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Application of automation in wastewater treatment

Control & Automation

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1 Introduction

Wastewater treatment is a cornerstone of modern society. Without treatment, sewage poses a serious risk to public health and the environment. As populations increased during the industrial era, the volume of waste dumped into rivers increased. Frequently, the drinking water supply for populated areas originated from the same bodies of water receiving untreated waste. This severe pollution contributed to outbreaks of waterborne diseases, such as Cholera.

During the mid-19th century in London, rapid population growth and increases in industrial waste being discharged into the River Thames culminated in an event known as the Great Stink of 1858. High temperatures and an extended dry spell intensified the fetid odours emanating from the river, prompting major engineering works to overhaul the sewer system.

An improved sewer network, designed by Joseph Bazalgette, transported wastewater away from London's densely populated regions and significantly improved public health conditions. Prior to 1858 London experienced three major cholera outbreaks. Since the construction of Bazalgette's system, there has been only one recorded outbreak occurring in a region of London that had not yet been connected to the sewer network. However, at this time wastewater was still being discharged untreated into the river, causing ecological damage and environmental degradation.

Advances in environmental engineering during the 20th century led to the development of treatment processes capable of removing waste matter before discharge. One crucial development, the Activated Sludge Process, allows organic matter to be biologically degraded through aeration of the sludge and introduction of microorganisms. As treatment plants grew in scale and complexity, manual operation and monitoring became increasingly non-viable (Olsson et al., 2014).

Modern treatment plants rely on Instrumentation, Control and Automation (ICA) systems to monitor conditions and maintain stable plant operation. Sensors collect real-time data on conditions, controllers analyse the data and determine corrective actions, and actuators adjust equipment accordingly to compensate for deviations from ideal operating parameters. This report examines the role of ICA technologies in wastewater treatment, and recent advances improving plant automation.

2 Wastewater Treatment Process

Wastewater treatment facilities are engineered to remove pollutants from wastewater prior to its release into the environment. Typically, treatment occurs in several stages, each designed to remove different categories of contaminants (Figure 1). Monitoring of each stage is essential to prevent the propagation of errors through the plant, which could negatively impact treatment performance and effectiveness.

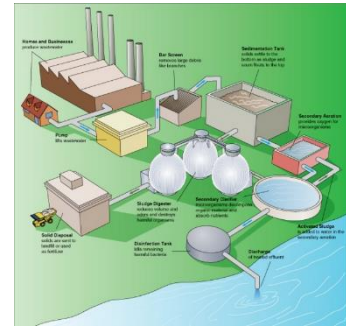


Figure 1, Steps in a typical wastewater treatment process

2.1 Preliminary Treatment

Preliminary treatment focuses on the removal of large debris and inorganic materials. Wastewater entering the plant passes through mechanical screens, filtering large solids. A grit chamber allows dense particulates such as gravel or sand to settle out of the flow.

Although the preliminary stage is relatively simple, monitoring remains of paramount importance. Large debris can cause damage to the pumps, valves and aeration equipment used in later stages. Flow rate sensors provide insight into incoming wastewater volume, while level sensors within the channels and tanks monitor flow conditions.

Wastewater inflow is dependent on several factors including population water habits, weather conditions, and industrial operating schedules. As such, automation is particularly important in regulating wastewater flow into the system and preventing overloading of the equipment.

2.2 Primary Treatment

Following the removal of debris, wastewater is channelled through slow flowing tanks known as clarifiers, where heavier particles suspended within the water settle at the bottom in the form of sludge. This process removes a significant portion of suspended solids before wastewater moves to biological treatment.

Sensors measure the blanket level of the sludge within the clarifier tanks to determine when sludge needs to be removed. If sludge accumulates excessively, it can reduce the effectiveness of the later treatments and put unnecessary strain on filters. In some cases, turbidity sensors are used to measure the clarity of the wastewater leaving the tank.

Automated monitoring of primary treatment provides an early warning system for plant operators. If abnormal sludge or turbidity measurements are detected, control systems can adjust hydraulic flows or the rate of sludge removal to prevent issues further downstream.

2.3 Secondary Treatment

The aim of secondary treatment is to remove dissolved organic matter within the wastewater. A common technique used for this process is the Activated Sludge Process. Microorganisms within the wastewater consume organic matter and adhere together into flocs, which can later be separated from the treated water (Figure 2).

To expedite the oxidation process, oxygen or air is pumped into the aeration tanks. Maintaining the correct dissolved oxygen levels is crucial for plant efficiency. Should oxygen concentrations drop too low, microbial metabolism slows and treatment efficiency decreases. Conversely, excessive aeration increases running costs without improving treatment performance.

Aeration systems are typically the most energy-intensive aspect of wastewater treatment, totalling “About 50% of the energy consumed...” (Monday et al., 2024). For this reason, precise control of aeration levels is essential for maintaining treatment efficiency and economical operation.

To provide data on the conditions within the aeration tanks specialised sensors report dissolved oxygen levels, ammonia levels, and concentration of suspended solids within the mixture. Using this sensor data, the aeration blowers are adjusted to maintain optimal metabolism of organic matter.

Continuous automated monitoring is essential, as deviations in dissolved oxygen, nutrient balance, or temperature can rapidly disrupt microbial activity.

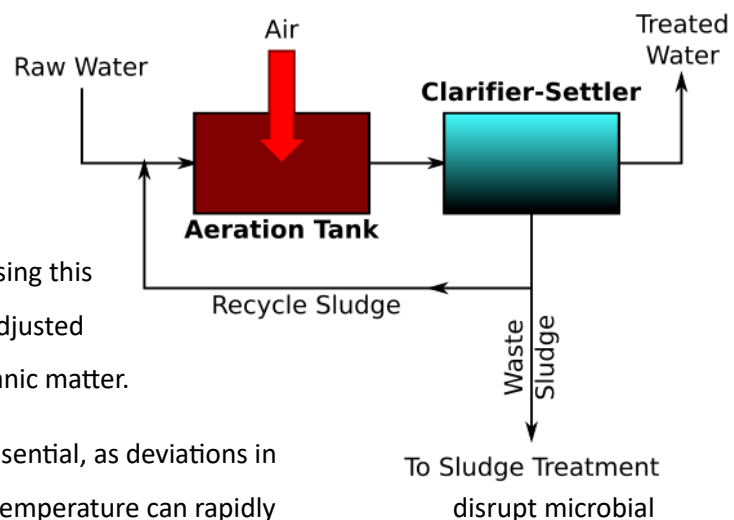


Figure 2, Activated Sludge Diagram

Some of the collected sludge is recycled back into the aeration tanks to maintain microbial populations, whilst the remaining sludge is processed. In many modern facilities, sludge digestion systems produce biogas which is used to generate renewable energy, further improving the sustainability of wastewater treatment plants.

2.4 Tertiary Treatment

The final treatment stage comprises filtration and disinfection. As this stage governs final effluent quality, rigorous standards must be maintained. Turbidity sensors measure the clarity of treated

water, whilst chemical analysers monitor disinfectant concentrations. If turbidity levels increase or disinfectant concentrations fall outside of acceptable ranges, automated systems can adjust treatment conditions or halt discharge to prevent environmental contamination.

These monitoring systems are aligned with regulatory compliance requirements. Automatic data logging provides continuous records of water quality measurements, allowing wastewater treatment facilities to demonstrate their compliance with regulations.

3 Instrumentation, Control and Automation Systems

Wastewater treatment plants rely on sensors, controllers and actuators to maintain ideal operating conditions, ensuring efficient and thorough treatment. These components form a closed-loop control system, constantly monitoring variables within the process and adjusting equipment accordingly (Olsson et al., 2005). Disturbances in one stage of treatment can influence performance in other stages. For effective operation of a wastewater plant, automation is crucial.

3.1 Sensors and Instrumentation

Sensors provide the data required for automated process control, by measuring important variables within the processes and feeding this data to the control system for analysis. Wastewater facilities utilise a range of sensors including flow rate, dissolved oxygen and turbidity sensors (Chougule, 2026).

Flow rate is often measured using magnetic flow meters for closed pipes, or ultrasonic sensors positioned over weirs or flumes. Flow rate sensors aid in keeping track of in and outflow within the plant, and to detect bottlenecks, which could be caused by blockages or failures in the system.

Depth level measurements, either from ultrasonic distance sensors or pressure sensors provide data on tank levels within the plant. Turbidity sensors measure the clarity of water by emitting an infrared light and measuring the scattered light returning to the sensor. Elevated turbidity levels can indicate that upstream treatments are not working as intended, or that solids are passing through the system.

Optical dissolved oxygen probes measure oxygen levels within a fluid through monitoring of red-light quenching. A luminophore within the sensor is excited using blue light, and in turn producing a red light. Oxygen presence quenches the luminosity, allowing the red-light sensor to determine dissolved oxygen levels.

An alternative oxygen measurement technology is the electrochemical Clark cell sensor, in which oxygen diffuses through a gas-permeable membrane and is reduced at a cathode, generating a current proportional to the concentration of dissolved oxygen. Although well established and low in cost, Clark cell sensors require regular membrane and electrolyte changes. Optical probes have largely superseded Clark cells in modern wastewater applications due to lower maintenance requirements, longer operational life, and superior resistance to the harsh environment.

Dissolved oxygen measurements are integral to the operation of the secondary stage, as insufficient oxygen levels will slow microbial metabolism and reduce treatment efficiency. Accurate sensor data

therefore allows the control system to maintain optimal biological conditions within the aeration tanks.

Wastewater environments can be harsh on instruments due to present contamination and biological growth within the medium. Robust sensors with minimal moving components are preferred, as they fare better and require less cleaning and calibration for accurate operation.

3.2 Process Controllers

Process controllers analyse data from the sensors and determine appropriate responses for actuators within the plant to maintain stable operation. Modern treatment facilities utilise programmable logic controllers (PLCs), industrial ruggedized computers designed to operate reliably and consistently in harsh environments (Kaittan et al., 2024).

Control systems often employ feedback loop controls, a process variable is compared to an ideal value, and adjustments are made to minimise the error. Proportional-Integral-Derivative (PID) controllers are widely used for this purpose. The proportional term produces a control response proportional to the current error, allowing large deviations from the setpoint to be quickly corrected. The integral term compares past error values over time, reducing steady-state error and improving settling time. The derivative term evaluates the rate of change of error, enabling the controller to anticipate future behaviour and reduce the likelihood of overshoot.

PLC programs are typically written in IEC 61131-3 languages such as Ladder Diagram (LD) or Function Block Diagram (FBD). Ladder Diagram is common in the water industry due to its readability for maintenance engineers, whilst FBD allows PID loops to be represented in a graphical format, simplifying readability and fault finding.

3.3 Actuators

Actuators convert control signals from the PLC into physical actions. Devices include pumps, valves, and aeration blowers. Together, sensors, controllers and actuators form a closed-loop automation system capable of maintaining nominal plant operation with minimal operator intervention.

Wastewater treatment plants operate continuously and constantly respond to changing conditions; automation is paramount to ensuring these conditions are met. Due to this extensive automation, wastewater treatment plants require a relatively low number of operators to supervise a large and complex treatment facility.

4 Supervisory Control and Regulatory Compliance

Overall plant control is typically coordinated by supervisory systems such as Supervisory Control and Data Acquisition (SCADA). These systems provide a centralised platform to monitor and manage the entire treatment facility.

SCADA systems collect data from individual PLCs throughout the plant and present information through a graphical user interface (Figure 3). Operators can observe real time conditions and view historical trends.

SCADA systems improve operational awareness and support the management of large, complex networks. One implementation monitored “220 pump stations, 3 wet weather facilities, 4 sludge transfer systems, and 43 wastewater treatment plants, producing nearly 250 million gallons of discharge per day.” (B Dieu, 2001, p. 267-281). The centralised architecture of SCADA systems also introduces a significant cybersecurity risk as successful intrusion could allow attackers to manipulate process setpoints (Brad, et al., 2021).



Figure 3, SCADA Graphical User Interface

Wastewater treatment plants must comply with environmental regulations regarding the quality of treated effluent discharged into water bodies. In the United Kingdom, one important regulatory framework is the Urban Waste Water Treatment Directive (UWWTD, Council Directive 91/271/EEC). This directive establishes minimum treatment requirements for wastewater and monitoring standards for treatment plants.

Automated systems facilitate compliance with regulations by continuously monitoring water quality and recording operational data.

5 Advances in Automated Wastewater Treatment

One area of advancement is the development of smart sensors capable of incorporating digital communication protocols, facilitating communication between sensors and PLCs, and self-diagnostic features intended to spot erroneous calibration and sensor fouling. These features reduce the risk of inaccurate data being fed into the closed loop system and reduce maintenance requirements.

Artificial Intelligence and Machine Learning integration into treatment facilities improve the accuracy of future plant behaviour predictions. Advanced algorithms analyse historical sensor data to identify patterns in plant behaviour linked to malperformance and suggest actions to correct the error. For example, machine learning models may predict aeration demand based on wastewater characteristics, enabling more efficient control of blower systems.

However, AI based control should be evaluated carefully against PID approaches. PID controllers remain dominant due to their straightforward and mathematically transparent nature. AI models trained on plant data may find trends in ways that are not easily understood by operators. As such, auditing of controller process and fault diagnosis can be difficult. AI control is most justified in scenarios where standard PID control proves insufficient, such as plants with highly variable flow rates and activated sludge processes (Gulshin et al., 2024).

Digital twin technology has gained attention within the industry; a virtual representation of the treatment plant simulates the behaviours of the real system. The simulated environment allows for testing of control strategies and plant performance optimizations, reducing risk and downtime (Wang et al., 2024). Digital twins are increasingly used during the design phase of new plants and for operator training.

As treatment plants become more digitally integrated, autonomous, and capable of communicating remotely through IoT, the ramifications of cybersecurity risks become more serious. A 2021 cyberattack on a Florida treatment facility resulted in changes to chemical dosing, illustrating the reality of these risks. Mitigations include separation of corporate and operational IT networks, multi-factor authentication for operator access, and regular penetration testing. Implementation costs are also substantial, requiring specialised equipment and fallback processes during system upgrades.

6 Conclusion

Wastewater treatment plays a monumental role in public health and the preservation of the environment. Historical challenges and outbreaks of waterborne disease demonstrated the necessity of wastewater management.

As wastewater treatment plants expanded in scale and complexity, manual operation and monitoring of processes proved insufficient. The integration of instrumentation, control and automation systems has become essential for ensuring reliable and efficient treatment of wastewater. Sensors provide real-time measurements of key variables, controllers analyse sensor data to determine ideal behaviour, and actuators, instructed by controllers, adjust plant equipment to maintain optimal plant conditions.

Supervisory systems enable plant-wide monitoring while supporting compliance with environmental regulations such as the UWWTD and Water Framework Directive. Emerging developments such as smart sensors, artificial intelligence and digital twin modelling are expanding the capabilities of automated treatment systems. Evaluation of these technologies is essential, the gap in transparency between PID based and AI based controllers must be balanced against the potential efficiency gains of the latter.

Together, these technologies allow modern treatment facilities to operate efficiently, reliably, and in alignment with environmental regulations, ensuring treated water can be returned to natural bodies of water.

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