

## **Operational Control Strategies for Wastewater Treatment Plants During Overflow Events in Saudi Arabia**

I. M. Elshaigy<sup>1</sup>, G.A. Gasmelseed<sup>2</sup>, I.H. Elamin<sup>3</sup>, Z. A. Hamad<sup>4</sup>

Department of Chemical Engineering, Faculty of Engineering, University of Science and Technology, Khartoum, Sudan.

1 Corresponding Author: elshaigy78yahoo.com

Telephone: +966554653025, +966542833810, +249912306041, +249919634134

doi.org/10.51505/ijaemr.2026.11502

URL: <http://dx.doi.org/10.51505/ijaemr.2026.11502>

Received: Sep 21, 2026

Accepted: Sep 28, 2026

Online Published: Oct 06, 2026

### **Abstract**

Wastewater treatment plants are extremely important for people's health and for water resource management, especially in fast-growing cities. These systems are facing more and more problems such as unexpected hydraulic loads, operational problems and environmental changes. These issues can reduce the effectiveness of treatment and cause spills and uncontrolled discharges. These challenges require improved monitoring and control systems that can respond to changing conditions while maintaining safe and stable operation. The main aim of the research is to study the performance of various control structures in maintaining the system stability in uncertain conditions and under unexpected flow changes. The present study takes into account the modeling and control of wastewater treatment processes with the different control frameworks and simulation scenarios that are closely representative of the real-world operating conditions described in the study. The results showed that advanced control strategies, especially robust control strategies, are more effective than conventional ones in handling overflow situations. The proposed control systems are more stable, faster and better at disturbance rejection in the presence of uncertain and varying hydraulic loads. This indicates their effectiveness in actual wastewater treatment conditions in Saudi Arabia.

**Keywords:** wastewater, water resources, treatment, and simulation scenarios.

### **1. Introduction**

An urban wastewater treatment system is one of the most important parts of infrastructure for protecting the environment, keeping people healthy and managing water resources in a way that is good for the long term. As urbanization and population/industrial growth continue, wastewater treatment plants (WWTPs) are increasingly susceptible to dynamic hydraulic loads, unexpected influent surges, or operational challenges that push treatment units beyond their optimal operating envelopes. These issues can lower treatment efficiency and raise the danger of

environmental and public health consequences, especially when overflow events result in the discharge of untreated wastewater into receiving water bodies [1].

Increased effluent quantities might present operational issues that are difficult for wastewater treatment plant operators and designers to anticipate. The initial step from a process control view point is to determine the flow rates at which problems may arise. These are referred to as overflow events and they can make a big, if not grand, difference in the effectiveness of the treatment process [2].

The present study is mostly based on the original study and it is on modeling, simulation and control of the processes for treating wastewater in this case. The study examines different control architectures, including classical feedback, optimal control, feedforward, and resilient H-infinity control, in various disturbance scenarios that mimic the uncertainties associated with real-world operation.

The research shows that a smart selection and tuning of controllers, in conjunction with simulation environments, can enhance process stability, decrease overflow occurrences, and boost the overall system robustness and treatment efficacy.

### *1.1. Statement of the Problem*

Monitoring of critical process variables at wastewater treatment plants is challenging due to variable flow rates, pollutant concentrations and equipment problems. The overflow may occur when the capacity is too large. This means that raw sewage is dumped into the environment and that is bad for people and bad for the environment.

The importance of overflows for the entry of different pollutants into the water is demonstrated in many studies [3], [4], [5]. This is especially true in Saudi Arabia, especially in Skaka and Al-Jouf, where climate change has increased soil moisture and the likelihood of flooding. Good process control is very important to avoid these risks in time.

### *1.2. Research Objectives*

The primary objective is to improve the controllability of wastewater treatment systems and their stability against varying conditions. The study is based on the following objectives:

- Model and simulate the system in different flow and disturbance situations to better understand how the system would work. See the number and size of the overflow events at the wastewater treatment plant AL Jouf.
- Consider various approaches to the control of wastewater treatment systems such as classical feedback, optimal control, feedforward, and H-infinity robust control.
- Assessing system performance and operating efficiency for different control techniques in varying hydraulic conditions.

### *1.3. Significance of the study*

The study highlights the pivotal role of treated wastewater in Saudi Arabia's water strategy, especially with the aim of using only treated wastewater by 2025 [6]. It highlights the importance of initiating programs that enhance wastewater treatment processes, which are essential to reduce pollution from treatment plant overflow events.

Moreover, the study creates awareness about general pollution caused by wastewater facilities thus creating important discussions about environmental impacts. It promotes the use of adaptive and robust controllers in treatment systems, which can help maintain stability, minimize overflow risks and ensure consistent effluent quality. The results are valuable for designers and engineers in choosing effective process control strategies applicable for variable loads and environmental conditions.

## **2. Theoretical Background and Literature review**

### *2.1. Theoretical framework*

Wastewater treatment is a series of physical, chemical, and biological processes that work together to remove harmful substances in raw sewage before it can be reused or discharged [7]. These typically start with a pre-screen, then primary sedimentation, biological degradation and finally clarification. All these steps help to reduce some types of pollution. The dynamic characteristics of these subsystems are a highly interactive and nonlinear process in which operating conditions can quickly propagate through the network and affect the efficiency of the entire system.

Understanding of the wastewater treatment in theory is essential in order to develop good monitoring and control systems. The flow rate, tank level, retention time, dissolved oxygen and microbiological activity are all working together at all times to change the quality of the effluent and the stability of the treatment. These interactions can be theoretically codified to characterize and predict how the system will respond to various types of disruptions.

These theoretical notions serve as the basis for the implementation and performance evaluation of advanced simulation and control methods in this work.

### *2.2. Simulation of the Artificial System*

Simulations can help us understand how wastewater treatment systems work under controlled conditions. This approach enables for the simulation of process changes without affecting the system's actual operation. Mathematical models can then be utilized to describe fluctuations in tank levels, inflow rates, and actuator reactions across the system. This facilitates the evaluation of control strategies and system design.

In Germany, a detailed model of the sewer system was calibrated to simulate an artificial system to measure the flow of water from a small natural river into a virtual urban catchment. The flow of the flow of this river is the base flow of this river that shows the functioning of the natural hydrological system. The simulation focuses on concentrations close to the river outlets. The simulation is based on three main factors, namely: base flow, combined sewer overflow (CSO) discharge and the treated wastewater from a treatment plant.

The sewer systems used virtual tracers simulated using SWMM with a “tanks in series” method [8]. The wastewater treatment plant model has up to 6 well-mixed tanks in series connected by pipes and weirs to keep the water levels constant. It was based on data from rain gauges within the natural catchment.

The research looked at managing storm water overflow for combined sewer systems using hydrologic and hydraulic performance (H&H) methods and life cycle assessment. These analyses are incorporated into the UWISE framework to develop a model that incorporates storm water control measures, and considers factors such as sub-watershed characteristics and drainage networks. The H&H model demonstrates how the hydraulic systems and CSOs function which highlights the importance of keeping sanitary and storm water separate. The study also examined how rainwater harvesting storage facilities can help with CSOs and provide clean water [9].

### *2.3. Effects of Wastewater*

The dumping of untreated or inadequately treated wastewater into natural waters can have very serious consequences for the environment, the economy and public health. Water quality can be degraded by high levels of organic & inorganic pollutants, suspended particles, nutrients like nitrogen and phosphorus, and disease-causing microbes, and can disrupt ecosystem balance. These poisons rob oxygen, enrich water with nutrients, kill fish and transmit waterborne diseases. This is especially true where there's too much trash for the streams and rivers to naturally dilute. Soil degradation mostly affects areas where crops are grown, which affects how plants and trees grow there. It is known that trees are very important for the environment and any changes in how they grow will affect the whole life cycle [10].

Treatment plants are also prone to poor performance when they receive too much wastewater or are short of treatment capacity. This is bad for the planet. A sudden increase in the influent load can cause the settling tanks to fill, the biological treatment to perform less well, and the levels of the tanks to increase and raise the risk of overflow.

Overflow events are not only an immediate impact on the environment, but also show that the process control system is not good at adapting to changes in operating conditions. Understanding what causes wastewater overflows and what happens when they occur is key to finding better ways to manage and control them.

#### *2.4. Wastewater Treatment*

Wastewater treatment is an important process that removes physical, chemical and biological impurities from sewage before it is released into the environment. The treatment process described in the study is multi-staged, beginning with influent collection and ending with clarified effluent release. These steps are designed to ensure that the water being discharged meets acceptable criteria, protects public health and does not destroy aquatic ecosystems [11].

There are many methods and chemicals to treat and purify wastewater. Most wastewater plants are situated in places that can be reached by vehicles or pipelines. Wastewater plants use two main processes to clean wastewater: primary treatment and secondary treatment. First the wastewater passes through a huge whole screen, to get rid of things like sticks and rags. These particles are the first to be filtered out so they will not cause damage to the equipment or pipelines further down the process. Next is the grit chamber.

In the last few decades, wastewater treatment plants have become more and more mechanical in their operation. This has been made possible by the great increase in the number of process variables which can be accurately assessed on-line and by a better knowledge of the biochemical processes. Some simple examples are mechanical aeration control, return sludge pumping and internal nitrate recirculation [12], [13]. Besides the method manipulation system, there is generally a machine for method surveillance or monitoring.

The first stage usually involves preliminary and primary treatment processes such as screening and sedimentation that remove large debris and suspended particulates. Then biological treatment is applied for the degradation of dissolved organic matter using microorganisms and aeration systems. The study highlights the sensitivity of biological processes to changes in flow rate and composition, particularly under peak load conditions that may disrupt microbial activity and lower treatment efficiency.

Secondary and tertiary treatment stages remove contaminants through filtration, nutrient reduction or disinfection as required by law. But the reality is that the success of these stages is very dependent on the stability of the hydraulic loads coming into the system. If the load variations are more than the capacity of the design, tanks may not be able to hold water for the desired time, which may cause flow of partially treated water downstream or complete overflow [14].

Therefore, the study underlines the importance of integrated control systems taking water quality criteria and hydraulic dynamics into account. The efficiency of the treatment depends not only on the process units, but also on the regulation of the valves, the balancing of flows and the coordinated control of the system, these issues are addressed in the subsequent modeling and controller-design analysis.

Therefore, wastewater treatment is the operational background and functional reason for the simulation and control analysis given in this study [15].

### *2.5. Research Gap:*

The control strategies for wastewater treatment plants have been extensively studied, including classical feedback control methods such as PID controllers, and more sophisticated approaches, such as optimal and model-based control. These studies demonstrate the importance of control systems in stabilizing processes under steady-state conditions.

Much of the present research has focused on conditions of high variability and uncertainty, such as when overflow occurs due to rapid hydraulic surges. Moreover, there are no complete quantitative comparisons of various control systems in terms of the performance indicators such as settling time, overshoot and disturbance rejection.

Moreover, most of the previous works simplify the system dynamics and do not properly deal with model uncertainty or robustness to real-time disturbances. This restricts its applications in real wastewater treatment systems with variable loads.

To overcome these shortcomings, this study performs a comparative analysis of different control techniques including PID, optimal, feedforward and H-infinity control by simulation under different hydraulic conditions. The novelty of this work lies in the fact that it concentrates on overflow scenarios, considers the uncertainty factors, and employs basic operational parameters in the quantitative evaluation of the system performance.

This approach gives a more complete picture of system behavior under extreme conditions and shows the effectiveness of robust control strategies to improve system stability and reduce environmental risks.

## **3. Methodology**

### *3.1. Mathematical Modelling of Tank System*

When the interconnected tanks contain water, the mass balance principle describes their dynamic behavior. The difference between the rates at which water comes in and goes out of each tank determines how much the water level changes. The mass balance principle is used to describe how the interconnected tanks behave over time. The tank dynamics are modeled by first-order transfer connections derived from mass balance equations used in linear system theory [16]. The following shows the underlying dynamic relationship:

$$Q(t) = A \frac{dh(t)}{dt} + q(t)$$

This equation shows that  $Q(t)$  is the flow rate in cubic meters per second ( $m^3/s$ ),  $A$  is the tank's cross-sectional area ( $m^2$ ),  $h(t)$  is the liquid level ( $m$ ), and  $q(t)$  is the flow rate out.

Gravity causes the water to flow out of each tank. This is shown using a nonlinear square-root discharge formula that mimics how real storage tanks work:

$$Q(t) = k\sqrt{h(t)}$$

$k$  is a discharge coefficient that has to do with the shape of the outlet.

Based on standard dynamic modeling principles [17].

The square root term adds nonlinear dynamics, so the system becomes linearized around the nominal operating level  $h_0$ . Define small changes from steady state as  $\Delta h$ . The model then becomes:

$$A \frac{d(h)}{dt} = Q - kh$$

where  $k$  is the linearized discharge gain.

The Laplace transform gives us the linear first-order transfer function, which shows how changes in water level are related to changes in inflow:

$$\frac{H(s)}{Q(s)} = \frac{1}{As + k}$$

This transfer representation is in line with what has been written about it before, and it is the basis for the controller design and simulation that will be discussed in the next sections.

### *3.2. Building Blocks of Control Systems*

Some of the output variables and disturbances affecting the process can be seen on line due to sensors. The right control methods attempt to keep the process as close to the goals as possible. The actuators work on the plant according to the controller's instructions.

Wastewater treatment plants have a number of subsystems that cooperate to process incoming flows. For each subsystem there are input and output variables, e.g. influent rate, tank levels, aeration flow, discharge rates. The system is described as a network of interconnected tanks, actuators and sensors, where the behavior of each component influences the overall performance and stability of the system. The flow balance defines the tank dynamics:  $Q = A (dh/dt)$ .

For each tank, there is a mathematical model that describes the work of these building blocks by using first order dynamics considering the input, output and storage. These equations are the

basis for the design and testing of different control systems. The transfer function approach makes it easier to look at system stability, transient response and controller effectiveness without doing physical experiments. It does this by relating input disturbances to output responses.

### 3.3. Structures of Control Systems

Wastewater treatment plants must deal with a wide range of changes in the volume and quality of the water they receive, therefore they must take the necessary precautions to maintain the system stable and avoid problems such as tank overflows. The study investigates a number of control structures that can be utilized to maintain stable water levels and improve the system's performance in a variety of scenarios.

#### 3.3.1. Conventional Feedback Control

Despite being a MIMO system, the diverse time constants in wastewater treatment allow the separation of control actions into SISO controllers. Essential methods for SISO controller design include on/off and PID control. Despite traditional PID and on-off controllers exhibiting suboptimal performance for time-varying and nonlinear systems, they remain widely utilized in wastewater treatment due to designers' familiarity with their features and industrial application. The control action  $u(t)$  in a PID-control system is calculated through a formula that considers the time evolution of the difference between the desired and actual behavior:

$$u(t) = K_p \left[ \epsilon(t) + \frac{1}{\tau_i} \int_0^t \epsilon(t) dt + \tau_d \frac{d\epsilon(t)}{dt} \right]$$

A weighted average coefficient  $K_p$  is given to each proportional, integral, and derivative action. It is critical to understand the dynamics of the process before adjusting the controller settings. While this method is commonly used because to its simplicity and resilience, feedback control reacts only after a disturbance occurs, which can result in delays or insufficient response to abrupt surges.

#### 3.3.2. Optimal Feedback Control

Optimal control differs from the old method in that it selects actuator signals that reduce performance metrics such as how far from the set point or how much energy is consumed over time.

Optimal control methods are used to design controllers that maximize the weighted performance objective ( $J$ ), which frequently includes tracking error and control effort.

$$J = \int_0^t \epsilon(t)^2 + u(t)^2 dt$$

If a linear model accurately characterizes the process behavior, the traditional linear quadratic (LQ) regulator theory can be applied to create an optimal feedback controller.

The study employs a mathematical model to determine the optimal control action depending on how the system evolves over time. This allows the controller to balance corrective actions against operational constraints. This method improves performance, but it requires detailed process models and computer processing.

### 3.3.3. MIMO Control

Because the tanks are connected, it is hard to control them with multiple inputs and outputs (MIMO). One reason for this is that there are a lot of temporal constants linked to the different (sub) processes. As stated before, SISO control methods are now possible. The process is MIMO, which could give it an edge in performance when designing controllers.

It is vital to remember that the abundance of different control loop configurations may present problems with controller design [18]. One study by Lech [19], [20] found that interactions between control loops in a wastewater treatment system could cause process instability.

The goal of MIMO controller design is to stop any interactions between loops. Using math models during the design phase makes it easy to quickly look at many different configurations and see if any of them might be unstable. Simulating a decoupled MIMO control system for a wastewater treatment plant that removes carbon.

### 3.3.4. Feedforward Control

Feedforward control allows for corrective measures to be made before projected disruptions affect tank levels by altering the actuator signals. This hybrid method works better when combined with feedback because it finds problems early, which makes it more responsive and lowers the risk of overflow. However, its effectiveness depends strongly on the accurate measurement or estimation of the incoming hydraulic load. It might not work as well when problems are hard to predict.

These control structures are the basis for judging how well something works in different situations. There are pros and cons to each method, and the controller designs used in later stages of the simulation build on these basic ideas.

### *3.4. Scenario. Three cases*

#### **Sudden Inflow Increase (Shock Load Conditions):**

This scenario simulates a fast rise in influent flow rate, similar to storm occurrences or unanticipated hydraulic surges that could cause overflow circumstances.

According to the Environmental Protection Agency [21], there are between 23,000 and 75,000 SSOs per year. As of 2004, the EPA estimated that upgrading every municipal treatment and collection system would cost around \$88 billion in order to reduce the frequency of overflow events to once every five years. This spending would be added to the approximately \$10 billion that has already been invested. Although the amount of untreated sewage released into the environment accounts for less than 0.01% of total treated sewage in the United States, the combined volume equals several billion gallons per year and causes tens of thousands of cases of gastroenteritis.

#### **Gradual flow variation (normal operational fluctuations):**

This scenario depicts the progressive changes in flow conditions that are typical of daily operation, as well as standard variations in wastewater inflow. Most wastewater in developing countries is still not treated before being discharged into the environment. As of 2001, the People's Republic discharged approximately 55% of all sewage without any treatment. The majority of the population in a reasonably industrialized Middle Eastern country has had untreated sewage pumped into the city's groundwater. 97 percent of the country's sewage is dumped into the environment untreated, ranking it below average in terms of wastewater treatment. Several countries require the use of real-time telemetry to measure and report SSO occurrences in order to inform the public, swimmers, and shellfishery operators.

#### **Disturbance with Model Uncertainty:**

This scenario assesses system performance under uncertain settings, which include modeling inaccuracies and external disruptions that alter system dynamics.

The study location is located around 40 kilometers east of Jeddah. Jeddah is one of Saudi Arabia's largest cities, with a population of over 3 million. Because groundwater and rainfall supplies are insufficient to meet population demands, desalination water is used. On average, each person consumes 200 l of water every day. On average, wastewater from the use of potable water in cities enters the environment at an 80% rate. Tanker tankers transport wastewater from underground cesspools to dumpsites in the 70-85% of Jeddah that lacks sewage facilities. One of the dump sites is the Al Misk Lake area, where Jeddah's entire residential sewage was dumped for more than ten years without treatment. Beginning in the mid-1990s, the dumping continued until 2008. During this time, it was estimated that over 800 tankers dumped 40,000 m<sup>3</sup> of wastewater into the lake each day. A flood control dam was built with the purpose of controlling the plume, but its effectiveness has yet to be verified.

## 4. Results and discussion

### 4.1. A model of a nominal tank

The wastewater system gets a steady flow of water when it is working normally, which is within the tank's design limits. In this case, the controller only works to keep the water level at the right set points. There are no sudden changes or hydraulic surges. The three tanks that are connected to each other, as explained in the study, behave in a steady and predictable way when the influent is constant.

These scenarios are intended to mimic realistic operating situations in wastewater treatment plants, particularly those with fluctuating and unpredictable hydraulic loads. The simulation results show that the levels in the tanks slowly get closer to their normal steady-state values. The expected dynamic pattern of the rise in each tank level is controlled by the intake, storage volume, and hydraulic coupling between units. The actuators make small changes to keep the water level where it should be because there is no disturbance. The system stays well within safety limits, so there is no chance of overflow. The step response of Tank 1 is presented in Figure 1 the corresponding step response of Tank 2 is presented in Figure 2.

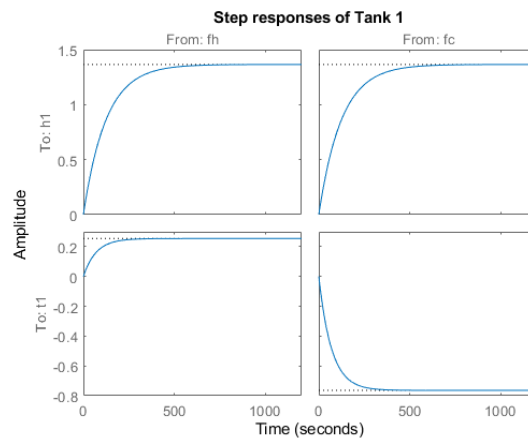


Figure 1 Step responses of Tank 1.

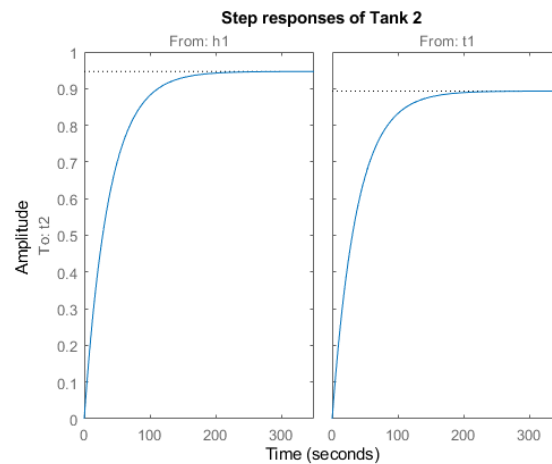


Figure 2 Step responses of Tank 2

#### 4.2. Actuator models

Actuator models are essential due to their inherent dynamics and saturations. They can be represented as first-order systems characterized by rate and magnitude saturations within specific frequency ranges. Typically, actuator performance is limited by the rate of change rather than pole locations. A perturbation model can help incorporate effects of rate limiting in linear modeling.

In the best situations, actuators keep the inflow steady as they get closer to steady-state levels. But when something happens outside of the system, actuators are very important for keeping the whole system stable. A rapid increase in water intake necessitates an immediate response from the actuator to avert rising water levels; however, physical limitations such as valve speed, stroke range, and nonlinearities may restrict the system's capacity to manage these shocks.

The actuator model has one input (the command signal) and two outputs (the actuated signal and the derivative). The actuator often adjusts to changes when there are small disturbances, which stops or slows down level overshoot. But when the input conditions are very high, the actuator can become saturated, which means it has reached its full capacity. At this time, there is no way to change the amount of water coming in, which makes it more likely that the tank will overflow because it is too full. The actuator dynamics and its response characteristics are illustrated in Figure 3.

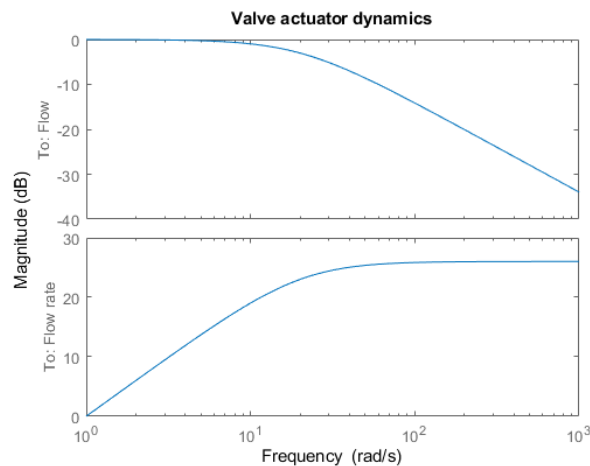


Figure3 Valve actuator dynamics

#### 4.2.1. Uncertainty on Model Dynamics

This section discusses the uncertainties in model dynamics, particularly regarding control systems. Linear models work well at lower frequencies, as shown by open-loop tests. But if this information is not used in the design process, the models might not work well in real life. An uncertainty model is created utilizing frequency-dependent weighting techniques to provide a consistent representation of model errors over the appropriate frequency range.

Open-loop studies demonstrate that the  $t_1$  response exhibits significant dynamic uncertainty due to mixing and thermal dissipation. The uncertainty can be expressed as a multiplicative model error ( $\Delta_2$ ).

The interactions between different model outputs, as shown by the multiplicative errors  $\Delta_1$  and  $\Delta_3$ , are also noted. The perturbed linear two-tank system used to represent model uncertainty is illustrated in Figure 4.

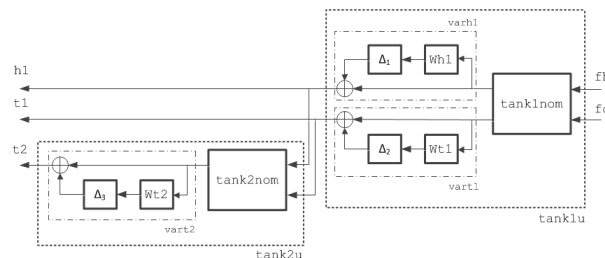


Figure 4 Schematic representation of a perturbed, linear two-tank system.

The frequency and size of modeling errors might vary throughout operational conditions, making it difficult to define system uncertainty. However, frequency-domain analysis can be used to

identify the frequency ranges in which the linear model deviates from the actual system behavior.

Important points are:

- The nominal model for h1 works well at frequencies above 0.3 Hz.
- For the t1 loop, uncertainty is more important than precision above 0.02 Hz, where it causes a noticeable phase lag and lowers gain because of unmolded dynamics.
- In the t2 loop, experiments with limit cycles show that uncertainty is more important than anything else above 0.03 Hz. To mitigate these uncertainties, proper control strategies must maintain reference tracking performance and resilient operation despite changes in system dynamics and modeling uncertainty.

#### 4.2.2. Setting a Controller Design

In examining the control design issue, it is important to monitor the setpoint commands for t1 and t2. H-infinity design strategies necessitate a reduction in closed loop gain. By selecting appropriate weighting functions that represent disturbance characteristics and performance needs, one can normalize frequency-dependent gain constraints. An illustrative weighted open-loop transfer function for the two-tank problem is provided. An illustrative weighted open-loop transfer function and the corresponding control design interconnection for the two-tank system are presented in Figure 5.

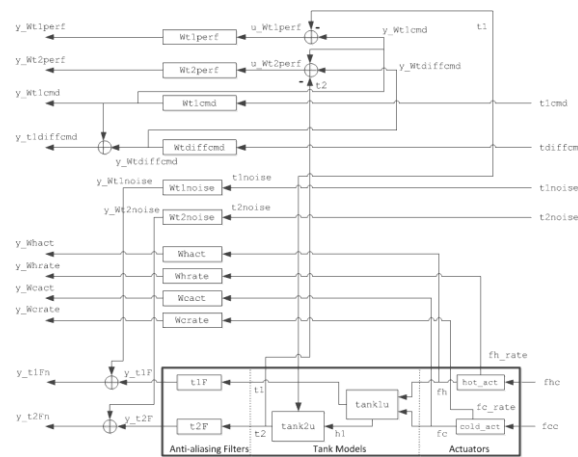


Figure 5 Control design interconnection for two-tank system

The significance of sensor noise, setpoint commands, tracking errors, and actuator weighting is then assessed. Sensor dynamics have minimal impact on the overall system, while sensor noise, including electronic noise from thermocouple compensators and poor grounding, is significant. Tracking errors at times t1 and t2 incur penalties through error weights, using first-order low-pass filters. It is concluded that t1 is more manageable than t2 in terms of control. The frequency-dependent penalties applied to the setpoint tracking errors are illustrated in Figure 6.

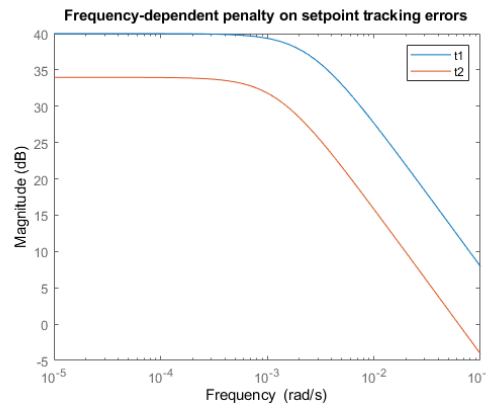


Figure 6 Frequency-dependent penalty on setpoint tracking errors

This is reflected in the weights used for reference (or "setpoint"). Changes in tank 2 have a significant impact on tank 1 because the majority of water flows into it from there. In addition,  $t_2$  is frequently adjusted to a value close to  $t_1$ . For example, it is more natural to use  $t_2-t_1$  weighting to represent setpoint weighting.

$${}_1W_{t_1\text{cmd}}w = \text{cmd},{}_1t$$

$${}_2W_{t_{\text{diff}}\text{cmd}}w + {}_1W_{t_1\text{cmd}}w = \text{cmd},{}_2t$$

#### 4.3. H-infinity. Controller Design

The controller  $k_0$  meets our criterion for frequency-domain tracking performance since it achieves the lowest closed-loop gain, which is around 0.9. It makes sense to replicate this design in the time domain to confirm that the performance weights are set correctly [22], [23]. The time-domain step response of the H-infinity controller ( $k_0$ ) is presented in Figure 7 and the corresponding actuator commands generated by the H-infinity controller ( $k_0$ ) are shown in Figure 8.

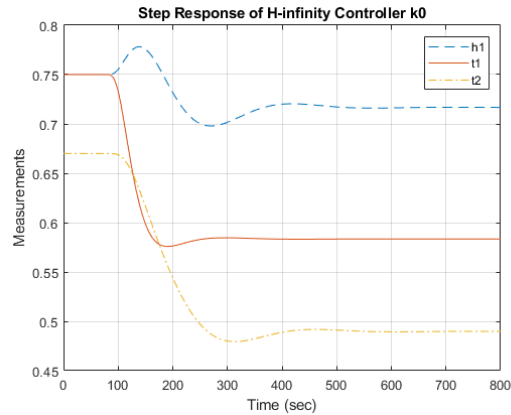


Figure 7 Step response of H-infinity controller k0

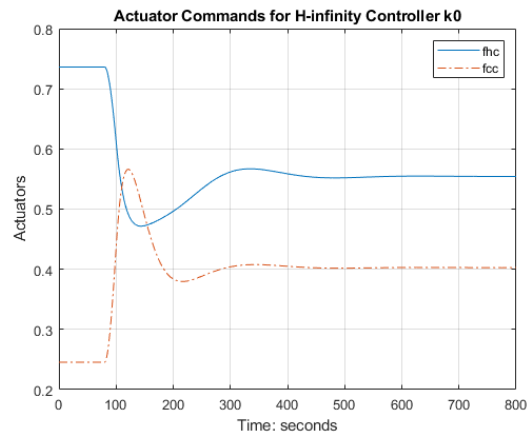


Figure 8 Actuator commands for H-infinity controller k0

#### 4.4. Robustness of the H-infinity Controller

The nominal tank models are designed for the H-infinity controller k0. Examining its performance with a perturbed model and model uncertainty constraints [24]. The worst-case performance across the model uncertainty set can be compared with the nominal closed-loop performance ( $\gamma_0$ ). The worst-case performance across the model uncertainty set can be compared with the nominal closed-loop performance ( $\gamma_0$ ). The resulting performance analysis for controller ( $k_0$ ) is presented in Figure 9.

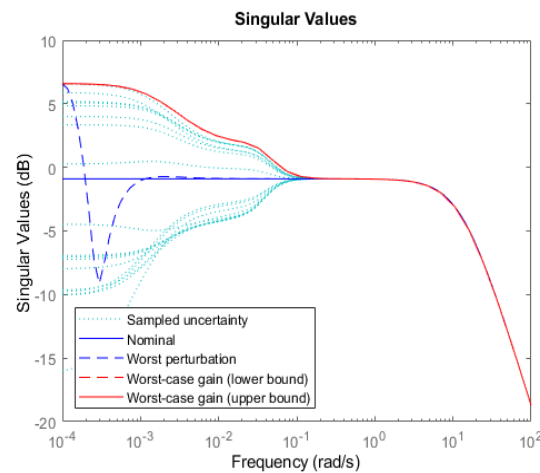


Figure 9 Performance analysis for controller k0

To assess the performance of the various control techniques under varied hydraulic conditions, a comparative analysis was performed using key performance characteristics such as settling time, overshoot, stability, and disturbance rejection. The comparative performance of the control strategies is summarized in Table1.

Table 1. Comparative Performance of Control Strategies under Overflow Conditions

| Control Method     | Settling Time (s) | Overshoot (%) | Stability | Disturbance Rejection | Overflow Risk |
|--------------------|-------------------|---------------|-----------|-----------------------|---------------|
| PID Control        | 120 – 150         | 20–30%        | Moderate  | Weak                  | High          |
| Optimal Control    | 80 – 100          | 10–15%        | Good      | Moderate              | Medium        |
| Feedforward        | 70–90             | 8–12%         | Good      | Moderate              | Medium        |
| H-infinity Control | 40–60             | 2–5%          | Very High | Strong                | Low           |

The comparative analysis of different control strategies under varying hydraulic conditions reveals significant differences in system performance. Conventional PID control exhibited slower dynamic response, with settling times ranging between 120 and 150 seconds and overshoot values reaching up to 30%, indicating limited capability in handling sudden disturbances.

However, optimum and feedforward control methods worked better, cutting settling time to about 70–100 seconds and keeping overrun to less than 15%. But their ability to handle a lot of uncertainty and unexpected changes in input stayed about the same.

The robust H-infinity control scheme outperformed all other methods tested. The device obtained a much shorter settling time (40-60 seconds) with little overrun (less than 5%). Furthermore, the H-infinity controller exhibited excellent disturbance rejection and system stability even in harsh operating conditions.

These findings demonstrate that advanced robust control strategies are more effective at reducing overflow hazards and increasing the operational reliability of wastewater treatment systems under unpredictable and dynamic hydraulic loads.

## **5. Conclusion**

The paper considers the interrelations between wastewater treatment plants, sewer systems and receiving water bodies. It highlights the requirement for integrated urban water management to improve the quality of discharge and to minimize the environmental impacts. It states that many modern designs consider sewage systems and treatment plants as independent components that can lead to performance objectives that are inconsistent with water quality standards based on the use of the water body. This paper is mainly about the operation of treatment plants, but also addresses the use of real-time control algorithms to improve their operation.

Good management requires modeling of drainage using inflow forecasting and sewer transport models [25]. Models can be as simple as black box models using experimental data or as complex as deterministic models using hydraulic data. The model inputs and the simulation scenarios are based on typical wastewater characteristics and operational conditions in wastewater treatment plants with variable hydraulic loads.

The results show that in the presence of problems, traditional PID control is not able to work properly, due to its large overshoot and slow response time. However, Advanced control techniques, such as optimum and feedforward control, can improve system performance; nevertheless, their efficacy may be diminished in the presence of significant model uncertainty. Advanced control techniques, such as optimum and feedforward control, can improve system performance; nevertheless, their efficacy may be diminished in the presence of significant model uncertainty.

The overall best performance was obtained using the robust H-infinity control method. It had much less overshoot ( $< 5\%$ ), less settling time (40–60 s) and good disturbance rejection capability. The risk of overflow is immediately reduced and the system is more stable with these changes.

The present results generally underline the importance of robust and flexible control systems in WWTPs, especially when hydraulic loads are variable and difficult to predict. Future studies may aim at the confirmation of these results using the real data and application of the models on real treatment systems.

### Author Contributions

- I. M. H. Elshaigy contributed to the conceptualization of the study, system modeling, control design, and manuscript preparation.
- G. A. Gasmelseed was responsible for simulation setup, data analysis, and interpretation of results.
- I. H. Elamin contributed to figures preparation, visualization, and technical review of the manuscript.
- Z. A. Hamad contributed to language editing, formatting, and manuscript revision.

### References

- Olsson G. 2019. Water and Wastewater Systems Analysis. IWA Publishing.
- Imam, E. H., & Elnakar, H. Y. (2014). Design flow factors for sewerage systems in small arid communities. *Journal of Advanced Research*, 5(5), 537–542. <https://doi.org/10.1016/j.jare.2013.06.011>
- Phillips, P. J., Chalmers, A. T., Gray, J. L., Kolpin, D. W., Foreman, W. T., & Wall, G. R. (2012). Combined sewer overflows: An environmental source of hormones and wastewater micropollutants. *Environmental Science & Technology*, 46(10), 5336–5343. <https://doi.org/10.1021/es3001294>
- Viviano, G., Valsecchi, S., Polesello, S., Capodaglio, A., Tartari, G., & Salerno, F. (2017). Combined use of caffeine and turbidity to evaluate the impact of CSOs on river water quality. *Water, Air, & Soil Pollution*, 228(9), 330. <https://doi.org/10.1007/s11270-017-3505-3>
- Weyrauch, P., Matzinger, A., Pawlowsky-Reusing, E., Plume, S., von Seggern, D., Heinzmann, B., Schroeder, K., & Rouault, P. (2010). Contribution of combined sewer overflows to trace contaminant loads in urban streams. *Water Research*, 44(15), 4451–4462. <https://doi.org/10.1016/j.watres.2010.06.011>
- Ouda, O. K. (2016). Treated wastewater use in Saudi Arabia: challenges and initiatives. *International Journal of Water Resources Development*, 32(5), 799-809 .
- Qasim, S. R. (2017). Wastewater treatment plants: Planning, design, and operation (3rd ed.). CRC Press.

- Dittmer, U., Bachmann-Machnik, A., & Launay, M. A. (2020). Impact of combined sewer systems on the quality of urban streams: Frequency and duration of elevated micropollutant concentrations. *Water*, 12(3), 850. <https://doi.org/10.3390/w12030850>
- Schütze M., Campisano A., Colas H. 2020. Real-time control of urban wastewater systems. *Water Science and Technology*.
- NSW, 2019. Available at: <https://www.environment.nsw.gov.au/topics/land-and-soil/soil-degradation>
- Wastewater Treatment Systems: Modelling Diagnosis and Control, IWA Publishing, London and Kosanovich, K.A. (2019).
- Olsson, G. and Newell, R.B. (2018). Model predictive control: past, present and future. *Comp. Chem. Engng*, 23(4–5), 667–682.
- Yuan, Z., Keller, J. and Lant, P. (2001). Modelling, Identification and Control of Activated Sludge Plants for Nitrogen Removal. PhD study, Technische Universiteit Eindhoven, The Netherlands.
- EPA, 1998. *How wastewater treatment works*. [Online] Available at: <https://www3.epa.gov/npdes/pubs/bastre.pdf>
- Supervisory control of wastewater treatment operation by PC-space control. To be presented at the 7th Scandinavian Symposium on Chemometrics (SSC7), Aug. 19–23, 2001, Copenhagen, Denmark. Rosen, C. and Yuan, Z. (2001).
- Ogata, K. (2002). *Modern control engineering* (4th ed.). Prentice Hall.
- Ogata, K. (2010). *Modern control engineering* (5th ed.). Prentice Hall.
- Stephanopoulos, G. (1984). *Chemical process control: An introduction to theory and practice*. Prentice-Hall.
- Lech, R. F., Lim, H. C., Grady, C. P. L. Jr., & Koppel, L. B. (1978a). Automatic control of the activated sludge process—I. Development of a simplified dynamic model. *Water Research*, 12(2), 81–90. [https://doi.org/10.1016/0043-1354\(78\)90011-8](https://doi.org/10.1016/0043-1354(78)90011-8)
- Lech, R. F., Grady, C. P. L. Jr., Lim, H. C., & Koppel, L. B. (1978b). Automatic control of the activated sludge process—II. Efficacy of control strategies. *Water Research*, 12(2), 91–99. [https://doi.org/10.1016/0043-1354\(78\)90012-X](https://doi.org/10.1016/0043-1354(78)90012-X)
- EPA, 2017. *Combined Sewer System*. [Online] Available at: <https://www3.epa.gov/region1/eco/uep/cso.html>
- Zhou, K., Doyle, J. C., & Glover, K. (1996). *Robust and optimal control*. Prentice Hall.
- Zhang Q., et al. 2021. Robust control strategies for wastewater treatment plants. *Journal of Process Control*.
- Syahidah Nurani Zulkifli, Herlina Abdul Rahim, and Woei-Jye Lau, “Detection of Contaminants in Water Supply: A Review on State-of the-Art Monitoring Technologies and their Applications,” *Sensors and Actuators B: Chemical*, vol. 255, pp. 2657-2689, 2018. [CrossRef] [Google Scholar] [Publisher Link]
- Vanrolleghem, P. A., Benedetti, L., & Jeppsson, U. (2005). Towards integrated modelling of urban wastewater systems. *Water Science and Technology*, 52(1–2), 1–9.