be adapted to networks of arbitrary size and complexity.

## 5 CONCLUSION

This study describes new advances in system-scale state estimation and control of urban drainage networks enabled by the PipeDream hydraulic solver. Through two example case studies, it is demonstrated that (i) data assimilation via Extended Kalman Filtering improves estimates of depths and discharges at ungaged locations in urban drainage networks, and (ii) model-predictive control can be applied to reduce flooding and CSOs. Distinct from previous work, the PipeDream hydraulic solver enables direct implementation of state estimation and control algorithms using the full Saint-Venant equations for unsteady flow and does not require the use of linearization or surrogate models. By providing an efficient solver that admits a state-space representation, the PipeDream solver is expected to provide a platform for future research into system scale estimation and control in urban drainage networks.

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