water

MDPI

Article

Conceptual Model of Digitization of the Municipal Wastewater Disposal Systems

Volodymyr Shtepa [1], Natalia Junakova [2,*], Nataliia Zaiets [3,4], Nataliia Lutska [5], Yelizaveta Chernysh [1,6,7] and Magdalena Balintova [2]

1 International Innovation and Applied Center "Aquatic Artery", Sumy State University, 2, Kharkivska st. 116, 40007 Sumy, Ukraine; aquartery@ecolog.sumdu.edu.ua (V.S.); e.chernish@ssu.edu.ua (Y.C.)
2 Institute for Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Kosice, Vysokoskolska 4, 04200 Kosice, Slovakia; magdalena.balintova@tuke.sk
3 Department of Control Systems, Technical University of Berlin, 10587 Berlin, Germany; digiwatersys@gmail.com
4 Department of Automation and Robotic Systems, National University of Life and Environmental Sciences of Ukraine, 03041 Kyiv, Ukraine
5 Department of Automation and Computer Technologies of Control Systems, National University of Food Technologies, 02000 Kyiv, Ukraine; lutskanm2017@gmail.com
6 Faculty of Tropical Agrisciences, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague, Czech Republic
7 Department of Water Supply and Wastewater Treatment, T. G. Masaryk Water Research Institute, Podbabska 2582/30, 16000 Prague, Czech Republic
* Correspondence: natalia.junakova@tuke.sk

Abstract: In the modern world, intelligent and digital wastewater disposal systems are increasingly in demand for real-time decision-making on the environmental efficiency of wastewater disposal. The aim of the study is to develop wastewater management processes for monitoring and predicting the parameters of sewerage networks. This paper presents the results of physical modeling of changes in the properties of aqueous solutions transported through the sewerage network to the treatment plant. It was found that the quality of wastewater without additional pollutants is stable, but under the influence of complex, disturbing factors, significant fluctuations in parameters are observed, requiring preventive control to prevent secondary pollution. In order to eliminate the disadvantages of prototypes and improve the environmental safety of wastewater disposal, a conceptual model of digitalization of the wastewater disposal system of water supply and sewerage facilities in the segment "Transport—wastewater treatment" based on the criteria of environmental efficiency of treatment facilities was justified and created. This model for regulating wastewater discharge parameters considers the quality indicators of domestic and industrial wastewater, which excite technological processes at municipal wastewater treatment plants and makes corrections through local treatment methods. This will reduce the risk of secondary pollution and increase management efficiency and environmental compliance of treatment facilities but, at the same time, requires significant investment, infrastructure modernization, qualified personnel and solutions to the issues of integrating processes into a single system. Also, a conceptual scheme of monitoring and forecasting sewerage network parameters and the sequence of sewerage system digitalization using the example of a settlement was created. Further research will be aimed at building a digital system of regulation of water supply and sewerage facilities in the segment based on the criterion of the ecological efficiency of treatment facilities with regard to disturbance.

Keywords: wastewater treatment plants; physical modeling; conceptual model; digitalization; environmental safety; environmental risk

check for updates

Citation: Shtepa, V.; Junakova, N.; Zaiets, N.; Lutska, N.; Chernysh, Y.; Balintova, M. Conceptual Model of Digitization of the Municipal Wastewater Disposal Systems. *Water* **2024**, *16*, 3483. https://doi.org/10.3390/w16233483

Academic Editor: Zhongbing Chen

Received: 24 October 2024
Revised: 21 November 2024
Accepted: 26 November 2024
Published: 3 December 2024

1. Introduction

Water collected from populated areas or industrial enterprises passes through a drainage system, which includes internal sewerage, drainage networks at the level of courtyards, streets and pumping stations, as well as treatment facilities, which play a key role in ensuring the environmental safety of geoecosystems [1,2].

Analyzing the existing technological regulations and operating features of water treatment equipment, we can conclude that the key and very complex tasks when implementing technological regulations directly in wastewater treatment plants (WTPs) [3–6] are:

- Control of technological processes at established sampling points of wastewater and sludge, characteristics of existing control devices for treatment facilities;
- Technological analysis of equipment operation according to production performance indicators;
- Regulation of resource consumption and cleaning efficiency in accordance with regulatory established criteria and indicators.

At the same time, the more complex the processing task, the more complex and less reliable the control over compliance with regulatory requirements. For example, when implementing a technological scheme for the chemical method of removing pollutants from the Siemens concern, it is necessary to simultaneously monitor more than 40 technological quantities (according to the manufacturer's requirements and the actual availability of a small number of sensors). Meanwhile, wastewater (domestic, industrial and atmospheric) usually contains a large amount of inorganic and organic components. Even with simple mixing of wastewater from various municipal and industrial facilities, biochemical reactions occur between the components, leading to the formation of new substances, sometimes more hazardous to the environment than the original ones (synthesis of toxicants). During chlorination, for example, oxidation products of inorganic and organic substances and their chlorine derivatives appear. In general, industrial wastewater mixed with household wastewater is subjected to biochemical treatment, and then unpredictable compounds can often be found in the treated solutions. In addition, there are impacts on the wastewater network from the occurrence of floods, spills and breakdown of infrastructure elements [7,8].

At the same time, at this stage of the development of water supply and sewerage systems (WSSs), a number of technological reasons have objectively emerged that cause the need to create new digital products. Using the example of sewerage systems of populated areas (enterprises), including water treatment plants, such negative factors include:

- Complexity of adaptive management of WTPs;
- Lack of system solutions for operational measurements and forecasts of wastewater quality and volume indicators directly in the wastewater disposal networks before they enter the WTP;
- Lack of operational control over the state of the wastewater disposal network and untimely maintenance and repair;
- Lack of means for impacting (on-site) intelligent monitoring of key wastewater polluting facilities—with justification for their excess of regulatory requirements for wastewater disposal and a logical forecast of the danger of the impact of their waste on the sewerage network and WTP;
- Unrepresentative (incorrect) formation of technical specifications for the construction (reconstruction, modernization) of wastewater disposal networks, including WTPs.

Enterprises use a certain number of specialized software products. However, this software does not solve the above-mentioned problems due to the fact that unified information systems of WTP enterprises do not exist—only fragmentary elements of the add-on over SCADA (Supervisory Control And Data Acquisition) have been implemented in the form of analytical modules for assessing the operation of biological treatment facilities, drinking water treatment plants, and pumping groups. Nevertheless, the disadvantages of SCADA are:

- SCADA only solves the tasks of technological dispatching without forecasting the development of risks and resource efficiency—there is no indirect assessment of the technological situation;
- Lack of solutions to related problems: maintenance and repair, resource and personnel management, analysis of economic efficiency; the user, in many cases, does not see the production value from the created and filled databases that are supported within the framework of SCADA functioning;
- There is no operational communication between the technical system and engineering and technological specialists (as a rule, only through a mobile SCADA operator—when the system considers that the situation is an emergency).

The situation is aggravated by the fact that it is necessary to maintain a significant list of measuring instruments in working order—at the same time, the user, due to the limited functionality of SCADA, does not see the need for this: control and measuring devices and other instrumental means fail without maintenance. Software products GPS-X, Sludge Expert, and Ecosim are used for mathematical modeling (design) and the simulation of technological processes and are a product solution for designers but are not intended for managing technological processes.

Thus, the importance of digitalization of the conceptual model of drainage and sanitation systems is important and necessary for several reasons [9–12]. Firstly, digitalization makes it possible to collect, analyze and interpret data on the state of the drainage system in real-time. This allows you to optimize water consumption, reduce losses and ensure more efficient water management. Secondly, digital technologies make it possible to prevent accidents and failures in the drainage system, as well as quickly respond to emerging problems. Automated monitoring and control systems help identify sources, prevent contamination and ensure the reliability of the entire system. Thirdly, digitalization makes it possible to reduce operating costs by optimizing the processes of maintenance and repair of the drainage system. Data analysis allows you to find bottlenecks in the infrastructure and optimize the use of resources. Fourth, digital technologies can help reduce negative environmental impacts by effectively managing pollution and optimizing wastewater treatment processes, thereby promoting environmental sustainability. Fifthly, innovation potential is increasing, namely, digitalization opens up new opportunities for the implementation of innovative solutions in the field of wastewater disposal, such as the use of the Industrial Internet of Things (IIoT), big data analytics (Big Data), artificial intelligence (AI), etc., the development of modern technologies, and an increase in the efficiency of the system as a whole.

In contrast to the traditionally used reactive management of complex objects, it is necessary to focus on prompt responses and subsequent prevention of incidents. Such proactive management involves preventing the occurrence of negative situations by creating fundamentally new predictive and proactive capabilities in the corresponding monitoring and management system when forming and implementing control actions based on the concept of system (complex) modeling, including using physical units.

Accordingly, the tasks related to the substantiation of conceptual approaches to the digitalization of water disposal processes based on physical and structural modeling based on the modern international regulatory framework and compliance with environmental requirements of regional regulatory documents are relevant.

The object of the study is the structure of water disposal systems in populated areas.

The subject of the study is the water disposal processes of populated areas.

The purpose of the study is to conduct physical modeling and develop a conceptual model for the digitalization of the water disposal system of populated areas.

From the international documents in this problem area, the following were selected for study: ISO 24525:2022 "Drinking water, wastewater and stormwater systems and services—Operation and maintenance of on-site domestic wastewater services"(https://www.iso.org/standard/76528.html, accessed on 10 November 2024). This standard establishes guidelines and requirements for the operation and maintenance of water, wastewater and storm drainage infrastructure on domestic sites. ISO 24521:2016 "Activities relating to drinking water and wastewater services—Guidelines for the management of basic on-site domestic wastewater services"(https://www.iso.org/standard/64679.html, accessed on 10 November 2024). This standard provides guidance for managing basic home wastewater and water treatment systems to ensure their safety and efficiency. ISO 9001:2015 "Quality management systems—Requirements"(https://www.iso.org/standard/62085.html, accessed on 10 November 2024). This standard sets general requirements for quality management systems, helping organizations provide customers with adequate quality products and services and improve efficiency. These standards contain recommendations and requirements that take into account specific regional conditions, which help ensure consistency of application in different parts of the world. In particular, the first standard includes recommendations for taking into account local climatic conditions or geographic features that may affect the maintenance and operation of wastewater and water supply systems on-site. For example, management guidelines for storm drainage systems may take into account typical rainfall or rainfall intensity in a particular region. The second standard includes recommendations for adapting the management of home wastewater treatment systems to regional infrastructure or resource availability. For example, recommendations for wastewater management in rural areas may take into account the lack of centralized systems and the need for more decentralized approaches. The third standard is not specific to the water or wastewater industries, but its application in these industries may include adaptation to regional standards and legislation to ensure compliance with local water and wastewater quality and safety requirements.

There are a number of studies aimed at improving the economic efficiency of wastewater treatment plants in various ways. In particular, the study in [13] aims to improve the ability of WTP to meet their energy needs by integrating renewable energy sources. Reference [14] proposes an integrated approach to assessing waste heat recovery in wastewater treatment plants, structured according to two main goals. Firstly, an artificial neural network (ANN) model is designed to accurately predict waste heat based on operating data, including biogas temperature, biogas pressure, and daily production in kWh and waste heat value in kWh. The second objective focuses on the economic assessment of the feasibility of waste heat based on their calculated values obtained using the ANN model. One study [15] compared the greenhouse gas emissions and energy consumption of a wastewater treatment plant in Mashhad (Iran) with an energy-self-sufficient wastewater treatment plant. Studies have shown that the use of anaerobic digestion reduces energy consumption and increases emissions, and the combination of anaerobic digesters and consumers by 70% and 53%, respectively, makes it possible to control emissions and energy consumption by selecting the optimal process for wastewater treatment plants.

An analysis of the international regulatory framework in this problem area has shown the need for greater detail on the use of information technologies when processing large amounts of data; the inclusion of requirements for the implementation of hardware and software systems in water supply and sewerage facilities for operational and distributed accounting and analysis of quality indicators of transported wastewater, and not only on the OS; and real-time forecasting of the formation of system requirements regarding changes in the values of wastewater pollutants by integrating forecast blocks into existing (projected) specialized automated process control systems.

The energy aspect of wastewater treatment plants in Poland has been analyzed [16], where the main focus is on improving energy efficiency through the use of highly efficient digestion and co-digestion of sewage sludge with poultry waste. The study showed that the use of these methods allowed the production of up to 2.54 GWh of electricity per year, which covers from 93.0 to 99.8% of the plant's energy needs. However, organic removal efficiency increased from 64% to 69–70%, highlighting the importance of using cosubstrates to optimize the energy balance and enhance contaminant removal in wastewater treatment plants.

Many scientific studies implement the use of artificial intelligence to enhance wastewater monitoring [17–20]. In [19], the use of artificial intelligence to optimize drinking water purification processes is considered. AI provides technical support for managing the drinking water purification process by analyzing data for diagnosing water quality, automating decision-making, and optimizing operations. The article also details the application of AI in water quality, coagulation/flocculation, disinfection, and membrane filtration processes, including contaminant monitoring, coagulation dose prediction, disinfection byproduct analysis, and membrane fouling control. Challenges posed by using AI to support water system management, such as generating efficient data, characterizing pollutants, and developing models for holistic drinking water treatment plants, are also reviewed. Scientists also conducted a systematic review of four aspects of the application of artificial intelligence in wastewater treatment [18]: technology, economics, management and wastewater reuse. ANN and fuzzy logic models are the most widely used methods in single models, while neuro-fuzzy logic and ANN-genetic algorithms are much more commonly used in hybrid models. A framework based on machine learning [20] was also presented to improve wastewater quality control in wastewater treatment plants by clarifying the relationships between operating variables and wastewater parameters. The framework consists of random forest models, deep neural network models, variable importance measurement analysis, and proportional dependence diagram analysis, and uses a novel approach to account for the impact of time delays between processes.

Hybrid modeling is also common [21–23], which combines the advantages of mechanistic and data-based models, but its application in the water supply and wastewater treatment sector remains undefined, stimulating the need for further research and development. Reference [21] discusses the importance of mathematical and hybrid modeling for maintaining water resources in the creation of a circular economy and ensuring sustainable future exploitation. The researchers of [23] combined machine learning with kinetic modeling to predict the reaction kinetics between micropollutants and chlorine in various aquatic environments. A framework was established to predict second-order explicit rate constants for chlorine micropollutants using machine learning algorithms and Morgan's molecular fingerprints. The developed framework showed high prediction accuracy, which was confirmed by experiments.

Among the analog solutions, the following software products were analyzed: ArcGIS, MapInfo, qGIS, GIS Zulu, GIS GeoLink, GRASS (GIS), CityCom, IndorGIS, SCADA TRACE MODE, and SIMATIC WinCC Open Architecture. They have a hierarchical structure and, as a rule, include the following components: measuring (sensory) blocks, information transmission blocks, interface converters, information transmission lines, controller units, database, and specialized software (control, information display, data analysis, report generation, geopositioning, etc.). The production problems solved by such software products within the framework of the digitalization of the water supply and sewerage facilities are as follows: connection to cartography; regulation of individual technological processes; monitoring of parameters (usually equipment condition); and support of administrative, organizational, accounting and economic planning activities. The key drawback of analog solutions is the lack of an integrated and operational approach in the context of "monitoring the environmental situation—storing and analyzing data—making real-time decisions on the environmental efficiency of wastewater disposal". The last element in such a chain is practically absent, which creates an environmental hazard for water bodies.

2. Materials and Methods

Based on a critical inductive analysis of existing structural solutions for water disposal systems, the following tasks of software for managing water disposal processes can be identified:

1. Monitoring water disposal process modes and formalizing the presentation of the entire process, its sections, and their complex interrelations in a form convenient for analysis and that can be understood by specialists.
2. Operational support for decision-making in wastewater management, with the ability to increase the efficiency (environmental and resource) of the technological process

and select the optimal method for its intensification—based on adaptive algorithms, in accordance with the requirements for maximum permissible concentrations stipulated by law, achieving maximum efficiency of equipment (air blower units of treatment facilities, etc.).

3. Monitoring the efficiency (environmental and resource) of technological processes of treatment facilities, increasing their reliability and efficiency of process control (response to external disturbances: changes in loads, salvo influxes of pollutants (including toxicants), fluctuations in biogenic element indicators, etc.) in order to determine and predict its critical points.
4. Ensuring the economic efficiency of operation, maintenance and repair of technological units of wastewater disposal systems at all stages of their life cycles (justification for modernization and reconstruction) while ensuring environmental safety of the environment.

In order to eliminate the shortcomings of prototypes and improve the environmental safety of wastewater disposal, the following enlarged structure of specialized information and management systems is proposed, as shown in Figure 1.

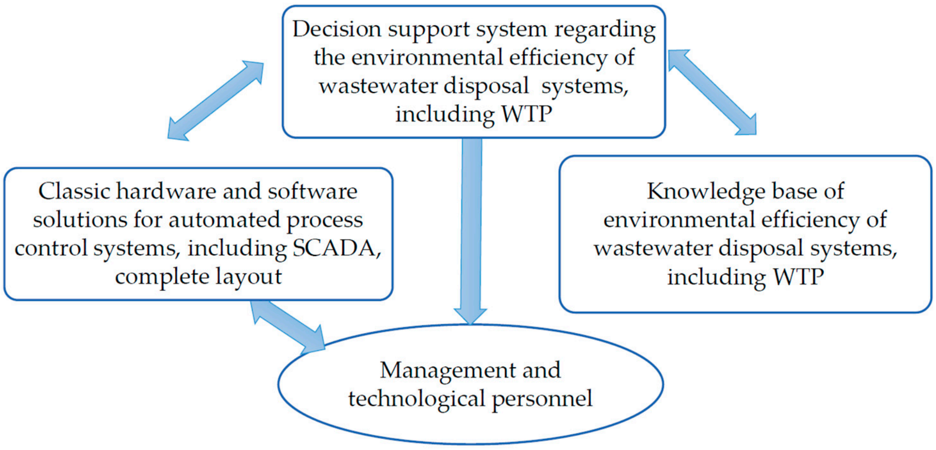

Figure 1. Structure of specialized information and management systems for environmental efficiency of wastewater disposal system.

Functional tasks of the subsystems of the specialized information and control system (Figure 1):

1. «Classic hardware…»: collection of information on the parameters of water disposal processes (primarily from measuring instruments), their primary analysis and processing, transfer of pre-processed information to the decision support system (DSS) and display of graphical trends for process personnel, and process control (including dispatching).
2. DSS: receipt of pre-processed information from «Classic hardware…»; generation of recommendations for making process decisions by process personnel based on data from «Classic hardware…» and information from the knowledge base; and generation of information for transfer to the knowledge base.
3. Knowledge base: storing information and knowledge of technological processes, and developing ontological solutions for the DSS.
4. Technological personnel: making and transferring management decisions to "Classic hardware…" based on the DSS recommendations and visual trends from "Classic hardware…".

At the same time, the key problem in implementing such an information and control system is the correct placement of its subsystems on a real drainage network, i.e., creating an object-oriented structural diagram and corresponding specialized models.

Thus, based on certain nonlinearity and nonstationarity of water disposal processes, to create profile models, it is justified to use the mathematical apparatus of artificial neural networks, which demonstrates efficiency in such conditions [24,25].

Then, in terms of automatic control theory [26,27]:

- The disturbing effects of wastewater quality indicators on municipal wastewater treatment plants are the values of wastewater quality indicators that cause any impacts not provided for by the technological documents of wastewater disposal processes and lead to a violation of the technological regime of wastewater treatment at wastewater treatment plants;
- The control by disturbance of wastewater disposal parameters is the measurement of quality indicators of subscribers' wastewater that cause disturbances, analysis of their deviations from technologically safe values for treatment facilities, and prediction of their impact on the efficiency of wastewater treatment at the municipal wastewater disposal system.

Based on the research (Tables 1–3) and the definitions formalized above, the conceptual model of the digitalization of the water disposal system of water supply and sewerage facilities in the segment "transportation—wastewater treatment" based on the criterion of environmental efficiency of treatment facilities should justifiably be created based on the principle of disturbance compensation, for example, according to Ponsel's methodology (Figure 2). In Figure 2, variables X1. . .XN are indicators of the quality of wastewater from domestic and industrial users whose wastewater does not have a disturbing effect on technological processes at the municipal WDS; Z1. . .ZM—indicators of the quality of wastewater from domestic and industrial users whose wastewater has a disturbing effect on technological processes at the municipal WDS; Y—complex indicators of the quality of wastewater discharged to the municipal wastewater disposal system. N is always >> M.

Table 1. Results of physical and chemical effects on wastewater ("stationary mode").

Test	pH	TDS, ppm	ORP, mV	NH_4, mg/L	NO_3, mg/L	NO_2, mg/L
Initial Wastewater (+15 °C)	8.24	761.00	−70.40	2.50	50.00	33.00
Waste water after 1 h of mixing	8.13	302.00	−66.50	1.50	12.50	37.00
Wastewater using pressure (0.5 h)	787	395.00	−50.70	1.50	12.50	0.90
Wastewater using aeration (7 min)	8.34	491.00	−77.40	1.50	12.50	0.80
Wastewater + NaOH	9.10	487.00	−122.00	1.50	12.50	2.00
Wastewater + HCl	5.95	440.00	61.40	1.50	12.50	2.00

Table 2. Results of the physico-chemical impact of industrial aqueous solutions on wastewater ("aerobic conditions").

Test	pH	TDS, ppm	ORP, mV	NO_3, mg/L	NO_2, mg/L	NH_4, mg/L
Initial wastewater at the WTP inlet (+17 °C) + aeration	8.29	589.00	−64.60	35.00	1.20	0.30
Wastewater at the WTP inlet + fats + aeration	7.27	430.00	−17.20	0.00	30.00	0.12
Wastewater at the WTP inlet + proteins + aeration	7.42	610.00	−24.50	7.00	31.00	0.10
Wastewater at the WTP inlet + fats + proteins	7.82	182.00	−47.70	23.00	35.00	0.20
Wastewater at the WTP inlet + fats + proteins + NaOH	8.48	863.00	−87.30	27.00	34.00	0.20
Wastewater at the WTP inlet + fats + proteins + HCl	7.20	616.00	−11.10	24.00	33.00	0.11
Wastewater at the WTP inlet + fats + proteins + pressure + temperature (+70 °C)	8.02	515.00	−59.60	31.00	32.00	0.00
Wastewater at the WTP inlet + fats + proteins + temperature (+70 °C)	7.83	283.00	−50.30	25.00	31.00	0.00

Table 3. Results of the physico-chemical impact of industrial aqueous solutions on wastewater ("anaerobic conditions").

Test	NH_4	NO_2	NO_3	pH	ORP
Initial Wastewater	0.1	0.1	0	6.6	−108
Wastewater + proteins	0.1	0.1	0	6.5	−152
Wastewater + fats	2.0	0.1	0	7.0	−187
Wastewater + proteins + fats	0.2	0.1	0	6.7	−198
Wastewater + proteins + temperature (+46 °C)	0.7	0.1	0	6.5	−96
Wastewater + fats + temperature (+46 °C)	2.0	0.1	0	7.0	−101
Wastewater + fats + proteins + temperature (+46 °C)	0.7	0.1	0	6.5	−203

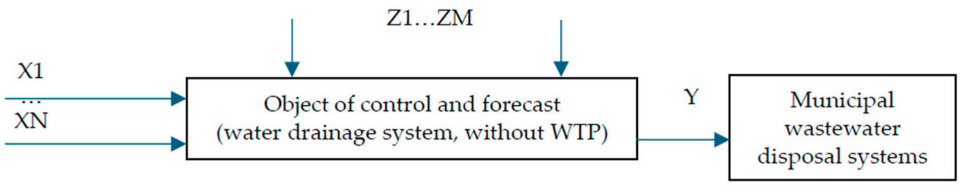

Figure 2. General block diagram of the municipal wastewater disposal system (WDS).

Disturbing influences of wastewater quality indicators are the values of wastewater quality indicators that cause any impacts not provided for by the technological documents of wastewater disposal processes and lead to a violation of the technological regime of wastewater treatment at wastewater treatment plants. Disturbance control is the measurement of quality indicators of subscribers' wastewater that cause disturbances, analysis of their deviations from technologically safe values for treatment facilities, and prediction of their impact on the efficiency of wastewater treatment.

Based on the analysis, a conceptual diagram for monitoring and forecasting the parameters of the wastewater disposal system (Figure 3) and the sequence of digitalization of the wastewater disposal system of a settlement without taking into account water treatment facilities (Figure 4) were developed.

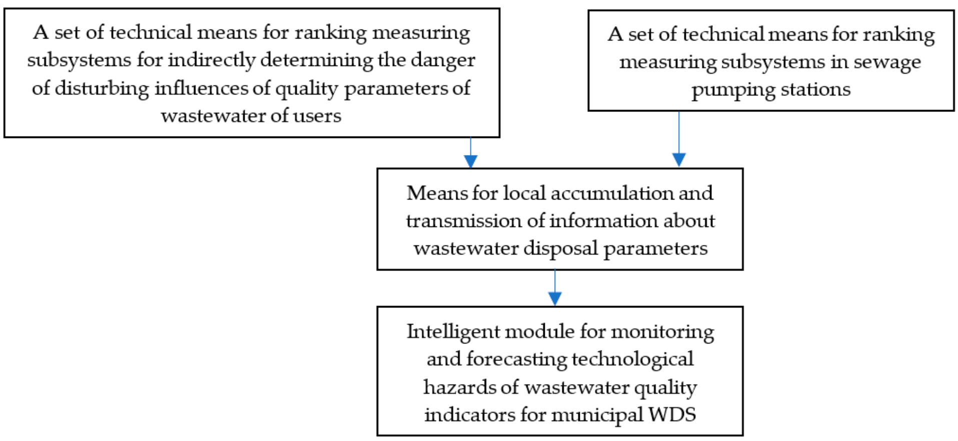

Figure 3. Conceptual diagram for monitoring and forecasting parameters of the wastewater disposal system.

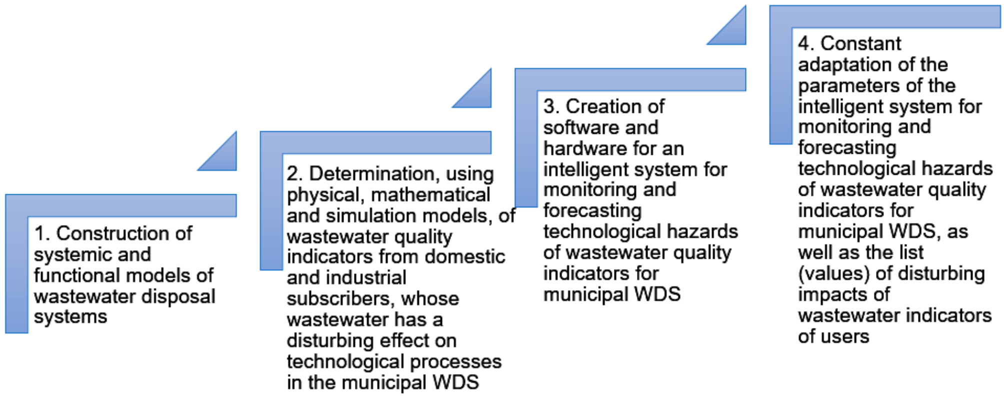

Figure 4. Sequence of digitalization of the municipal wastewater disposal system of a populated area.

As part of our research, a component of stage 2 of the sequence of digitalization of wastewater disposal systems was implemented—conducting physical studies of changes in the parameters of wastewater in the sewerage network under various conditions of such a process in order to form a structural model of a potential digital system.

3. Results

As part of the research work, a conceptual model of digitalization of the water disposal system of water supply and sewerage facilities in the segment "transportation—wastewater treatment" was justified and created based on the criterion of environmental efficiency of treatment facilities.

Initially, physical modeling of changes in the properties of aqueous solutions that are transported through the sewer network to water treatment facilities was performed. The model solution used was wastewater from a populated area (number of inhabitants—about 140 thousand) collected "at the head" of the municipal WTP during one of the peak sewerage flows (time—9:00 for all stages of the research).

Such an aqueous solution, within the framework of simulating disturbances and impacts causing (potentially causing) deviations in the quality indicators of municipal wastewater from their initial values in a conditionally "stationary mode", was subject to the following physical and chemical influences: mixing in a shaker for 1 h in order to simulate transportation in the network drainage; retention under a pressure of 3 atmospheres for 0.5 h; aeration with air for 7 min; adding hydrochloric acid to lower the pH; and adding sodium hydroxide to increase the pH. Assessment of a number of wastewater quality indicators was carried out in laboratory conditions based on the Lurie method (Table 1, Figure 5).

The next step was physical modeling to simulate the impact on the quality indicators of transported municipal wastewater from aqueous solutions discharged by industrial enterprises under aerobic conditions.

Three types of water were used:

- Wastewater at the WTP inlet + model protein solution;
- Wastewater at the WTP inlet + model fat solution;
- Wastewater at the WTP inlet + model protein-fat solution.

Model solutions were prepared as follows:

To simulate protein contaminants in wastewater, a concentrated protein suspension was used, which was obtained by dissolving combined fish feeds in an aqueous solution at a temperature of +65–70 °C. In total, 1 kg of feed was dissolved in 6 L of water. This suspension, after 24 h of settling, was filtered to remove coarse suspended matter and added to the wastewater in a ratio of 1:20. The model fat solution was prepared by soaking animal subcutaneous fat in water and crushing to increase the contact area with the aqueous solution. The proportion of 1:6 was also maintained, where 1 part was occupied by the fat component, and 6 parts by water; the water temperature, as in the case of the protein solution, was +65–70 °C. After 24 h of soaking, the resulting solution was added to the wastewater in a ratio of 1:20. To obtain a protein–fat solution, the created model solutions were mixed in equal proportions (1:1) and also added to the wastewater in a ratio of 1:20.

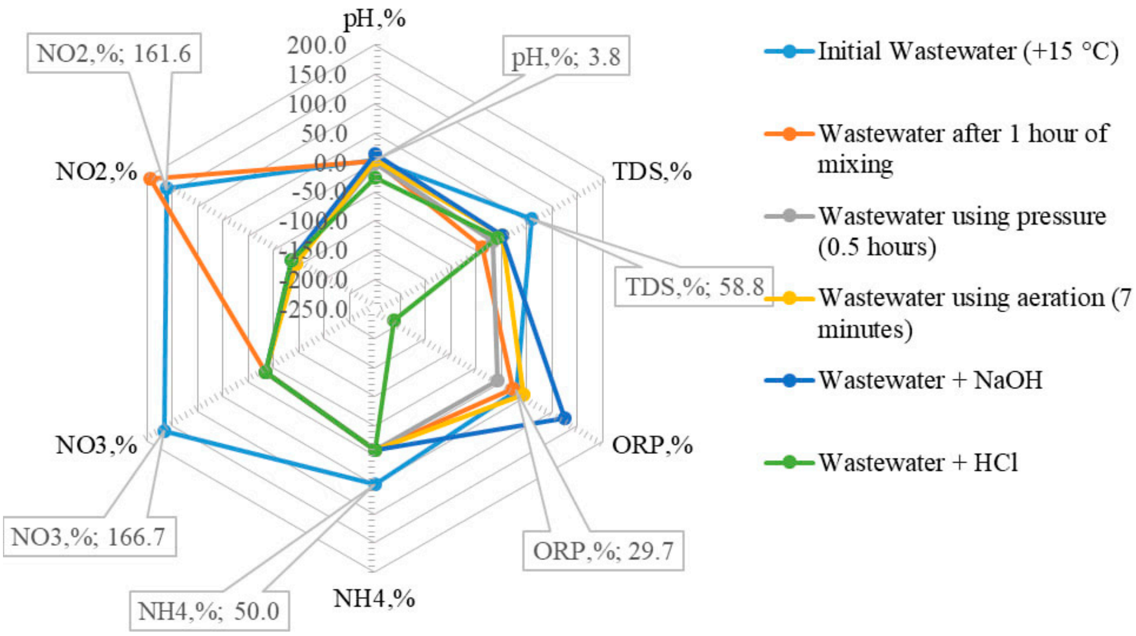

Figure 5. Diagram of deviation of research results on changes in wastewater quality indicators from their mathematical expectations (without disturbing influences on aqueous solutions of external factors).

Measurements were carried out after 6 h (all samples, except “pressure”, were processed with a shaker in order to simulate transportation in the sewer network). All solutions were also aerated with air for 20 min. In order to simulate the effect of high temperature on wastewater, a number of solutions were heated to a temperature of +70 °C; hydrochloric acid and sodium hydroxide were added similarly to the previous experiment (Table 2, Figure 6).

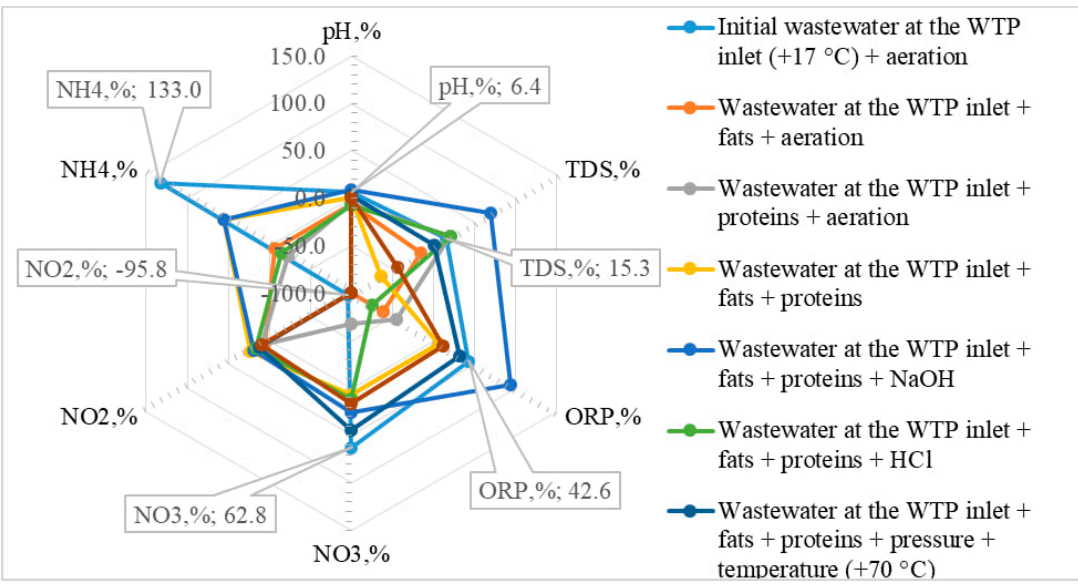

Figure 6. Diagram of the consequences of research results on changes in the quality of wastewater from their mathematical expectations under aerobic conditions (with the presence of disturbing effects on aqueous solutions of external factors).

The final stage of physical modeling was the simulation of anaerobic conditions when the quality indicators of transported municipal wastewater are affected by aqueous solutions discharged by industrial enterprises (Table 3, Figure 7). There was no pressure applied to the water and no chemical pH adjustment was made; when stirring for 6 h, contact with atmospheric air was not allowed.

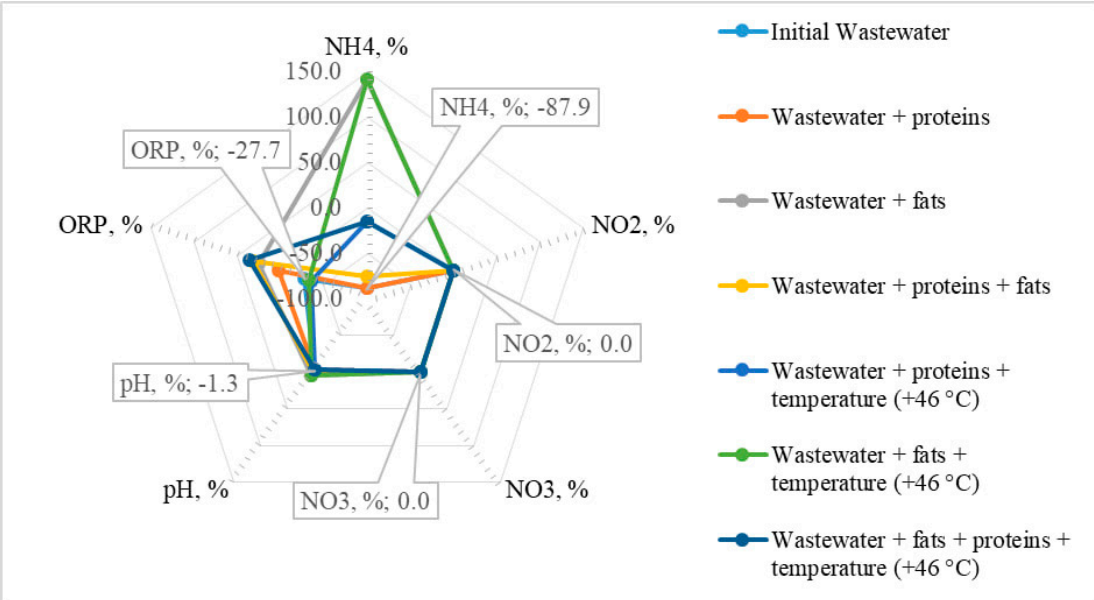

Figure 7. Diagram of deviation of research results on changes in wastewater quality indicators from their mathematical expectations under anaerobic conditions (with the presence of disturbing effects on aqueous solutions of external factors).

The third stage of the experiment was carried out under anaerobic conditions, which suggests the active activity of ammonifying bacteria. This process is confirmed by both increased ammonia/ammonium values, as well as a decrease in pH to the neutral side, which is favorable for their operation. The high content of this compound in the model fat solution can be explained by the presence of a certain amount of muscle fibers, which are pure proteins, which, as a result of soaking, were presumably largely exposed to the community of ammonifying bacteria. In the case of a similar experiment conducted previously under aerobic conditions, a high amount of nitrate and nitrite ions was observed at low ammonia/ammonium values, which may be explained by the insufficient time of keeping subcutaneous fat with inclusions of muscle fibers in an aqueous solution to initiate the effective work of the community of ammonifying microorganisms, processing nitrites and nitrates. Based on the research results (see Tables 1–3), preliminary conclusions can be made about the conceptual need to change approaches to designing water disposal process management.

4. Discussion

An analysis of the results of physical modeling allowed us to draw the following general conclusions:

- The quality indicators of municipal wastewater under the influence of factors occurring in the sewerage network without disturbing influences in the form of introduced additional pollutants are quite stable and predictable: fluctuations in values occur only for "pH" and "ORP", which is caused by the bio-chemical multifactorial formation of their values and specifics of instrumental measurements;
- As a result of the complex disturbing effects of acids, alkalis, temperature, organic pollutants of protein and fatty natures in aerobic conditions, significant amplitude fluctuations in the parameters of aqueous solutions from the value of their mathematical

expectation take place: for ammonium nitrogen—about 10%–100%, for nitrites—about 20%–50%, for nitrates–about 10%–40%;
- As a result of the complex disturbing effects of temperature and organic pollutants of protein and fatty natures under anaerobic conditions (6 h of stirring), significant amplitude fluctuations in the parameters of aqueous solutions occur from the value of their mathematical expectation only for ammonium nitrogen: about 20%–100%;
- Disturbing influences in the form of pollutants in discharged wastewater from individual users (usually industrial enterprises), under certain conditions, can potentially form indicators of the quality of wastewater at their inlet that are unacceptable for the municipal WDS—which must be preventively counteracted not only at the stage of such pollutants entering the sewerage network but also by preventing the creation of conditions for the formation of secondary pollutants in pipelines, sewage pumping stations and other sewerage technological units.

In the approaches of automatic control theory, a conceptual model of digitalization of the municipal wastewater disposal systems in the segment "transportation—wastewater treatment" has been developed based on the criterion of environmental efficiency of treatment facilities (Figure 8) within the framework of regulating wastewater disposal parameters by disturbance (Poncelet principle). In Figure 8, variables X1. . .XN, Z1. . .ZM and Y are as described in Figure 2; OKZ1. . .OKZM are indicators of the quality of wastewater from domestic and industrial users, whose wastewater has a disturbing effect on technological processes at the municipal WDS after organizational measures to correct such a negative impact; XZ1. . .XZN are indicators of the quality of wastewater from domestic and industrial users, whose wastewater has a disturbing effect on technological processes at the municipal WDS, after correcting such a negative impact using local wastewater treatment approaches.

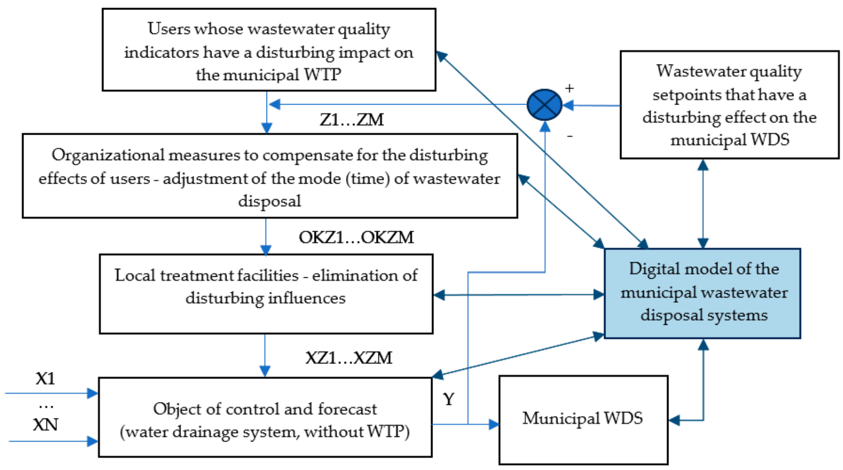

Figure 8. Conceptual model of digitalization of the municipal wastewater disposal systems in the segment "transportation—wastewater treatment".

The results of physical modeling (Tables 1–3) make it possible to focus attention when digitalizing wastewater disposal on the preventive elimination of the negative impact of wastewater from individual users of the wastewater disposal network on the municipal WDS (see Figure 8). The expected positive results from the digitalization of the sanitation system of a populated area will allow to:

- Implement operational control over wastewater disposal and treatment (adapting software to classical wastewater treatment process schemes and process schemes using modern technologies for removing biogenic elements);
- Ensure optimization and increased efficiency (environmental and resource) of the water disposal and water treatment process and promptly apply optimal methods for its intensification;

– Increase the validity and efficiency of management decision-making (according to preliminary estimates);
– Reduce the time for making management decisions by an order of magnitude;
– Virtually eliminate errors in information support;
– Significantly optimize data search and extraction;
– Reduce the time for planning operations several times;
– Improve the quality and effectiveness of information interactions between stakeholders by increasing the degree of integration of information flows and resources, including communications with design organizations;
– Achieve completeness, relevance and reliability of information on drainage and treatment processes;
– Ensure comprehensiveness and a synergistic effect in solving problems of information and analytical support for water disposal;
– Improve the efficiency of data collection, comparison, analysis and reporting, as well as improve the implementation of regulatory indicators;
– Reduce the risks of man-made emergencies;
– Systematically improve the qualifications and retrain specialists of enterprises in the field of digital technologies;
– Form and scale to other objects of the knowledge base and digital models (digital twins);
– Improve the economic efficiency of operation, maintenance and repair (validity of modernization and reconstruction) of process units at all stages of their life cycles;
– Optimize (significantly reduce the cost) the architecture of automation hardware, including the minimization of the use of measuring systems;
– Create a single end-to-end unified software product for designers and operators of biological treatment facilities (managers, economists, technologists, engineers, operators) with the ability to form local centers for operational management of the life cycles of wastewater disposal systems.

Numerical values from the profit of using digital wastewater management systems can be determined only at specific sites (after normal operation). At the same time, the location of the main controllers, when implemented on real systems, must be performed at the WTP with the placement of the DSS, Knowledge Base subsystems on them.

It is advisable to take the efficiency of WTP functioning as the criterion of ecological and energy efficiency:

$$EF = \frac{\left[\left(\frac{L1_{output}-GDK1}{GDK1_{ref}} \cdot 100\ \%\right) + \ldots + \left(\frac{LN_{output}-GDKN}{GDKN_{ref}} \cdot 100\%\right)\right] \cdot \sum_{i=1}^{N} Q_i}{\sum_{i=1}^{N} W_i} \quad (1)$$

where *L1output*, …, *LNoutput* are the actual values of the relevant wastewater quality indicators (in units of measurement in accordance with regulatory documents for assessing wastewater quality indicators); *GDK1*, …, *GDKNref* are the standard values of the relevant wastewater quality indicators (in units of measurement in accordance with regulatory documents for assessing wastewater quality indicators); *Q* is the operating time of technological units of treatment facilities that ensure the standardization of the corresponding indicators of wastewater quality, h; *W* is the electricity consumed for water purification, kW·h; *N* is the number of wastewater quality indicators.

To solve the listed digitalization problems, from the point of view of mathematical support, it is advisable to use the following technologies: artificial intelligence (AI), Internet of things (IoT), big data, analytical data processing, digital twins, and machine learning. The main area of application of the listed solutions is the intelligent analysis of information obtained as a result of monitoring and automation of decision-making in real-time, forecasting dangerous situations, etc. In this case, it is advisable to integrate such technologies into the following subsystems of the digital system (see Figure 1):

– Classic hardware: Internet of Things, digital twins, and artificial intelligence.

- DSS: artificial intelligence, digital twins, machine learning, and big data.
- Knowledge base: artificial intelligence, machine learning, and big data.
- Technological personnel: Artificial Intelligence (AI).

Accordingly, the enlarged sequence of implementing a well-founded conceptual scheme will include three stages:

- Design and development of the mathematical and technological core.
- Development and experimental processing of applied digital services using the created mathematical and technological core.
- Implementation, adjustment and trial operation. Transition to regular operation.

At the first stage, based on an in-depth, consistent study of the subject area (including physical modeling), technical design and prototyping, an intelligent system of unified solutions is built—an "engine" for applied digital services.

5. Conclusions

The analysis of regulatory documents and operational features of water treatment equipment indicates the need to control technological processes at wastewater and sediment sampling points, taking into account the characteristics of existing devices for monitoring and regulating resource consumption in accordance with established regulatory criteria. It is important to implement hardware and software systems at water supply and sanitation facilities for operational analysis and distributed accounting of wastewater quality at all stages of their transportation and not just at the purification stage. It is necessary to tighten requirements for forecasting changes in pollution indicators in real-time through the integration of forecast blocks into specialized automated control systems.

The analysis of physical modeling conducted in the article showed that the quality indicators of municipal wastewater without additional pollutants are stable, and fluctuations are observed only for pH and ORP. Under the influence of acids, alkalis, temperature and organic pollutants in aerobic conditions, the amplitude fluctuations reach: for ammonium nitrogen—10%–100%, nitrites—20%–50%, and nitrates—10%–40%; in anaerobic conditions (6 h of mixing), fluctuations are observed only for ammonium nitrogen—20%–100%. Pollutants in wastewater from industrial users can create unacceptable indicators for municipal WTP, which requires preventive measures at the stage of their receipt and prevention of secondary pollution.

Using approaches from the theory of automatic control, a conceptual model of digitalization of municipal wastewater disposal systems in the segment "transport—wastewater treatment" was developed based on the criterion of environmental efficiency of treatment facilities. Such a model has the following advantages: reduces the risk of secondary pollution due to preventive measures; increases management efficiency due to the digitalization of processes and the use of automated systems; ensures environmental compliance of treatment facilities through the integration of environmental criteria into the management system; and provides operational analysis and forecasting of wastewater quality in real-time. At the same time, the following disadvantages should be noted: significant initial costs for the implementation of digital control systems, which is associated with the need to modernize existing equipment and infrastructure; requirements for highly qualified personnel to service automated systems; complexity of integrating different stages of the water disposal and treatment process into a single system.

Further research is aimed at developing algorithms for predicting pollution indicators in real-time, optimizing transport and treatment processes, integrating digital solutions with existing technologies, studying the impact of different types of pollutants, and analyzing the economic feasibility of digitalizing wastewater disposal and water treatment systems.

Author Contributions: Conceptualization, V.S., N.Z., and N.L; validation, N.Z. and N.L.; formal analysis, V.S. and N.J.; investigation, V.S.; resources, N.J.; data curation, V.S. and N.J.; writing—original draft preparation, V.S. and N.Z.; writing—review and editing, N.L., Y.C., and M.B.; visualization,

V.S. and N.L.; supervision, M.B.; funding acquisition, N.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Slovak Research and Development Agency under the contract No. APVV-20-0140 and by the Scientific Grant Agency of the Ministry of Education, Science, Research, and Sport of the Slovak Republic, as well as the Slovak Academy of Sciences, under project VEGA Grant No. 2/0108/23.

Data Availability Statement: The authors declare that all data supporting the findings of this research are available in this article.

Acknowledgments: This research has been supported by the Slovak Research and Development Agency (contract No. APVV-20-0140) and by the Slovak Grant Agency for Science (Grant No. 2/0108/23). It was supported by the institutional funds of T. G. Masaryk Water Research Institute. We are thankful for the Czech government's support, which allowed this scientific cooperation to start. Finally, we are thankful for the support provided by the International Innovation and Applied Centre "Aquatic Artery" (Sumy, Ukraine).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bassin, J.; Castro, F.; Valério, R.; Santiago, E.; Bassin, I. Chapter 16—The impact of wastewater treatment plants on global climate change. In *Water Conservation in the Era of Global Climate Change*; Elsevier: Amsterdam, The Netherlands, 2021; p. 410. [CrossRef]
2. Obaideen, K.; Shehata, N.; Sayed, E.; Abdelkareem, M.; Mahmoud, M.; Olabi, A. The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. *Energy Nexus* **2022**, *7*, 100112. [CrossRef]
3. Gallego-Schmid, A.; Tarpani, R.R.Z. Life cycle assessment of wastewater treatment in developing countries: A review. *Water Res.* **2019**, *153*, 63–79. [CrossRef] [PubMed]
4. Fatimah, Y.A.; Govindan, K.; Murniningsih, R.; Setiawan, A. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *J. Clean. Prod.* **2020**, *269*, 122263. [CrossRef]
5. Hasan, H.A.; Muhammad, M.H. A review of biological drinking water treatment technologies for contaminants removal from polluted water resources. *J. Water Process Eng.* **2020**, *33*, 101035. [CrossRef]
6. Kehrein, P.; Van Loosdrecht, M.; Osseweijer, P.; Garfí, M.; Dewulf, J.; Posada, J. A critical review of resource recovery from municipal wastewater treatment plants–market supply potentials, technologies and bottlenecks. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 877–910. [CrossRef]
7. Hughes, J.; Cowper-Heays, K.; Olesson, E.; Bell, R.; Stroombergen, A. Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Clim. Risk Manag.* **2021**, *31*, 100262. [CrossRef]
8. Ranieri, E.; D'Onghia, G.; Lopopolo, L.; Gikas, P.; Ranieri, F.; Gika, E.; Ranieri, A. Influence of climate change on wastewater treatment plants performances and energy costs in Apulia, south Italy. *Chemosphere* **2024**, *350*, 141087. [CrossRef]
9. Adedeji, K.B.; Ponnle, A.A.; Abu-Mahfouz, A.M.; Kurien, A.M. Towards digitalization of water supply systems for sustainable smart city development—Water 4.0. *Appl. Sci.* **2022**, *12*, 9174. [CrossRef]
10. Banerjee, C.; Bhaduri, A.; Saraswat, C. Digitalization in Urban Water Governance: Case Study of Bengaluru and Singapore. *Front. Environ. Sci.* **2022**, *10*, 816824. [CrossRef]
11. Boyle, C.; Ryan, G.; Bhandari, P.; Law, K.M.; Gong, J.; Creighton, D. Digital transformation in water organizations. *J. Water Resour. Plan. Manag.* **2022**, *148*, 03122001. [CrossRef]
12. Guandalini, I. Sustainability through digital transformation: A systematic literature review for research guidance. *J. Bus. Res.* **2022**, *148*, 456–471. [CrossRef]
13. Alrbai, M.; Al-Dahidi, S.; Al-Ghussain, L.; Alahmer, A.; Hayajneh, H. Minimizing grid energy consumption in wastewater treatment plants: Towards green energy solutions for water sustainability in Jordan. *Sci. Total Environ.* **2024**, *926*, 172139. [CrossRef] [PubMed]
14. Al-Dahidi, S.; Alrbai, M.; Al-Ghussain, L.; Alahmer, A. Maximizing energy efficiency in wastewater treatment plants: A data-driven approach for waste heat recovery and an economic analysis using Organic Rankine Cycle and thermal energy storage. *Appl. Energy* **2024**, *362*, 123008. [CrossRef]
15. Aghabalaei, V.; Nayeb, H.; Mardani, S.; Tabeshnia, M.; Baghdadi, M. Minimizing greenhouse gases emissions and energy consumption from wastewater treatment plants via rational design and engineering strategies: A case study in Mashhad, Iran. *Energy Rep.* **2023**, *9*, 2310–2320. [CrossRef]
16. Masłoń, A.; Czarnota, J.; Szaja, A.; Szulżyk-Cieplak, J.; Łagód, G. The enhancement of energy efficiency in a wastewater treatment plant through sustainable biogas use: Case study from Poland. *Energies* **2020**, *13*, 6056. [CrossRef]
17. Hu, W.; Tian, J.; Li, X.; Chen, L. Wastewater treatment system optimization with an industrial symbiosis model: A case study of a Chinese eco-industrial park. *J. Ind. Ecol.* **2020**, *24*, 1338–1351. [CrossRef]

18. Zhao, L.; Dai, T.; Qiao, Z.; Sun, P.; Hao, J.; Yang, Y. Application of artificial intelligence to wastewater treatment: A bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. *Process Saf. Environ. Prot.* **2020**, *133*, 169–182. [CrossRef]
19. Li, L.; Rong, S.; Wang, R.; Yu, S. Recent advances in artificial intelligence and machine learning for nonlinear relationship analysis and process control in drinking water treatment: A review. *Chem. Eng. J.* **2021**, *405*, 126673. [CrossRef]
20. Wang, D.; Thunéll, S.; Lindberg, U.; Jiang, L.; Trygg, J.; Tysklind, M.; Souihi, N. A machine learning framework to improve effluent quality control in wastewater treatment plants. *Sci. Total Environ.* **2021**, *784*, 147138. [CrossRef]
21. Schneider, M.Y.; Quaghebeur, W.; Borzooei, S.; Froemelt, A.; Li, F.; Saagi, R.; Torfs, E. Hybrid modelling of water resource recovery facilities: Status and opportunities. *Water Sci. Technol.* **2022**, *85*, 2503–2524. [CrossRef]
22. Alvi, M.; Batstone, D.; Mbamba, C.K.; Keymer, P.; French, T.; Ward, A.; Cardell-Oliver, R. Deep learning in wastewater treatment: A critical review. *Water Res.* **2023**, *245*, 120518. [CrossRef] [PubMed]
23. Zhao, J.; Shang, C.; Yin, R. Developing a hybrid model for predicting the reaction kinetics between chlorine and micropollutants in water. *Water Res.* **2023**, *247*, 120794. [CrossRef] [PubMed]
24. Zhu, M.; Wang, J.; Yang, X.; Zhang, Y.; Zhang, L.; Ren, H.; Ye, L. A review of the application of machine learning in water quality evaluation. *Eco-Environ. Health* **2022**, *1*, 107–116. [CrossRef] [PubMed]
25. Alekseevsky, D.; Chernysh, Y.; Shtepa, V.; Chubur, V.; Stejskalová, L.; Balintova, M.; Fukui, M.; Roubík, H. Enhancing Ecological Efficiency in Biological Wastewater Treatment: A Case Study on Quality Control Information System. *Water* **2023**, *15*, 3744. [CrossRef]
26. Chen, Y.; Song, L.; Liu, Y.; Yang, L.; Li, D. A review of the artificial neural network models for water quality prediction. *Appl. Sci.* **2020**, *10*, 5776. [CrossRef]
27. Lowe, M.; Qin, R.; Mao, X. A review on machine learning, artificial intelligence, and smart technology in water treatment and monitoring. *Water* **2022**, *14*, 1384. [CrossRef]