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Application of automation in wastewater treatment



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Abstract

Instrumentation, Control and Automation (ICA) are essential components of modern wastewater treatment facilities, supporting efficient, reliable, and compliant operations. The growing complexity of treatment processes, along with stricter environmental requirements, has led to the widespread adoption of advanced automation systems to improve overall performance and process optimisation.

This report critically examines the application of ICA in wastewater treatment, focusing on sensors, controllers, actuators, and supervisory systems such as SCADA and Distributed Control Systems (DCS). The historical development of automation is explored alongside modern advancements including artificial intelligence and model predictive control.

A case study of the Beckton wastewater treatment plant demonstrates the practical implementation and benefits of automation. The analysis shows that automation significantly enhances efficiency, energy optimisation, and regulatory compliance, although challenges remain in terms of cost, system complexity, and cybersecurity.

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1 Introduction

Wastewater treatment removes contaminants from sewage and industrial effluents through complex biological, chemical, and physical processes that require careful control (Metcalf & Eddy, 2014). Instrumentation, Control and Automation (ICA) systems enable efficient operation by continuously monitoring process variables and adjusting system performance in real time (Vanrolleghem & Lee, 2003). This reduces manual intervention, improves stability, and ensures compliance with environmental regulations such as the EU Urban Wastewater Treatment Directive (EuropeanCommission, 2018).

This report examines the role of ICA in wastewater treatment, focusing on sensors, controllers, actuators, supervisory systems, and recent technological advancements.

2 Historical Development

The development of automation in wastewater treatment has evolved alongside advancements within industrial control systems. Early wastewater management systems, dating back to ancient civilisations such as the Indus Valley and Roman Empire, primarily focused on drainage and basic sanitation rather than treatment. It was not until the late 19th and early 20th centuries, with the rapid growth of urban populations, that structured wastewater treatment processes began to emerge (Metcalf & Eddy, 2014)

Initial treatment methods were largely manual and relied on simple physical processes such as sedimentation and filtration (Tchobanoglous, et al., 2014). Early treatment plants, often referred to as “sewage farms,” depended heavily on natural processes and operator judgement, with minimal instrumentation or control (Spellman, 2013). However, even at this stage, basic mechanical control mechanisms such as float valves were used to regulate water levels, demonstrating early applications of feedback control within wastewater systems (Bennett, 1996)

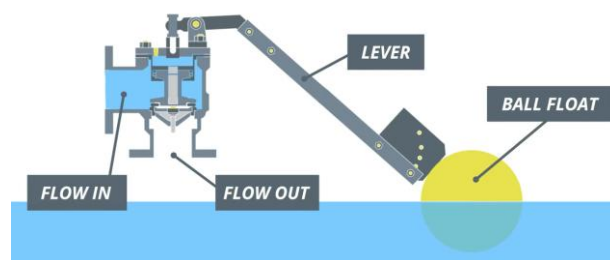


Figure 1 - Float Valve Diagram (Valves, 2019)

The introduction of biological treatment processes, particularly the activated sludge process in the early 20th century, marked a significant advancement in wastewater treatment technology. This process required more precise control of variables such as aeration and sludge concentration, highlighting the need for improved monitoring and control systems (Metcalf & Eddy, 2014)

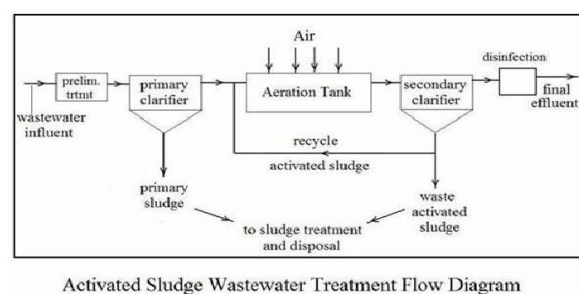


Figure 2 - Activated sludge process diagram (narodnatribuna, 2023)

By the mid-20th century, industrialisation and environmental awareness led to stricter wastewater regulations, driving the adoption of advanced treatment processes and early automation using pneumatic control systems (Seborg, et al., 2017). The shift to digital control in the 1960s and 1970s marked a major advancement, with PLCs and DCS enabling more reliable and efficient process control (Bolton, 2015).

In recent decades, increasing process complexity and regulatory demands have accelerated the adoption of integrated ICA systems, allowing modern treatment plants to operate with real-time monitoring, optimisation, and improved compliance (Olsson, 2012).

3 Wastewater treatment process

A typical wastewater treatment plant consists of several stages, including preliminary, primary, secondary, and tertiary treatment processes (Metcalf & Eddy, 2014). Each stage is designed to remove specific types of contaminants and requires careful monitoring and control.

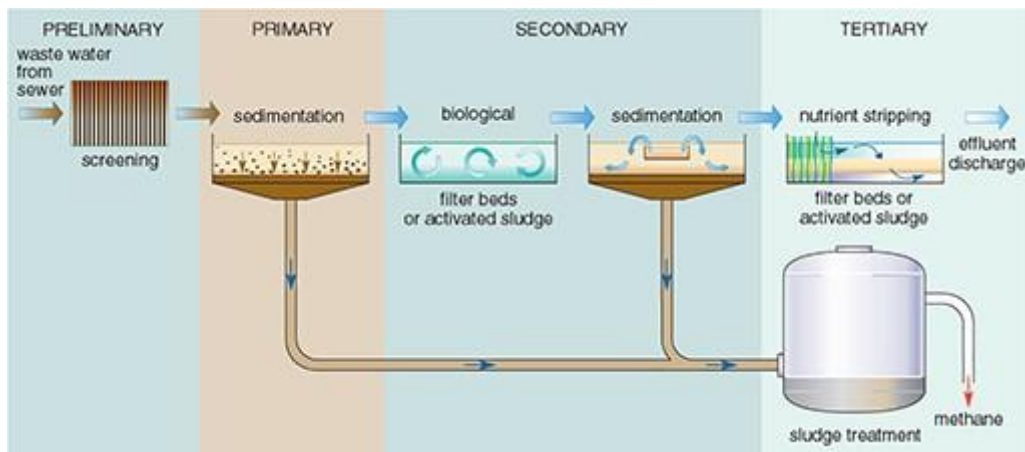


Figure 3 - Flow Diagram for the wastewater treatment process (Novo, 2022)

3.1 Preliminary treatment

Preliminary treatment is the initial stage of wastewater treatment and is primarily concerned with the removal of large solid materials that could damage downstream equipment or interfere with treatment processes (Metcalf & Eddy, 2014). This stage typically involves screening and grit removal. Screens, which may be coarse or fine, remove large debris such as plastics, rags, and organic matter, while grit chambers remove heavier inorganic materials such as sand and gravel through sedimentation (Tchobanoglous, et al., 2014; Spellman, 2013).

3.2 Primary treatment

Primary treatment involves the removal of suspended solids and organic matter through sedimentation processes. Wastewater is directed into primary clarifiers, where flow velocity is reduced to allow heavier particles to settle as sludge, while lighter materials such as oils

and grease rise to the surface and are removed by skimming mechanisms (Metcalf & Eddy, 2014; Tchobanoglous, et al., 2014)

3.3 Secondary treatment

Secondary treatment is a biological process designed to remove dissolved and biodegradable organic matter. The most common method is the activated sludge process, where microorganisms break down organic pollutants in the presence of oxygen (Metcalf & Eddy, 2014). This stage is highly dependent on maintaining optimal environmental conditions such as dissolved oxygen, temperature, and nutrient availability for effective microbial activity (Grady, et al., 2011).

3.4 Tertiary treatment

Tertiary treatment, also known as advanced treatment, is the final stage of wastewater treatment and is designed to remove remaining contaminants to achieve high-quality effluent suitable for discharge or reuse (Metcalf & Eddy, 2014). This stage may include processes such as filtration, nutrient removal, and disinfection. These processes are essential for removing nitrogen and phosphorus, which can cause eutrophication in receiving water bodies (EPA, 2020).

4 Sensors within Wastewater Treatment

Sensors are critical components of automation systems, providing real-time data on process conditions. In wastewater treatment, sensors are used to measure parameters such as flow, pressure, level, temperature, pH, and dissolved oxygen (Metcalf & Eddy, 2014; Vanrolleghem and Lee, 2003; Olsson, 2012).

4.1 Common sensor technologies

- **Flow sensors** - Electromagnetic and ultrasonic flow meters used to measure volumetric flow rate of wastewater (Metcalf & Eddy, 2014).
- **Level sensors** - Ultrasonic, radar, or pressure-based sensors used to monitor tank and channel levels (Bourgeois, et al., 2001).
- **Pressure sensors** - Diaphragm-based transducers used to measure system pressure and detect blockages (Seborg, et al., 2017)
- **Temperature sensors** - Thermistors or RTDs used to monitor process temperature affecting biological activity (Grady, et al., 2011).



Figure 4 - Temperature sensors (Testo, 2026)

- **pH sensors** - Electrochemical probes used to measure acidity or alkalinity of wastewater (Metcalf & Eddy, 2014).
- **Dissolved oxygen (DO) sensors** - Optical or electrochemical sensors used to control aeration in biological treatment (Olsson, 2012).
- **Turbidity sensors** - Used to measure suspended solids and water clarity (EPA, 2020).
- **Nutrient sensors** - Used to detect concentrations of ammonia, nitrate, and phosphate (Vanrolleghem & Lee, 2003).

4.2 Challenges

Despite their importance, sensors in wastewater environments face significant challenges, including fouling, corrosion, and calibration drift. These issues can reduce measurement accuracy and negatively impact control system performance (Vanrolleghem and Lee, 2003; Olsson, 2012). As a result, regular maintenance and calibration are essential to ensure reliable operation

Advancements in sensor technology, including smart sensors with self-diagnostic capabilities, are helping to improve reliability and reduce maintenance requirements. (Qin and Badgwell, 2003; Zhang et al., 2020).

5 Process Controllers

Process controllers are responsible for interpreting sensor data and determining appropriate control actions to maintain system stability (Seborg, et al., 2017). The most widely used control strategy in wastewater treatment is the Proportional–Integral–Derivative (PID) controller.

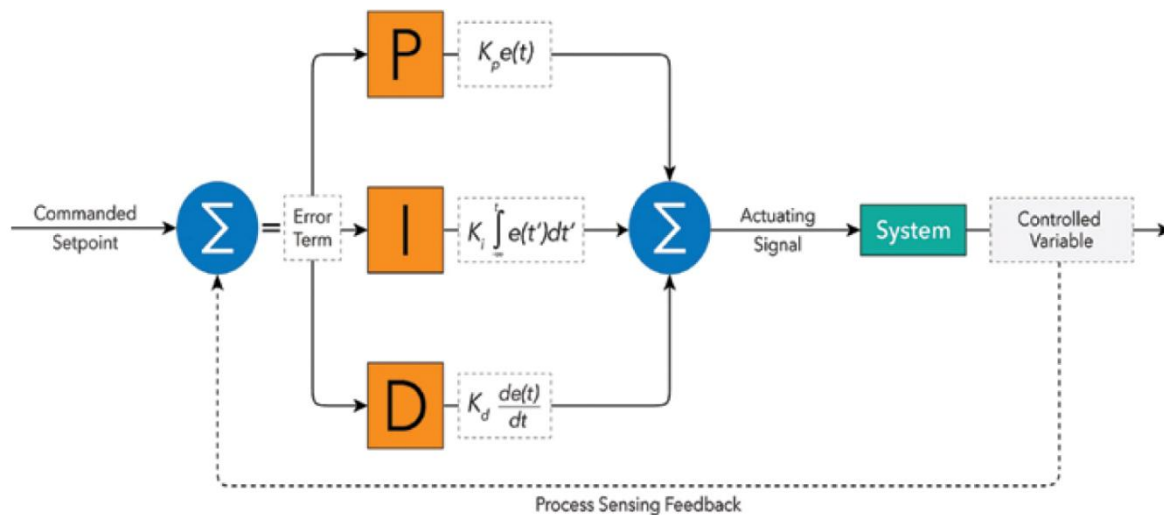


Figure 5 - PID Control system Diagram (Fity.Club, 2023)

PID controllers operate by calculating the error between a measured variable and a desired setpoint and adjusting the control output accordingly (Åström & Murray, 2010). They are widely used in wastewater treatment for applications such as dissolved oxygen control in aeration tanks, flow regulation, and chemical dosing processes (Metcalf & Eddy, 2014).

Digital PID controllers offer improved performance compared to analogue systems, including greater flexibility and resistance to noise (Bolton, 2015). However, PID control has limitations, particularly in systems with strong nonlinearities, time delays, and complex biological interactions, which are common in wastewater treatment processes (Seborg, et al., 2017).

Programmable Logic Controllers (PLCs) are commonly used for discrete control tasks such as pump operation, sequencing, and alarm handling due to their reliability and robustness (Bolton, 2015). In contrast, Distributed Control Systems (DCS) provide integrated control for continuous processes across the entire treatment plant, enabling coordinated control of multiple process variables and improved system optimisation (Olsson, 2012).

6 PLC vs DCS vs SCADA Comparison

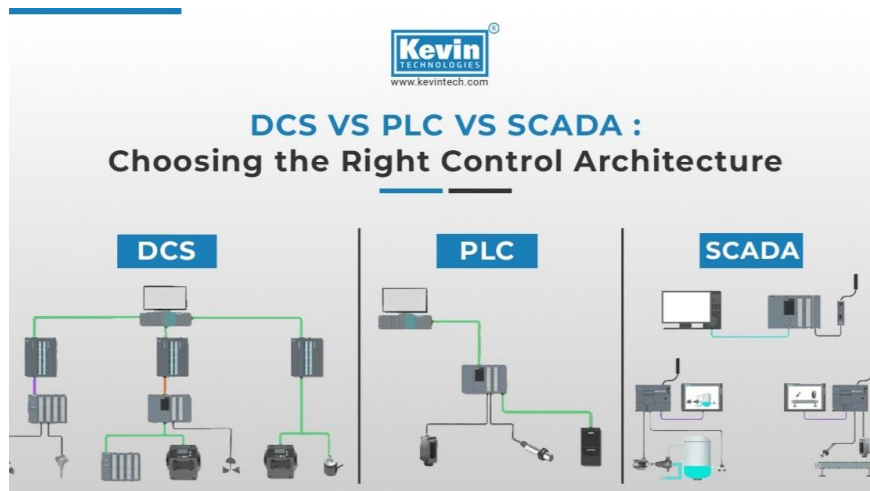


Figure 6 - PLC vs DCS vs SCADA Diagram (Technologies, 2025)

Programmable Logic Controllers (PLC), Distributed Control Systems (DCS), and Supervisory Control and Data Acquisition (SCADA) systems are all used in wastewater treatment automation, but they serve different functions.

PLCs are typically used for discrete control tasks such as pump operation, sequencing, and alarm handling, and are valued for their reliability, robustness, and cost-effectiveness (Bolton, 2015).

DCS systems, in contrast, are designed for continuous process control and provide distributed control across large-scale operations, offering greater scalability and improved coordination of complex processes (Olsson, 2012).

SCADA systems operate at a supervisory level, enabling real-time monitoring, data acquisition, visualisation, and remote control of plant operations (EPA, 2020). They integrate data from multiple PLC and DCS units, allowing operators to oversee the entire treatment process from a central control system.

From a critical perspective, PLCs are highly flexible but can become complex when managing large systems. DCS systems provide superior process control but are more expensive and less flexible. SCADA systems enhance operational visibility but introduce cybersecurity risks due to network connectivity (EPA, 2020).

Modern wastewater treatment plants typically adopt a hybrid control architecture, combining PLCs for local control, DCS for process integration, and SCADA for supervisory monitoring, enabling efficient, reliable, and scalable plant operation (Olsson, 2012).

7 Actuators and Control elements

Actuators are the final control elements in automation systems, converting control signals into physical actions that regulate process variables (Seborg, et al., 2017). Common types include pneumatic, hydraulic, and electric actuators.

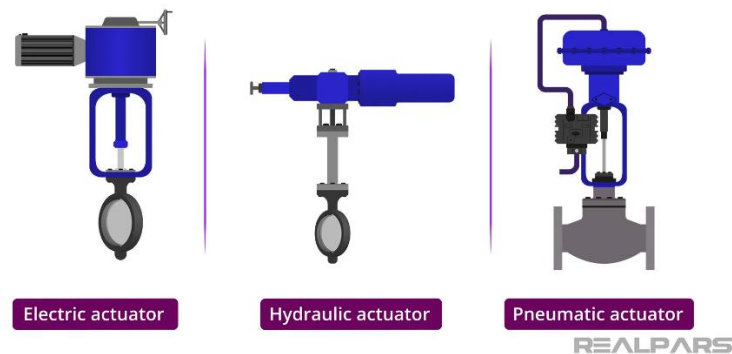


Figure 7 - Common actuators (Mortenson, 2021)

In wastewater treatment plants, actuators extend beyond simple valve control and include a wide range of mechanical equipment essential for process operation (Metcalf & Eddy, 2014; Spellman, 2013). These include:

- **Control valves**
Regulate flow, pressure, and level within treatment processes
- **Pumps**
Used to transport wastewater, sludge, and chemicals between treatment stages
- **Blowers**
Supply air for aeration in biological treatment processes
- **Mixers and agitators**
Ensure proper mixing of chemicals and biological contents
- **Gate actuators and sluice gates**
Control flow in open channels and tanks

Pneumatic actuators are widely used in wastewater treatment due to their robustness, reliability, and suitability for harsh and potentially hazardous environments (Bolton, 2015; Spellman, 2013). Control valves are particularly important, as they regulate fluid flow and maintain process stability across different treatment stages (Metcalf & Eddy, 2014).

Pumps are essential actuators in wastewater systems, used to transport influent, effluent, and sludge, with flow rates typically controlled by variable frequency drives (VFDs) (Grundfos, 2018). Blowers are critical in secondary treatment, supplying oxygen to biological processes, where airflow control is necessary to maintain optimal dissolved oxygen levels while minimising energy use (Rosso, et al., 2008).

Mixers and agitators maintain uniform conditions in tanks, particularly in anaerobic and anoxic processes (Grady, et al., 2011). While pneumatic actuators remain common, electric actuators are increasingly adopted due to their higher efficiency, precision, and compatibility with digital control systems (ABB, 2020).

8 Supervisory Control Systems

SCADA systems provide high-level monitoring and control of wastewater treatment processes, allowing operators to visualise data, detect faults, and respond to changes in real time (EPA, 2020; Olsson, 2012).

These systems use communication networks such as Industrial Ethernet and fieldbus technologies to connect sensors, controllers, and actuators (Bolton, 2015). This integration enables efficient data exchange and improved coordination between system components.

However, increased connectivity also introduces cybersecurity risks, as networked systems may be vulnerable to unauthorised access or cyber-attacks (EPA, 2020). As a result, robust security measures, including firewalls, encryption, and system redundancy, are required to protect system integrity and ensure reliable operation.

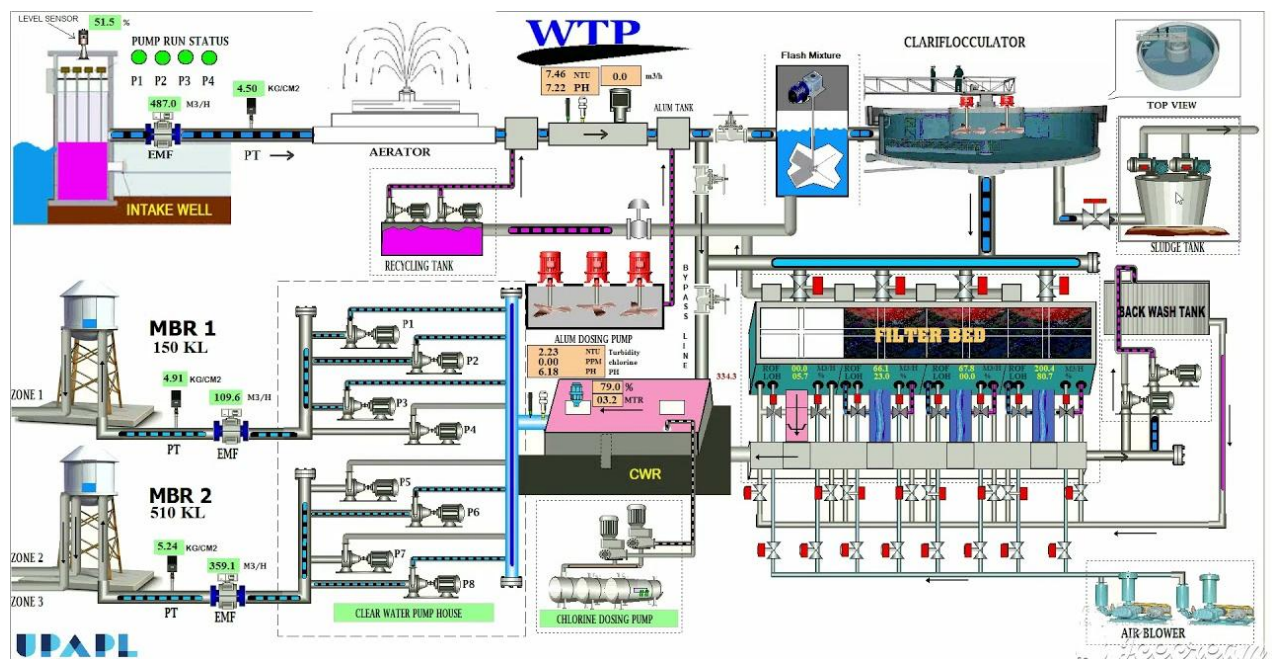


Figure 8 - SCADA system example (Leichhardt, 2025)

9 Advanced Control Strategies

Advanced control strategies such as Model Predictive Control (MPC) and adaptive control are increasingly being applied in wastewater treatment to address the limitations of conventional control methods (Qin and Badgwell, 2003; Zhang et al., 2020).

MPC uses predictive models to optimise control actions, making it particularly effective for managing complex, multivariable systems. In wastewater treatment, MPC has been applied to aeration control, reducing energy consumption while maintaining treatment performance (Olsson, 2012).

Adaptive control systems adjust controller parameters in real time to accommodate changing process conditions, such as variations in influent load or temperature, thereby improving system robustness and stability (Seborg, et al., 2017). This is particularly beneficial in wastewater treatment, where process conditions can be highly variable and difficult to model accurately.

Despite their advantages, these approaches require accurate models and higher computational resources, which can limit their widespread implementation.

10 Regulations and Standards

Wastewater treatment plants must comply with strict environmental regulations, including the EU Urban Wastewater Treatment Directive and standards set by regulatory bodies such as the United States Environmental Protection Agency (European Commission, 2018; EPA, 2020). These regulations impose limits on parameters such as biochemical oxygen demand (BOD), suspended solids, nutrient concentrations, and pathogen levels to protect public health and the environment (Metcalf & Eddy, 2014).

Automation systems play a key role in ensuring compliance by providing continuous monitoring, data logging, and alarm management. Real-time data acquisition enables operators to detect deviations from regulatory limits and implement corrective actions promptly, reducing the risk of non-compliance (Olsson, 2012; Vanrolleghem and Lee, 2003). In addition, automated reporting systems improve traceability and support regulatory auditing requirements.

Failure to comply with environmental regulations can result in significant financial penalties, legal action, and environmental damage, including water pollution and ecosystem disruption (EPA, 2020; DEFRA, 2021). Consequently, the integration of reliable automation systems is essential for maintaining compliance and ensuring sustainable wastewater management.

Wastewater treatment regulations vary across regions but share the common goal of protecting environmental and public health. The EU Urban Wastewater Treatment Directive sets standard limits for pollutants such as BOD and suspended solids across member states (European Commission, 2018). The UK largely follows similar standards post-Brexit, with enforcement by agencies such as the Environment Agency (DEFRA, 2021). In the United States, the EPA regulates discharges through the NPDES permit system, which allows more site-specific limits under the Clean Water Act (EPA, 2020).

Despite differences in approach, all frameworks increasingly rely on continuous monitoring and reporting, highlighting the importance of automation systems in ensuring compliance.

11 Emerging Technologies

Emerging technologies such as artificial intelligence (AI), digital twins, and the Internet of Things (IoT) are increasingly transforming wastewater treatment automation by enabling more advanced monitoring, control, and optimisation capabilities (Zhang et al., 2020; Olsson, 2012).

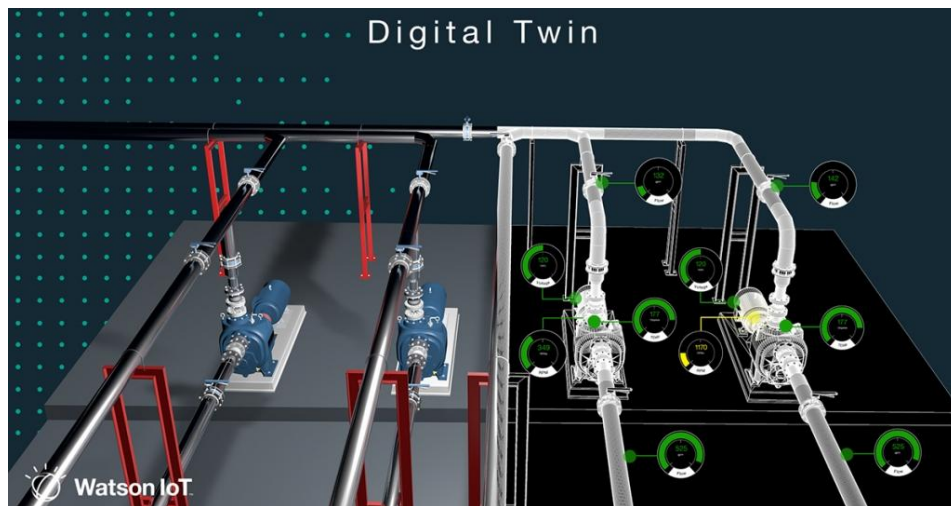


Figure 9 - Digital Twin example (Theta, 2019)

Artificial intelligence (AI) is used in wastewater treatment for predictive maintenance and process optimisation, improving efficiency and reducing downtime through data analysis. Applications include aeration control, fault prediction, and enhanced decision-making. Digital twin technology enables virtual modelling of treatment plants, allowing simulation and optimisation of processes without affecting real operations.

The Internet of Things (IoT) supports real-time connectivity between sensors and control systems, enabling remote monitoring, particularly in large or distributed facilities.

While these technologies improve efficiency and decision-making, they also introduce challenges such as increased system complexity, high costs, data dependency, and greater cybersecurity risks, requiring robust data management and security measures (EPA, 2020; Zhang et al., 2020).

12 Beckton Wastewater Treatment Plant

Beckton Wastewater Treatment Plant in London is one of the largest treatment facilities in Europe and demonstrates the application of advanced automation in large-scale operations (ThamesWater, 2022).



Figure 10 - Beckton Sewage Treatment Plant (Bell, 2017)

Automation is essential in large-scale wastewater treatment facilities such as Beckton due to the sheer size, complexity, and continuous operation of the plant. With multiple treatment stages, extensive pipe networks, and numerous mechanical components distributed across a wide area, manual control would be impractical and inefficient (Metcalf & Eddy, 2014). Automation enables operators to monitor and control the entire plant from a central control room using SCADA systems, providing real-time visibility of process conditions and equipment status (Olsson, 2012; EPA, 2020).

This centralised control allows operators to adjust pumps, blowers, and valves remotely, ensuring rapid response to changes in flow, load, or system faults. It also improves safety by reducing the need for personnel to access hazardous or remote areas of the plant (Bolton, 2015). Furthermore, automation supports coordinated operation across different treatment stages, ensuring that processes remain balanced and efficient (Vanrolleghem & Lee, 2003).

Without such systems, maintaining consistent treatment performance and regulatory compliance at a site of this scale would be extremely challenging. Therefore, automation is not only beneficial but critical for ensuring reliable, efficient, and safe operation in large wastewater treatment facilities.

13 Critical Evaluation

Automation provides significant benefits in wastewater treatment, including improved efficiency, reduced human error, and enhanced regulatory compliance through continuous monitoring and control (Olsson, 2012). It enables real-time data collection and process optimisation, allowing plants to operate closer to optimal conditions while reducing energy consumption and costs (Rosso, et al., 2008). Additionally, automation improves consistency in treatment performance.

However, challenges remain. High capital and maintenance costs can limit implementation, particularly for smaller facilities (EPA, 2020). Increasing system complexity also makes management and troubleshooting more difficult, while reliance on digital systems introduces cybersecurity risks (Zhang, 2020). Furthermore, dependence on accurate sensor data means faults such as drift or fouling can negatively impact performance (Vanrolleghem & Lee, 2003).

Overall, a balanced approach combining automation with skilled human oversight is essential to ensure reliable, efficient, and sustainable wastewater treatment operations.

14 Conclusion

Automation has become essential in modern wastewater treatment, enabling efficient, reliable, and compliant operation. The integration of sensors, controllers, actuators, and supervisory systems allows treatment plants to operate with minimal human intervention while maintaining high performance and adherence to environmental standards (Metcalf & Eddy, 2014; Olsson, 2012).

Throughout this report, it has been shown that ICA systems play a critical role in optimising treatment processes, improving energy efficiency, and ensuring regulatory compliance. Technologies such as SCADA, PLCs, and advanced control strategies enable real-time monitoring and control, allowing wastewater treatment plants to respond effectively to changing conditions and operational demands.

Future developments in artificial intelligence, digitalisation, and advanced control strategies are expected to further enhance automation capabilities, enabling more predictive, adaptive, and energy-efficient systems. However, challenges related to cost, system complexity, cybersecurity, and reliance on accurate data must be addressed to ensure successful implementation.

Overall, the continued advancement and integration of automation technologies will be essential in meeting increasing environmental regulations and sustainability goals, positioning ICA systems as a fundamental component of the future of wastewater treatment.

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