INSTITUTE FOR HOMELAND SECURITY

Twin Streams: Simulating Biological Wastewater Treatment with Leak-Sensitive Digital Twin Systems

Xing Liu, Ph.D.

Sam Houston State University™

Twin Streams: Simulating Biological Wastewater Treatment with Leak-Sensitive Digital Twin Systems

Xing Liu, Ph.D.
Department of Computer Science
Sam Houston State University

Abstract

The growing need for sustainable urban infrastructure produced the rapid integration of digital twin technology in environmental systems like wastewater management. In this work, we introduce a Simulink-based digital twin system to simulate, monitor, and optimize the dynamics of a smart wastewater treatment system. The system models several key components like influent flow dynamics, chemical treatment reactions, and sensor-based feedback loops within a virtual environment for real-time control and performance monitoring. The simulation integrates dynamic input parameters and chemical interactions to replicate realistic operational conditions. Special attention is given to process synchronization, sensor integration, and the determination of optimal control strategies for reducing pollution load. The system enables testing under variable flow conditions, fault injection analysis, and possible integration with IoT platforms. Our findings confirm the prediction accuracy of the proposed model in estimating treatment efficiency and helping decision-making in smart water infrastructure planning. This research shows how digital twins can close the gap between theoretical wastewater system designs and practical, real-time environmental implementations.

Keywords: Digital Twin, Wastewater Management, Simulink, Environmental Simulation, Smart Infrastructure, Process Control, Chemical Modeling, Real-Time Monitoring

Contents

Introduction

Urbanization, industrial expansion, and increasing environmental problems brought new challenges to the sustainable management of municipal Wastewater Treatment Plants (WWTPs). These systems are integral to protecting public health and the environment, yet they are inherently complex, nonlinear, and can allow operational inefficiencies and failures. In recent years, digital twin (DT) technology has emerged as a transformative pattern for enhancing the monitoring, optimization, and control of such infrastructure systems. A digital twin is a real-time, dynamic digital replica of a physical system that enables simulation, diagnosis, and decision-making through continuous synchronization with operational data.

The integration of digital twins in WWTPs presents a significant opportunity to improve process visibility, fault detection, and predictive maintenance. By creating a virtual representation of biological and chemical processes within the treatment plant, operators can simulate different failure scenarios, optimize resource allocation, and enhance effluent quality management. Liu et al. demonstrated the use of convolutional autoencoder-based digital twin frameworks for real-time fault detection in WWTPs, addressing failures such as sludge bulking and toxic impacts with improved detection performance and early warning capabilities [1]. Similarly, a study by Chen and Kao explored the role of DTs in supporting proactive maintenance and energy optimization in WWTPs, further highlighting the value of real-time process monitoring and adaptive control [2].

Despite these advancements, practical implementations remain limited due to the complexity of biochemical interactions, variability in influent composition, and difficulties in real-time data acquisition and model calibration. To address these challenges, recent research has emphasized the integration of machine learning, control theory, and digital modeling. A promising direction involves the development of simulation-based digital twins using Simulink/Matlab, which allow for replicating dynamic system behavior under different load conditions and control strategies.

In this paper, we present a digital twin model developed in Simulink that simulates the core processes of wastewater treatment process. Our implementation focuses on key state variables such as biomass concentration, chemical oxygen demand (COD), and ammonia nitrogen (NH_4^+-N) to evaluate treatment performance over time. Our implementation incorporates a leak simulation module that dynamically alters influent flow conditions, offering a practical testbed for investigating system responses to anomalies such as pipeline leakage or pump failure. Also, the system enables real-time visualization and signal logging, allowing users to analyze component-level behaviors, simulate different operational scenarios, and gain deeper insights into system interactions. The model includes fault tracking and future integration with optimization frameworks. The goal is to demonstrate a replicable and scalable framework for digital twin modeling that can support more intelligent and sustainable wastewater treatment operations. This effort builds upon the foundation of prior digital twin methodologies.

Related Works

Digital twin (DT) technology has emerged as a transformative solution in the water and wastewater sectors, offering real-time modeling, monitoring, and control capabilities. Recent research has focused on integrating DTs into both collection systems and water resource recovery facilities (WRRFs) to enhance operational efficiency and system responsiveness. Lumley et al. [3] explored the application of two digital twin platforms (Future City Flow and TwinPlant), demonstrating how coordinated DTs can facilitate predictive control under wet-weather conditions. Their study emphasized the potential of DTs to bridge the gap between collection networks and WRRFs, providing utilities with tools for system-wide optimization, improved energy efficiency, and reduced overflow risks.

The advancement of simulation environments for water quality and hydrologic modeling has also been central to recent innovations. Bowen et al. [4] introduced a Simulink-based modeling framework for teaching and research, incorporating mass-balance principles to model eutrophication and stormwater runoff. Their work illustrates how dynamic system modeling environments such as MATLAB/Simulink can enhance understanding of complex processes in natural and engineered water systems, enabling both educators and practitioners to create modular, reusable simulations without traditional programming overhead.

Complementing these efforts, Liu et al. [1] proposed a digital twin-based fault detection framework tailored for wastewater treatment processes. Their system utilizes a convolutional autoencoder to monitor anomalies such as sludge bulking and toxic impacts, leveraging Bayesian fusion and multi-block modeling to ensure robust fault detection. This approach highlights the importance of combining deep learning with DTs to address the nonlinear, dynamic nature of WWTPs and to ensure process reliability through virtual fault replication and real-time diagnostics.

Emerging sensor technologies have also contributed to real-time monitoring within digital twin ecosystems. Antonini et al. [5] developed a novel camera-based sensor system for low-turbidity wastewater monitoring. Their machine learning-enhanced solution achieves high accuracy in classifying turbidity levels and predicting absorbance values, even in challenging effluent conditions. This innovation not only enhances monitoring granularity but also aligns with the goals of DT frameworks that rely on high-resolution, continuous data streams to update and validate their virtual counterparts.

Wang et al. [6] present a comprehensive review of digital twins tailored for wastewater treatment systems, defining the foundational concepts, key technological enablers, and domain-specific applications. Their work highlights how DTs are evolving from mere simulation tools into dynamic systems that integrate hardware (e.g., sensors, pumps, reactors) and software (e.g., hybrid models, IoT platforms, control systems). Notably, the authors stress the importance of model-based system engineering (MBSE), IoT, and AI in realizing real-time feedback loops essential for optimized decision-making in wastewater operations. The review also underscores the scalability challenges and integration complexity when transitioning WWTPs from static to intelligent infrastructures.

The optimization of operational strategies in municipal wastewater plants using DT modeling is further investigated by Chen and Kao [2]. This study demonstrates the use of dynamic simulations and historical data analytics to improve plant-wide process control. It showcases how DTs can serve as a decision-support tool, aligning with sustainability goals while addressing variability in influent characteristics. The application of predictive models, coupled with scenario-based simulations, is shown to significantly enhance the overall system responsiveness, especially under changing load conditions.

In parallel, Marino et al. [7] explore sensor-based innovations in wastewater quality monitoring that complement the DT paradigm. Their study validates the effectiveness of protein-like fluorescence sensors in capturing key water quality parameters such as COD and contaminants of emerging concern (CEC) in real time. These sensors offer low-cost, high-frequency insights that are otherwise difficult to obtain through traditional lab-based methods. Their integration into advanced oxidation process (AOP) systems and tertiary treatment setups reveals a promising route to enable continuous feedback for DT-based models, potentially reducing carbon footprint through process optimization.

Additionally, the role of real-time control (RTC) in pollution-based sewage system management is thoroughly examined by Gesser et al. [8]. Their review categorizes control-oriented modeling techniques that integrate water quality parameters such as COD and ammonia directly into the control algorithms. These pollution-based RTC (P-RTC) systems enhance overflow prevention and optimize inflow distribution to WWTPs. Importantly, the work outlines how simplified dynamic models, probabilistic approaches, and machine learning algorithms can be harmonized with DT platforms to refine real-time control decisions and increase network resilience.

In contrast to existing studies that primarily emphasize either static process modeling, predictive analytics, or fault detection in isolation, our work proposes an integrated digital twin framework that not only simulates dynamic flow variations and leak conditions in real time but also incorporates biological reaction behavior and system-level responsiveness. Unlike prior efforts that focus on steady-state assumptions or narrow system parameters, our implementation enables multi-variable simulation and user-driven testing within a flexible Simulink environment. This holistic approach allows stakeholders to visualize, assess, and refine wastewater management strategies under realistic operational scenarios bridging the gap between conceptual modeling and deployable smart infrastructure. Through its significance on modular design, control toggling, and leak scenario injection, our system advances the practical applicability of digital twins in wastewater treatment plant.

System Architecture

The proposed digital twin architecture for wastewater treatment is designed to simulate and analyze the dynamic behavior of a biological wastewater treatment plant under varying operational and environmental conditions. The system consists of modular components representing physical subsystems, such as influent flow control, biological reaction chambers, clarifiers, and sludge handling units, each modeled as parameterized blocks in Simulink. These modules are interconnected to reflect the physical topology of a real-world wastewater treatment plant, allowing for closed-loop simulation and real-time analysis of key variables like chemical oxygen demand (COD), ammonium concentration (NH_4^+-N), heterotrophic and autotrophic biomass levels, and sludge flow.

A central feature of the architecture is the Leak Simulation Module, which introduces anomalies into the influent stream to assess system resilience and response strategies. This module acts as a configurable disturbance generator, capable of injecting synthetic leakage profiles or flow disruptions. A switching control mechanism enables manual override or automated input control through set-point variation, supporting a wide range of simulation scenarios.

The Biological Reactor Block models microbial activity and nutrient transformation based on Monod kinetics. It dynamically adjusts COD and NH_4^+-N concentrations based on biomass interaction, enabling accurate emulation of treatment efficiency over time. The Clarifier Sludge Module captures sedimentation behavior and residual nutrient levels in the treated effluent, completing the process cycle.

Signal logging and visual output blocks are embedded throughout the system to facilitate data extraction and performance evaluation. Users can simulate the effect of policy changes, leaks, or inflow rate variations, and observe system-wide impacts in real time. The Simulink model is flexible and scalable, supporting future integration with supervisory control systems or IoT sensor networks.

Fig. 1 illustrates the overall system model, showing the interconnections between the influent control units, biological reactor, leak simulation, and effluent monitoring subsystems.

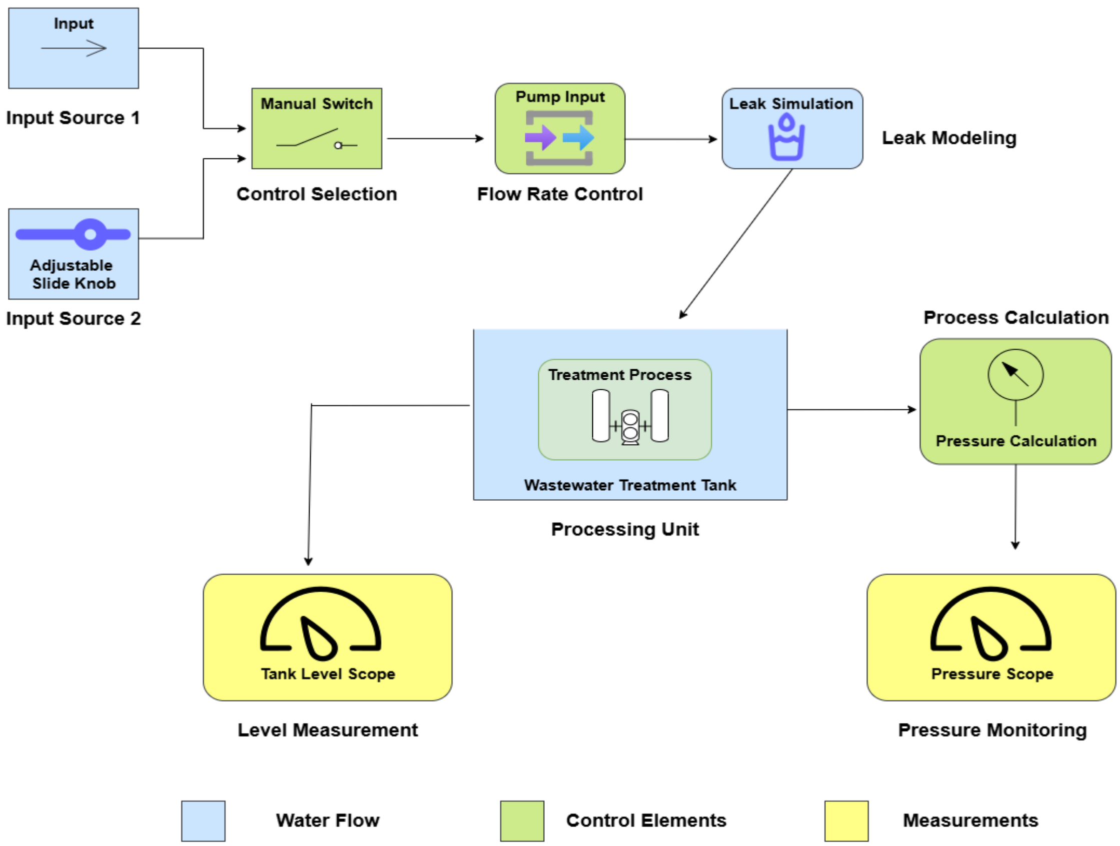

Figure 1: System architecture of the Digital Twin-based Wastewater Treatment System, integrating input control, leak simulation, biological processing, and real-time monitoring of level and pressure metrics, enabling dynamic analysis and system optimization.

Main Approach

This section details the simulation methodology used to construct and evaluate the digital twin for the wastewater treatment plant system. The model captures both physical dynamics (e.g., flow regulation, leaks, tank levels) and biological treatment processes (e.g., COD and ammonium degradation), with integration of virtual sensors and adjustable parameters to mirror operational variability.

Input Control and Flow Regulation

The simulation begins with dual input sources: a step function for automated input and manual control via a slide knob as in Fig. 2. A switching mechanism determines the mode of control. The selected signal is amplified through a pump gain block, emulating variable influent conditions based on system demand or external triggers. Leak disturbances are introduced through a custom function block (LeakSimulation) to simulate real-world anomalies such as pipe bursts or valve malfunctions.

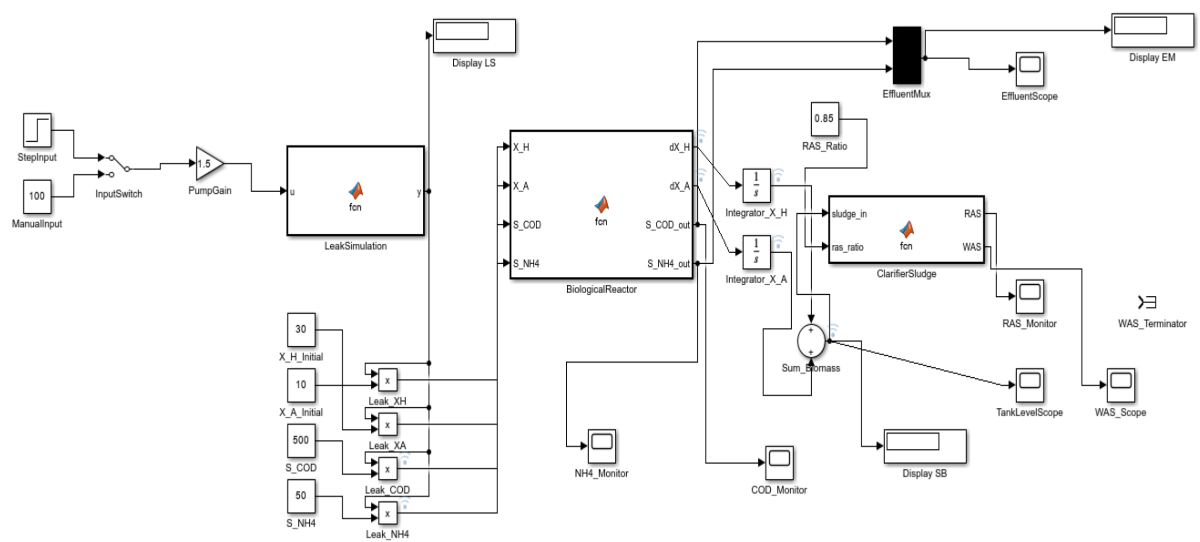

Figure 2: Digital Twin Model – Wastewater Treatment System Simulink Model.

Biological Reactor and Clarification Process

The wastewater stream passes into a biological reactor modeled after the Activated Sludge Process (ASP), which supports the growth of aerobic microorganisms for pollutant degradation as in Fig. 3. Also In addition, a summary of key notations is provided in Table 1.

Summary of Notations

Notation	***Description***
S_{COD}	Soluble Chemical Oxygen Demand (mg/L)
S_{NH_4}	Ammonium concentration (mg/L)
X_H	Heterotrophic biomass concentration (mg/L)
X_A	Autotrophic biomass concentration (mg/L)
RAS	Return Activated Sludge flow rate (mg/L)
WAS	Waste Activated Sludge flow rate (mg/L)
S_COD_out	Effluent COD concentration (mg/L)
$S\_NH_4^+\_out$	Effluent ammonium concentration (mg/L)
dX_H	Change in heterotrophic biomass over time
dX_A	Change in autotrophic biomass over time
$Pump_{Gain}$	Gain applied to pump input signal
T	Simulation time (seconds)

This subsystem incorporates two key microbial pathways:

- **Heterotrophic Oxidation**: Organic pollutants, measured by Chemical Oxygen Demand (COD), are metabolized by heterotrophic bacteria. The kinetics of biomass growth and decay follow Monod-based differential equations:

$$\frac{dX_H}{dt} = \mu_H \cdot X_H \cdot \left(\frac{S_{COD}}{K_S + S_{COD}}\right) - b_H \cdot X_H$$

- **Autotrophic Nitrification**: Ammonium (NH_4^+-N) is biologically oxidized to nitrate (NO_3^-–N) via autotrophic bacteria (e.g., Nitrosomonas, Nitrobacter), governed by:

$$\frac{dX_A}{dt} = \mu_A \cdot X_A \cdot \left(\frac{S_{NH4}}{K_{NH4} + S_{NH4}}\right) - b_A \cdot X_A$$

After microbial treatment, the flow enters a clarifier module which separates solid biomass from treated effluent. A fraction of the biomass (Return Activated Sludge – RAS) is recycled to sustain microbial population, while excess sludge (Waste Activated Sludge – WAS) is removed to prevent overaccumulation.

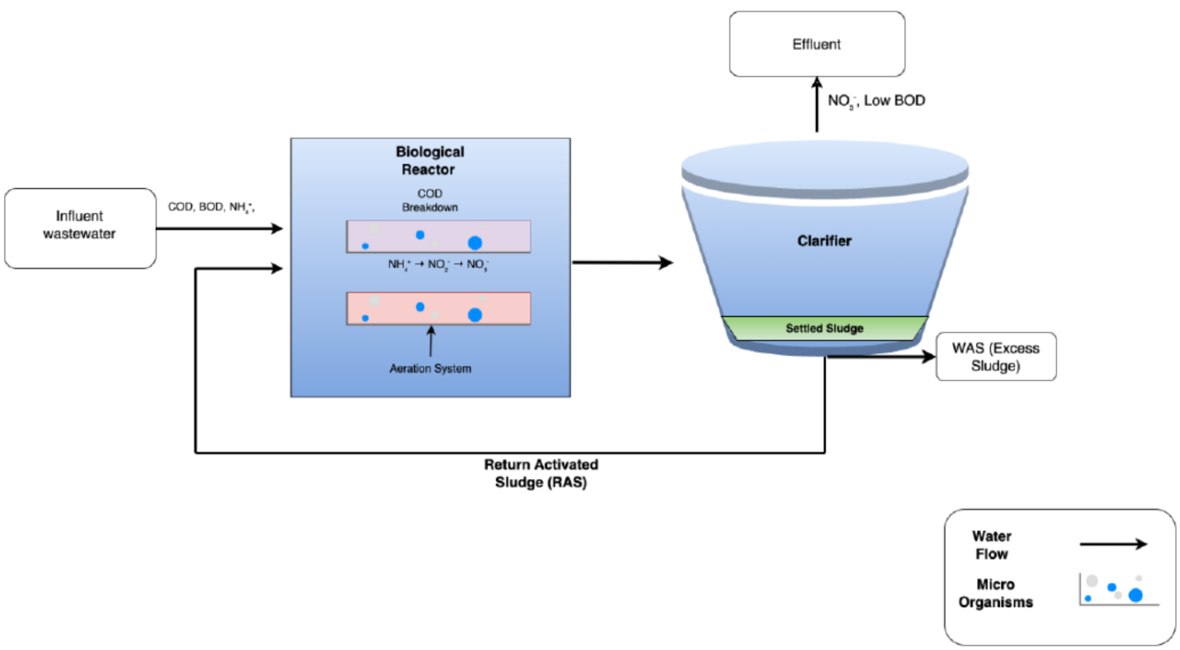

Figure 3: Biological Treatment Process (biochemical process breakdown).

Monitoring and Visualization

Real-time monitoring is embedded through virtual scopes in Simulink, measuring tank levels, effluent quality, sludge balance, and nitrogen content. Key outputs include “TankLevelScope”, “COD_Monitor”, “NH4_Monitor”, and “EffluentScope”. These indicators enable simulation-based evaluation of treatment performance under varying conditions and disturbances.

Integration of Control and Sensing

The model is designed to dynamically adjust flow and react to simulated disturbances. By tuning parameters such as PumpGain, RAS_Ratio, and initial biomass concentrations, the digital twin can mimic realistic operational strategies used in Wastewater Treatment plants. This adaptability facilitates predictive diagnostics and control optimization, advancing the utility of digital twin frameworks in environmental engineering.

Performance Evaluation

To evaluate the performance and responsiveness of the proposed digital twin system, we conducted a comprehensive simulation study using MATLAB/Simulink. The simulation assessed the dynamic behavior of key parameters within the wastewater treatment process, particularly under controlled leak scenarios and input perturbations. The primary focus was on the concentration profiles of COD (Chemical Oxygen Demand), (Ammonium), RAS (Return Activated Sludge), tank biomass level, and WAS (Waste Activated Sludge) output. Fig. 4 presents the time-series plots of critical system outputs during the simulation period. As shown in the top-left and top-right plots, the COD and concentrations remained relatively stable over the course of the simulation. The COD concentration stabilized around 750 mg/L, while fluctuated minimally around 70 mg/L. These trends indicate that the biological reactor component of the digital twin was effective in consistently regulating pollutant concentrations, even in the presence of simulated disturbances.

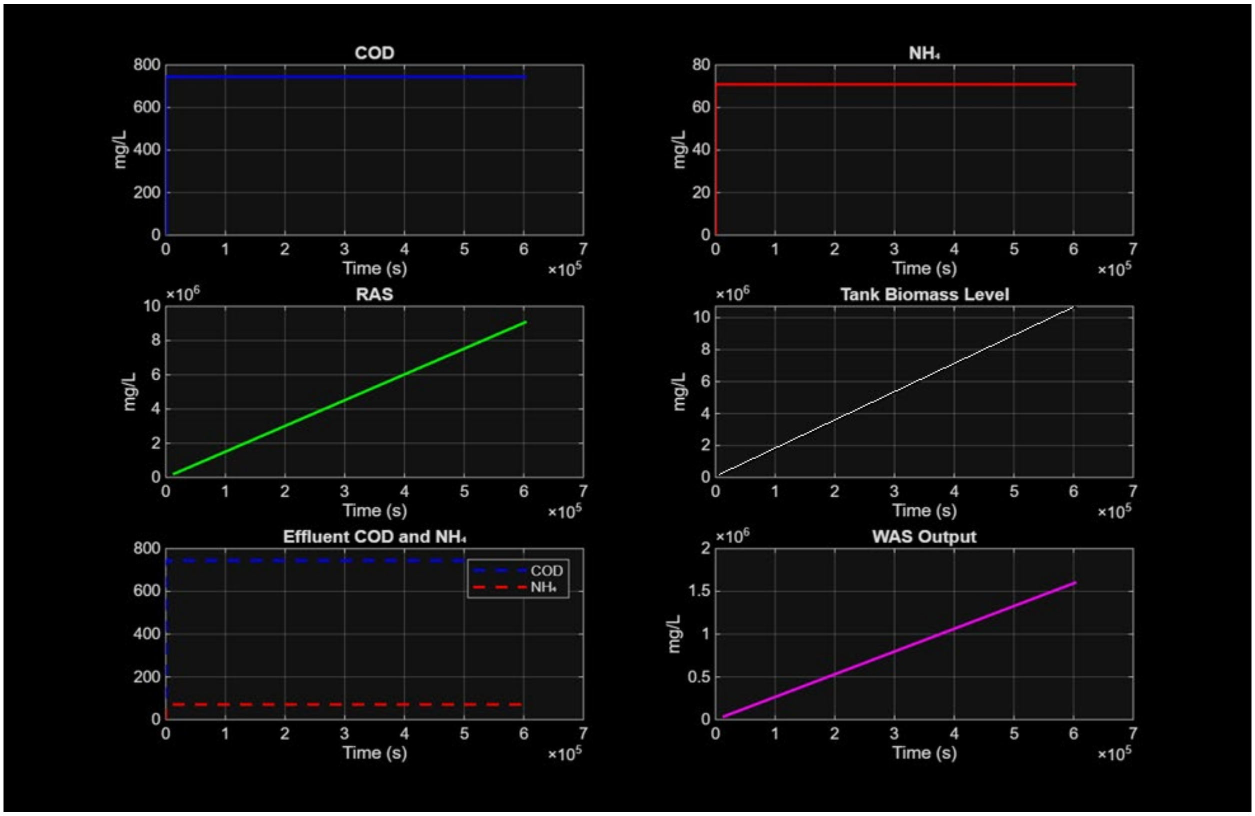

Figure 4: Simulation results of the Simulink model

The middle-left subplot depicts the progressive increase of RAS concentrations, suggesting the accumulation of activated sludge being redirected into the treatment process. In parallel, the middle-right subplot highlights the linear rise in total biomass within the tank. These growth trends align with expected biological dynamics and validate the proper functioning of sludge recirculation and microbial proliferation within the model.

The bottom-left plot overlays effluent COD and levels, both of which remain well below influent values, confirming effective pollutant removal and degradation over time. The levels in the effluent, in particular, were reduced to nearly 10% of their initial concentrations, indicating successful nitrification processes.

Finally, the WAS output curve in the bottom-right subplot shows a steady upward trajectory, reflecting the removal of excess sludge. This behavior is consistent with the sludge balance principle and demonstrates the ability of the model to simulate and control solids retention and discharge effectively.

Overall, the performance metrics indicate that the digital twin implementation provides a stable, responsive, and biologically accurate simulation of a wastewater treatment plant. The integration of control modules for flow input and leak modeling adds a valuable layer of realism and demonstrates the potential for predictive diagnostics and system optimization in real-world deployments.

Conclusion

This paper presents a simulation-based digital twin framework for wastewater treatment systems, focusing on replicating core processes such as biological treatment, sludge management, and flow regulation. By integrating real-time control inputs, leak simulation, and biological reaction modeling into a cohesive Simulink environment, the proposed system enables accurate replication of key performance indicators such as COD reduction, ammonium degradation, and biomass accumulation.

The experimental results demonstrated that the model effectively captures the dynamic behavior of a wastewater treatment process, maintaining effluent quality within acceptable limits even under fluctuating inputs and simulated anomalies. The integration of monitoring scopes for tank levels, effluent concentration, and sludge flow further enhances system observability and lays the foundation for predictive diagnostics.

Unlike traditional static simulations, the digital twin architecture offers a modular, real-time platform that can adapt to changing environmental conditions and operational configurations. This adaptability is essential for future applications involving remote supervision, control optimization, and anomaly detection in smart water infrastructure.

Future work may focus on enhancing the digital twin's fidelity through integration with live sensor data, implementing fault-tolerant control strategies, and expanding the model to include additional treatment stages such as disinfection and advanced nutrient removal. Another promising direction involves leveraging digital twins for cybersecurity monitoring by detecting anomalous sensor readings that may indicate system faults or potential hacking attempts. Even a single deviation from expected behavior can be critical in infrastructure systems like wastewater treatment. Incorporating anomaly detection logic and integrating AI models that learn “normal” operation patterns could transform digital twins into proactive tools for intrusion detection. Additionally, future extensions may consider integrating temperature-dependent kinetics into the biological reactor block. Since temperature significantly affects microbial activity, reaction rates, and oxygen solubility, modeling its impact would enable simulation of seasonal variations, thermal shock events, or failures like aerator malfunction. As digital twin technology continues to evolve, its application in sustainable urban water management holds significant promise for improving efficiency, transparency, and resilience in environmental systems.

References

[1] W. Liu, S. He, J. Mou, T. Xue, H. Chen, and W. Xiong, “Digital twins-based process monitoring for wastewater treatment processes,” *Reliability Engineering & System Safety*, vol. 238, p. 109416, Oct. 2023, doi: 10.1016/j.ress.2023.109416.

[2] K.-J. Chen and C.-M. Kao, “Optimization of municipal wastewater treatment plants management through digital twin modeling,” *Journal of Environmental Engineering*, vol. 151, no. 4, Apr. 2025, doi: 10.1061/joeedu.eeeng-8046.

[3] D. J. Lumley, F. Polesel, H. Refstrup Sørensen, and L.-G. Gustafsson, “Connecting digital twins to control collections systems and water resource recovery facilities: From siloed to integrated urban (waste)water management,” *Water Practice & Technology*, vol. 19, no. 6, pp. 2267–2278, May 2024, doi: 10.2166/wpt.2024.128.

[4] J. Bowen, D. Perry, and C. Bell, “Hydrologic and water quality model development using simulink,” *Journal of Marine Science and Engineering*, vol. 2, no. 4, pp. 616–632, Nov. 2014, doi: 10.3390/jmse2040616.

[5] G. Antonini, J. M. Pearce, F. Berruti, and D. Santoro, “A novel camera-based sensor for real-time wastewater quality monitoring,” *Water Practice & Technology*, vol. 19, no. 9, pp. 3778–3793, Aug. 2024, doi: 10.2166/wpt.2024.211.

[6] A.-J. Wang *et al.*, “Digital twins for wastewater treatment: A technical review,” *Engineering*, vol. 36, pp. 21–35, May 2024, doi: 10.1016/j.eng.2024.04.012.

[7] L. Marino, R. Todesco, E. Gagliano, D. Santoro, and P. Roccaro, “Real-time wastewater quality monitoring by fluorescence sensors: Validation for COD and CEC monitoring and implication for carbon footprint reduction,” *Science of The Total Environment*, vol. 963, p. 178464, Feb. 2025, doi: 10.1016/j.scitotenv.2025.178464.

[8] R. da Silva Gesser, H. Voos, A. Cornelissen, and G. Schutz, “A review of pollution-based real-time modelling and control for sewage systems,” *Heliyon*, vol. 10, no. 11, p. e31831, Jun. 2024, doi: 10.1016/j.heliyon.2024.e31831.

INSTITUTE FOR HOMELAND SECURITY

The Institute for Homeland Security at Sam Houston State University is focused on building strategic partnerships between public and private organizations through education and applied research ventures in the critical infrastructure sectors of Transportation, Energy, Chemical, Water / Wastewater, Healthcare, and Public Health.

The Institute is a center for strategic thought with the goal of contributing to the security, resilience, and business continuity of these sectors from a Texas Homeland Security perspective. This is accomplished by facilitating collaboration activities, offering education programs, and conducting research to enhance the skills of practitioners specific to natural and human caused Homeland Security events.

[Institute for Homeland Security](#)
[Sam Houston State University](#)

Liu, X. (2025). Twin Streams: Simulating Biological Wastewater Treatment with Leak-Sensitive Digital Twin Systems (Institute for Homeland Security Report No. 2025-1028). Institute for Homeland Security.
https://doi.org/10.17605/OSF.IO/MZGF8