https://doi.org/10.71573/cqe7mz81

Preventing Sewer System Overflows Through State Machine-Controlled Storage Tanks

Wellington T. Martins [1] https://orcid.org/0009-0003-3537-2381,
Moisés T. da Silva [2] https://orcid.org/0000-0002-8405-3518, *Mario A. P. Ramirez* [3,*],
Sebastian F. Reinecke [3] https://orcid.org/0000-0003-2705-0692
& Thiago A.M. Euzébio [1,3,4] https://orcid.org/0000-0003-2974-8621

[1] *Programa de Pós-Graduação em Instrumentação, Controle e Automação de Processos de Mineração, Universidade Federal de Ouro Preto e Instituto Técnologico Vale - Ouro Preto, MG*
[2] *Universidade Federal Rural de Pernambuco, Unidade Acadêmica de Belo Jardim, Belo Jardim, PE, Brasil*
[3] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Fluid Dynamics, Dresden, 01328, Germany*
[4] *Virtus-CC, Campina Grande, Brasil*
**Corresponding author email: m.parra-ramirez@hzdr.de*

Abstract
Automatic process control is a proven method for enhancing safety, productivity, and cutting operational costs across different industries. While some sectors have embraced advanced controllers, others are just starting to implement closed-loop systems. Urban sanitation systems often rely on basic on-off controllers, despite the critical role they play in managing urban effluents. Poor control can lead to environmental overflows. In our study, we maintain controller simplicity by using finite state machines but introduce two key enhancements: a centralized control strategy that monitors the entire tank system simultaneously and a fine-tuned strategy through optimization to minimize system overflows objectively. Testing the new controller in a simulated urban setting, considering effluent flow rates, quality variations, and rainfall changes, we achieved a significant 56% reduction overflow compared to the initial control proposal.

Highlights
- Finite State Machines enhanced efficiency in urban effluent storage tank-level control.
- The proposed controller is tuned using Simulated Annealing.
- A centralized control strategy that monitors the entire tank system simultaneously and minimizes overflows.

Introduction
Level control in tanks is a common application in process control, with various approaches employed for this purpose (Bishop, 2008). When dealing with many coupled tanks in a sewer system, level control can be challenging due to process delays, nonlinear characteristics, and complexities that may undermine the effectiveness of the control system (Basci e Derdiyok, 2016). In this context, it is essential to adopt suitable control strategies to address these challenges and achieve effective control. A sector that stands out in the use of tank level controls is sewer network systems, through storage tanks. The control of these tanks is crucial to reduce the frequency of overflows into water bodies, which are one of the main sources of water contamination (Botturi et al., 2020; Rathnayake e Faisal Anwar, 2019), thus posing a significant challenge for sewer system managers.

The literature presents several approaches to reduce overflow in storage tanks. Mahmoodian et al. (2017) use neural networks to maximize the available space in the pipes of the sewage system. Fu et al. (2010) study the control and distribution of storage tanks to minimize the impact of residential growth on water quality. Zhang et al. (2017) propose flow redistribution according to the capacity of the wastewater treatment plant (WWTP) to reduce overflows. Euzébio et al. (2023) introduce a control for pumps in tanks, reducing overflow and energy costs compared to traditional methods.

In this paper, we propose a new level control strategy for an integrated tank system designed to enhance storage capacity within urban sewer networks. Our proposal is based on a Finite State Machine (FSM), with parameter tuning achieved through an optimized solution. The controller operates centrally, monitoring the levels of all tanks simultaneously for decision-making. The objective is to balance the tank levels to reduce the volume of pollutants overflowed into the river. The proposed control strategy is compared to a decentralized control approach presented by Saagi et al. (2017).

Methodology

The Simulation Model of an Urban Sewer System

The BSM-UWS simulation model (Saagi et al., 2017) simulates the interaction between subsystems such as the sewage network, stormwater, and the WWTP, including water capture, rainfall generator, valve and pump control, and effluent transport, with storage tanks to prevent overflow.

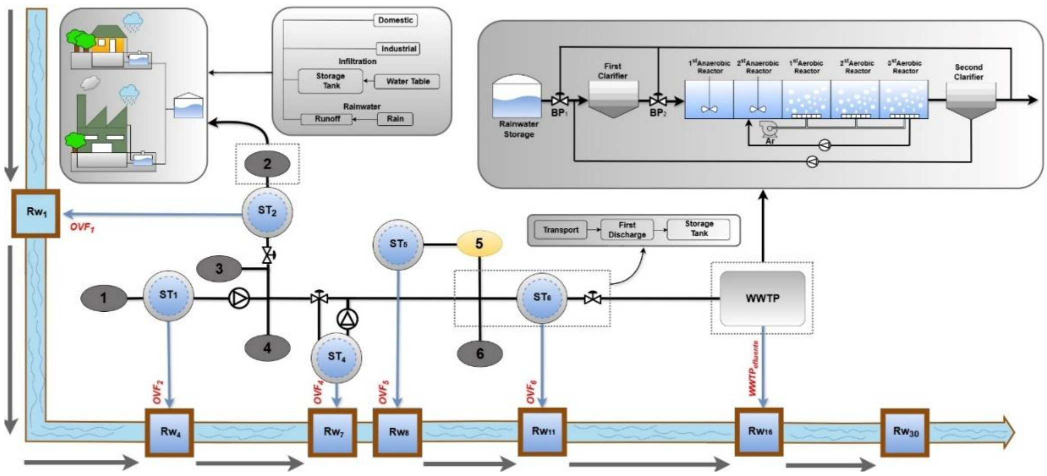

Figure 1. Basic schematic of the BSM-UWS. Adapted from: Saagi et al. (2017).

The proposed control system and parameter tuning method using Simulated Annealing

The FSM control strategy was implemented in the tank system of the BSM-UWS model, consisting of five tanks (ST_1, ST_2, ST_3, ST_4, and ST_6), with ST_5 isolated and having no impact on the control process. The goal is to minimize overflows by utilizing the available storage capacity of the entire system of tanks. In FSM1 (Figure 2a), which controls Pump 1, three operating modes (0%, 63%, and 100%) are defined based on the levels of Tanks 1 and 4, using hierarchical states and reference levels (L_h, L_{i1}, L_{i2}). Transitions include dead zones and a 30-minute delay to prevent wear, except under critical low-level conditions. FSM2 (Figure 2b), controls a valve with two opening modes (50% and 100%), based on the levels of Tanks 2 and 4. FSM4 (Figure 2c), combines the control of a pump, operating similarly to FSM1, and a valve, which redirects all bypass flow ($Q_{deviation}$) to Tank 4 if Tank 6's level exceeds L_h; otherwise, a percentage ($P_{deviation}$) is sent to Tank 4, with the remaining flow directed to Tank 6.

The parameters L_h, L_{i1}, L_{i2} and $P_{deviation}$ are crucial for the effective operation of the FSM, but determining them through trial and error can be time demanding, especially as the number of parameters increases. To overcome this challenge, a tuning methodology based on the Simulated Annealing metaheuristic was developed, suitable for discrete optimization problems. The objective was to minimize the total overflow of the process by adjusting the ideal values of the control parameters, as defined by the cost function (1). The constraints for this problem are described by (2) to (7). The limits from 50% to 100% of $P_{deviation}$ were defined based on the operational limits of the simulator. In constraints (8), (9), and (10), a step size of 0.1 was chosen for each decision variable. This choice was made to reduce the solution space, resulting in a more computationally efficient search.

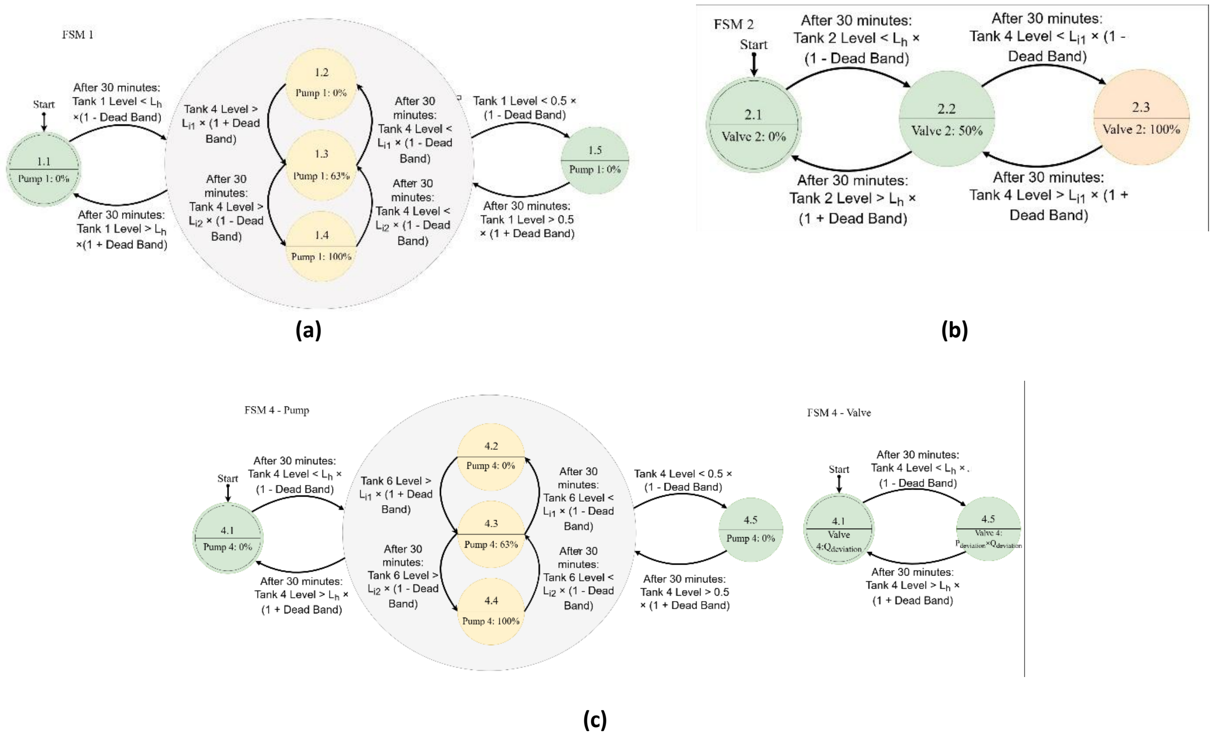

Figure 2. Finite State Machine for the storage tank system of the BSM-UWS.

Objective Function:

$$min_{L_h, L_{i1}, L_{i2}, P_{deviation}} = Overflow_{ST1} + Overflow_{ST2} + Overflow_{ST3} + Overflow_{ST4} + Overflow_{ST6} \quad (1)$$

Subject to:

$$\frac{Lim_{tank}}{2} \leq L_h \leq Lim_{tank} \quad (2)$$

$$0 \leq L_{i1}, L_{i2} \leq Lim_{tank} \quad (3)$$

$$50\% \leq P_{deviation} \leq 100\% \quad (4)$$

$$L_h = \{2{,}5 + 0{,}1n \mid n \in \{0,1,2,\dots,25\}\} \quad (5)$$

$$L_{i1}, L_{i2} = \{0{,}1n \mid n \in \{0,1,2,\dots,50\}\} \quad (6)$$

$$P_{deviation} = \{0{,}5 + 0{,}1n \mid n \in \{0,1,2,\dots,5\}\} \quad (7)$$

Results and discussion

The tuning was performed using the Simulated Annealing algorithm, aiming to minimize overflows in the sewer system over a 20-day period, including both dry and rainy periods. The termination criterion was met when the objective function stabilized, indicating convergence to an optimal value (Figure 3a). The optimal solution obtained (Figure 3b) was applied to a scenario with a 6-hour precipitation delay between the tanks, and subsequently, the Benchmark and Optimized FSM strategies were compared. Additionally, there was a redistribution of volumes among the storage tanks, with a reduction in the volume directed to tank 6, as shown in Figure 3c. In terms of the storage tanks, an overall reduction of approximately 56% in the total overflow volume was observed. River quality improved, with an increase in the minimum dissolved oxygen concentration (Cmin,OD) and a reduction in the time below the permissible limit (Texc,OD), achieving a decrease of up to 15.35% (Table 1). At the WWTP, the bypassed volume was reduced by up to 13.57%, improving the overflow quality index, although the effluent quality and operational cost indices showed minimal variation.

Conclusions and future work

Improvements in river quality were observed, such as higher minimum dissolved oxygen concentrations and reduced time below the permissible limit, although the maximum un-ionized ammonia concentration remained unchanged. At the WWTP, the strategy reduced bypassed volume, improving the overflow quality index and the efficiency of directing wastewater for treatment, despite no significant improvements in effluent quality and operational cost indices, highlighting the need for complementary strategies. These results underscore the potential of the FSM Optimal strategy to enhance sewer system performance under variable rainfall conditions.

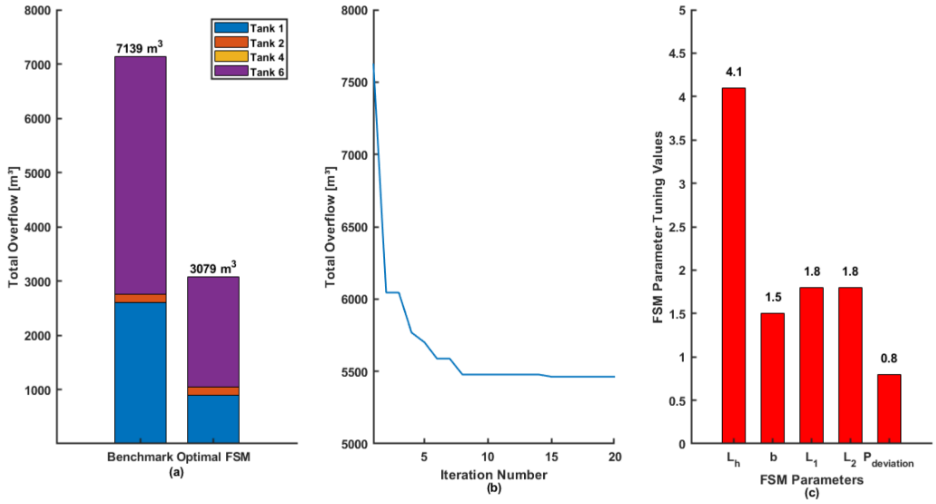

Figure 3. (a) Convergence of the objective function defined as the total overflow of the storage tank systems, (b) optimal values found for the FSM parameters and (c) comparative analysis of the operating categories of integrated Benchmark tanks and with Optimal FSM

Table 1. Performance of the various subsystems (Sewer, River, and WWTP) of the BSM-UWS.

	Benchmark	Optimal FSM	Difference (%)
Performance of the Sewer System			
Total Overflow [m³]	7139	3079	-56.87%
Overflow Quality Index [Kg Unit Pollutants/Day]	6345	2463	-61.18%
Overflow Frequency	10	6	-40.00%
Overflow Duration [h]	7	5	-28.57%
Performance of River Quality			
C_min,OD [g O_2/m³]	4.80	4.96	3.30%
C_max,NH_3 [g N/m³]	0.03	0.03	0.00%
T_exc,NH_3 [h]	59.25	62.17	-4.93%
T_exc,DO [h]	62.08	57.5	-7.38%
Performance of the Treatment Plant			
Effluent Quality Index [Kg Unit Pollutants/Day]	6721.38	6740.59	-0.29%
Operational Cost Index	20399.67	20408.59	-0.04%
Bypass Quality Index [Kg Unit Pollutants/Day]	64.05	57.44	-11.51%
Total Volume Diverted (Bypass) [m³]	577130	529970	-8.17%

References

Ba¸sçi, A. e Derdiyok, A. (2016). Implementation of an adaptive fuzzy compensator for coupled tank liquid level control system. Measurement, 91, 12–18.

Bishop, R.C.D.R.H. (2008). Modern Control Systems. Pearson Prentice Hall.

Botturi, A., Ãzbayram, G., Tondera, K., Gilbert, N., Rouault, P., Caradot, N., Gutierrez, O., Daneshgar, S., Frison, N., Akyol, Ã., Foglia, A., Eusebi, A., e Fatone, F. (2020). Combined sewer overflows: A critical review on best practice and innovative solutions to mitigate impacts on environment and human health. Critical Reviews in Environmental Science and Technology, 51, 1–34. doi:10.1080/10643389.2020.1757957.

Euzébio, T.A., Ramirez, M.A., Reinecke, S.F., e Hampel, U. (2023). Energy price as an input to fuzzy wastewater level control in pump storage operation. IEEE Access, PP, 1–1. doi:10.1109/ACCESS.2023.3310545.

Fu, G., Khu, S.T., e Butler, D. (2010). Optimal distribution and control of storage tank to mitigate the impact of new developments on receiving water quality. Journal of Environmental Engineering, 136(3), 335–342.

Mahmoodian, M., Delmont, O., e Schutz, G. (2017). Pollutionbased model predictive control of combined sewer networks, considering uncertainty propagation. International Journal of Sustainable Development and Planning, 12, 98–111. doi: 10.2495/SDP-V12-N1-98-111.

Saagi, R., Flores-Alsina, X., Kroll, S., Gernaey, K.V., e Jeppsson, U. (2017). A model library for simulation and benchmarking of integrated urban wastewater systems. Environmental Modelling & Software, 93, 282–295.

Zhang, D., HÃ¸lland, E., Lindholm, G., e Ratnaweera, H. (2017). Hydraulic modeling and deep learning based flow forecasting for optimizing inter catchment wastewater transfer. Journal of Hydrology, 567. doi:10.1016/j.jhydrol.2017.11.029.