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Research Article

Effective Control and Management of Pump Station Electrical Equipment

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Abstract: This study presents an integrated methodological framework for optimizing the control and management of electrical power equipment in municipal pump stations through the combined application of SCADA architecture and adaptive variable frequency drive (VFD) regulation. Unlike conventional approaches based on fixed operational set-points or isolated equipment-level upgrades, the proposed framework enables system-level evaluation of energy efficiency, hydraulic stability, operational reliability, and fault response performance. A mathematical model of pump station operation was developed in MATLAB/Simulink, incorporating key variables such as energy consumption, pipeline pressure, volumetric flow rate, shutdown frequency, and fault recovery time. The framework was validated using real operational data from three municipal pump stations in Taraz, Kazakhstan, representing heterogeneous infrastructure conditions. The results demonstrate a reduction in electrical energy consumption by 15-20%, a decrease in pump shutdown frequency by 50-70%, and a reduction in mean fault recovery time from 4-6 hours to 1-2 hours. In addition, the system reliability coefficient increased from 0.75-0.89 to 0.95-0.98. The simulation results showed strong agreement with field data, with model prediction errors not exceeding 6-8% for key operational parameters. Economic analysis indicates a payback period of approximately 2.2-2.5 years following modernization. The proposed framework provides a transferable decision-support methodology for evaluating and implementing energy-efficient and reliability-oriented control strategies in municipal water supply systems, particularly for aging infrastructure operating under variable hydraulic conditions.

Keywords: *Automation; Electrical power engineering; Energy efficiency; Frequency converters; Pump stations; SCADA systems; Water resource management.*

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1. Introduction

Modern pump stations play a crucial role in ensuring a reliable water supply and the efficient operation of sewage systems, making them critical components of urban and industrial electrical power infrastructure. Given the increasing demand for water resources and the tightening requirements for energy consumption and environmental sustainability, automation systems have become an integral part of pump station operations. The integration of advanced electrical power and automation technologies significantly enhances equipment efficiency, reduces operational costs, and ensures a higher level of monitoring and control over its performance [1-3].

Pump stations primarily function to transport water to the required height and maintain pressure in the water supply and sewage systems. These processes require substantial electrical power resources, making pump stations one of the largest energy consumers within water network systems, with energy consumption accounting for up to 85%. Therefore, optimizing their operation is essential for reducing operational expenses and increasing the overall efficiency of water systems. Despite their evident significance, traditional approaches to the design and operation of pump stations often fail to incorporate

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the potential of modern automation technologies. This results in inefficient resource utilization and a decline in overall system performance [4-6].

The automation of pump station operations requires addressing several existing challenges. Modern automated systems incorporate sensors, actuators, and software solutions that enable real-time monitoring and control of pump operations. These systems enable adaptation of equipment performance to current operational conditions, optimization of energy consumption, and extension of pump service life [7-9]. A key aspect of automating electrical power equipment is the implementation of SCADA (Supervisory Control and Data Acquisition) systems, which enable centralized monitoring of pump station parameters and rapid response to any deviations [10-12].

SCADA systems facilitate real-time data acquisition, analysis, and visualization, enabling operators to swiftly identify and resolve malfunctions. For instance, data on pressure, water flow, and energy consumption allow for prompt responses to load variations, the prevention of emergencies, and the optimization of pump operating modes. The integration of frequency converters into automated systems further reduces energy consumption by regulating the rotational speed of pump motors in line with the current load. Studies indicate that the implementation of frequency converters can lower energy consumption by 10–15% and extend equipment lifespan by 20% [13, 14].

Optimizing pump station operations through the automation of electrical power equipment requires a comprehensive approach that integrates mathematical modelling and advanced algorithms. One such method is the use of genetic algorithms, which facilitate the determination of optimal pump operation modes by considering variations in demand and the technical characteristics of electrical power equipment. These algorithms enable precise calculation of parameters such as pump rotational speed, thereby minimizing energy costs and enhancing overall station efficiency. For example, genetic algorithms can account for temporal load fluctuations, adjusting pump operation to align with current operational conditions [15-17].

An additional tool for selecting the optimal parameters of pump stations is the Analytic Hierarchy Process (AHP), which enables multicriteria analysis by considering both technical and economic factors. AHP is widely applied for evaluating various alternatives and determining the most rational solutions in the design of pump stations. For instance, this method allows for the assessment of parameters such as the number of pumps, the complexity of the control system, and investment and operational costs. The application of AHP facilitates the balancing of technical and economic requirements, which is particularly crucial in the context of budget constraints and the need for infrastructure modernization [18-20].

One of the key challenges in modernizing pump stations is the integration of new technologies with existing systems. Many pump stations have been in operation for decades, and their equipment may be technologically obsolete. Implementing automation systems requires not only technical upgrades but also adapting existing systems to new operational conditions. A phased introduction of electrical power automation technologies, including the deployment of SCADA systems and frequency converters, minimizes risk and ensures a smooth transition to more efficient operational methods [21, 22].

The benefits of automating electrical power equipment in pump stations extend far beyond improved energy efficiency. Automation enhances operational reliability and reduces equipment downtime by enabling the prompt detection and resolution of faults. Moreover, automated systems ensure greater control precision, enabling optimal resource allocation and preventing excessive water and energy consumption. In the long term, these improvements contribute not only to cost reduction but also to the environmental sustainability of water supply systems [23].

Amid growing urbanization and increasing water resource demands, the development of electrical power automation systems has become an integral part of water network management strategies. The integration of artificial intelligence (AI) and the Internet of Things (IoT) offers new opportunities to enhance the efficiency of pump stations. For instance, IoT sensors facilitate real-time data collection on the condition of electrical power equipment and operational parameters, while AI-driven analytics enable predictive maintenance by identifying potential failures before they occur. These approaches help optimize maintenance planning and mitigate the risk of system failures, ensuring more reliable and efficient water management [24-26].

Recent developments in smart water infrastructure increasingly rely on Industry 4.0 concepts, particularly Digital Twins and Cyber-Physical Systems (CPS). Digital twin technology enables the creation of real-time virtual replicas of pump stations and water distribution networks, allowing operators to simulate hydraulic behaviour, predict equipment degradation, and evaluate operational scenarios before implementing physical changes. Similarly, cyber-physical architectures integrate sensors, communication networks, control algorithms, and computational models into unified platforms that support adaptive and data-driven infrastructure management. Recent studies demonstrate that the integration of digital twins and CPS technologies significantly improves monitoring accuracy, predictive maintenance capabilities, and operational optimisation of water supply systems [27-29].

Examples of the successful implementation of automation systems for electrical power equipment in pump stations can be found across various countries and industries. In urban water supply systems, such as in London, the deployment of SCADA systems has led to a 20% reduction in energy costs by automating pump operations. In rural areas of Australia, automation has simplified pump management in remote regions, significantly reducing the need for on-site operators. In industrial applications, such as beverage production plants in Germany, automation has enabled precise water dosing and resulted in a 15% decrease in energy consumption [30-32].

Despite the demonstrated advantages of automation technologies, several studies highlight significant practical limitations to their implementation in municipal water infrastructure. In particular, deploying SCADA systems and advanced control platforms may involve significant capital investment, complex system integration, and the need for specialized technical personnel for maintenance and operation. In addition, the implementation of advanced optimization or AI-based control algorithms may increase system complexity and reduce operational transparency for infrastructure operators. These challenges are particularly relevant for aging municipal water networks where financial resources and technical expertise may be limited. Consequently, modern pump station modernization strategies must balance technological sophistication with practical deployability and operational reliability.

Although variable frequency drives (VFDs) have been used for pump speed regulation for several decades, their implementation in many municipal water supply systems remains limited to isolated equipment-level upgrades without integrated performance evaluation. In many cases, VFD installation is performed as a standalone modernization measure without systematic analysis of hydraulic stability, operational reliability, and long-term economic performance.

The present study, therefore, focuses not on the introduction of VFD technology itself but on the development of an integrated methodological framework for evaluating and implementing pump station modernization. The proposed framework combines simulation-based modelling, SCADA-driven monitoring, adaptive pump speed regulation, and reliability-oriented performance analysis within a single decision-support structure.

This approach enables quantitative assessment of energy efficiency, operational stability, failure response behaviour, and economic performance across heterogeneous pump station infrastructures, thereby extending conventional equipment-level modernization strategies toward system-level optimisation of municipal water supply networks.

Although variable frequency drives are widely recognised as an effective tool for improving pump energy efficiency, several studies highlight potential operational trade-offs associated with low-speed pump operation. Operating pumps at very low rotational speeds may lead to unstable hydraulic regimes, including low-flow cavitation, increased vibration, and accelerated mechanical wear of pump components. Consequently, optimisation of pump speed must consider not only energy savings but also mechanical stability and long-term equipment reliability. Recent research therefore emphasises the importance of balancing energy efficiency with safe hydraulic operating conditions when implementing adaptive pump speed control strategies [9, 12, 14].

The potential of automating electrical power equipment in pump stations extends to other sectors, including energy, oil and gas, agriculture, and transportation. For instance, at nuclear power plants, automation minimizes human error and enhances the reliability of cooling systems. In oil pipelines, automated systems monitor pressure, temperature, and leakage, thereby mitigating the risk of operational failures. In agriculture, automated irrigation management systems have led to a 30% reduction in water consumption, while in railway networks, automation has improved power supply stability and enhanced the reliability of train operations [33-35].

The automation of electrical power equipment in pump stations is a key approach to enhancing the efficiency and reliability of water systems. The application of technologies such as SCADA, frequency converters, IoT, and artificial intelligence enables the optimization of energy consumption, cost reduction, and improved management quality. The further development of automated systems involves their integration with other components of water networks, thereby facilitating the creation of intelligent, environmentally sustainable water supply systems. The adoption of modern automation approaches will be a crucial step toward ensuring the efficient operation of pump stations, following the growing energy efficiency and environmental sustainability requirements.

The development of pump station control systems has evolved through several technological stages. Early water supply infrastructure relied on manual control of pump operation, where system operators directly regulated pump start–stop cycles and pressure levels based on local observations. With the advancement of industrial automation, basic programmable logic controller (PLC) systems and SCADA platforms were introduced, enabling remote monitoring and automated regulation of pump parameters. More recently, the emergence of smart water infrastructure and IoT-enabled monitoring systems has further expanded the capabilities of pump station management by integrating real-time data analytics, predictive diagnostics, and adaptive control strategies.

The scientific contribution of this study lies in the development of an integrated control and evaluation methodology for pump station modernization rather than the isolated application of individual automation technologies. While SCADA systems and variable frequency drives are widely used in modern industrial automation, their implementation in many municipal infrastructures remains fragmented and poorly evaluated from a system-performance perspective.

This study differs from previously reported approaches in several important aspects. While earlier studies such as Zhao *et al.* [3], Xia *et al.* [5], and Chen *et al.* [30] primarily focus on individual technological solutions, such as SCADA monitoring, AI-based optimisation algorithms, or standalone VFD implementation, the present research proposes an integrated methodological framework that simultaneously evaluates energy consumption, hydraulic stability, shutdown frequency, fault recovery time, and operational reliability of pump stations. Unlike conventional approaches that analyse these parameters separately, the proposed framework combines simulation-based modelling, SCADA-driven monitoring, adaptive pump speed regulation, and field-validated performance assessment within a unified evaluation structure. This system-level perspective enables a comprehensive analysis of pump station modernization outcomes and provides a transferable methodology applicable to heterogeneous municipal water supply infrastructures.

In contrast to previous studies that typically analyse energy savings or automation upgrades separately, the present work proposes a unified methodological framework that combines supervisory control architecture, adaptive pump speed regulation, and simulation-based operational assessment. The framework integrates hydraulic performance parameters, electrical energy consumption, equipment reliability indicators, and failure response dynamics within a single evaluation structure. The methodology was validated using operational data from three heterogeneous municipal pump stations in Taraz, Kazakhstan, allowing cross-facility comparison under real infrastructure conditions. This approach enables simultaneous assessment of energy efficiency improvements, reliability enhancement, and economic performance, providing a transferable framework for modernization of aging water supply infrastructure.

Current automation systems used in municipal pump stations commonly rely on predefined operating set-points for pump activation, pressure regulation, and flow control. While such strategies provide basic operational stability, they often fail to respond to dynamically changing hydraulic conditions typical of aging water distribution networks, including variable head losses, transient pressure fluctuations, and uneven demand patterns. As a result, pump operation may remain suboptimal in terms of energy efficiency, operational reliability, and system responsiveness.

To address this limitation, the present study proposes an integrated methodological framework that combines simulation-based modelling, SCADA-driven monitoring, adaptive pump speed regulation using variable frequency drives, and field-based operational performance evaluation. This approach enables dynamic assessment of pump station behaviour and provides a structured methodology for improving energy efficiency and operational stability in municipal pumping infrastructure.

The primary objective of this study is to develop and implement an effective automation system for managing electrical power equipment in pump stations, thereby improving reliability, energy efficiency, and sustainability. This will enable the optimization of operational processes, reduction of energy and maintenance costs, stable water supply assurance, and minimization of accident risks. The scientific contribution of this study lies in the development of an integrated methodological framework for the modernization and performance evaluation of municipal pump stations. The main contributions of this work can be summarized as follows: (1) a system-level methodological framework is proposed that integrates SCADA-based monitoring, adaptive pump speed control using variable frequency drives, and simulation-based performance evaluation within a unified analytical structure; (2) a mathematical model of pump station operation is developed, incorporating key operational parameters including energy consumption, hydraulic pressure, volumetric flow rate, shutdown frequency, and fault recovery time; (3) a simulation-based validation approach is implemented in the MATLAB/Simulink environment, enabling the analysis of pump station behaviour under variable hydraulic conditions; (4) the proposed framework is validated using real operational data from three municipal pump stations, demonstrating its applicability under heterogeneous infrastructure conditions; (5) a multi-criteria evaluation of modernization effectiveness is conducted, showing improvements in energy efficiency, operational reliability, and fault response performance.

These contributions collectively provide a transferable decision-support methodology for optimizing pump station operation in municipal water supply systems.

2. Materials and Methods

2.1. Research Objects

This section presents the research methodology developed to evaluate and improve the operational efficiency of municipal pump station electrical equipment. The methodology consists of four interconnected components: (1) an operational audit of the pre-modernization state of pump station electrical infrastructure; (2) development of a mathematical model describing pump station operation in terms of hydraulic pressure, volumetric flow rate, electrical energy consumption, and equipment reliability indicators; (3) simulation-based verification of control logic using a MATLAB/Simulink modelling environment; and (4) field implementation and comparative performance evaluation following modernization.

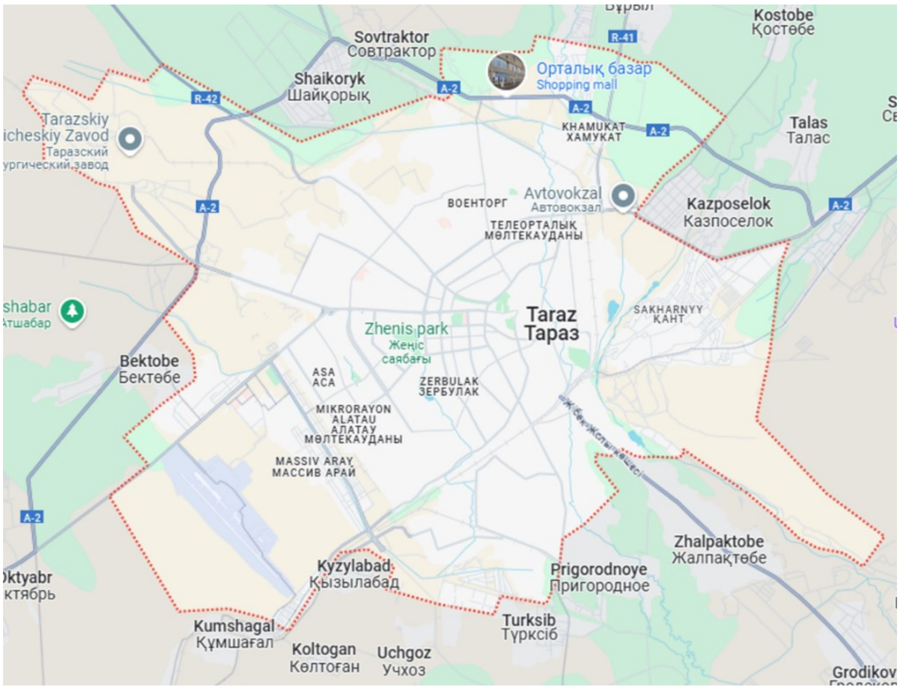

Figure 1. Map of Taraz[1]

[1] Source: https://www.google.com/maps/place/Taraz

To ensure robustness of the methodology, three municipal pump stations with heterogeneous operational characteristics were selected as case-study facilities. These stations differ in installed capacity (20,300-77,760 m³/day), reliability category (I and III), pump configuration, and seasonal operating regime. Such variation enables cross-validation of the proposed methodology under different hydraulic and operational conditions typical for municipal water supply infrastructure.

The proposed methodological framework allows simultaneous assessment of energy efficiency, operational reliability, failure response dynamics, and economic performance following automation modernization. The objects of this study are three pump stations located in Taraz, Kazakhstan (Figure 1).

Taraz, the administrative center of Zhambyl Region, Kazakhstan, faces several challenges in the water supply and sanitation sector. The city's primary sources of drinking water are groundwater and, to a lesser extent, the Talas and Asa rivers. However, the deterioration of the water supply network and treatment facilities has resulted in water losses and a decline in water quality. The sewer system primarily serves the central districts of the city, while in suburban areas, septic tanks are commonly used. Moreover, the wastewater treatment facilities require modernization, as their efficiency remains insufficient, and wastewater discharge poses an environmental threat.

To address these issues, plans have been proposed to replace outdated infrastructure, introduce energy-efficient technologies, and implement strict control over industrial wastewater discharges. The modernization of water supply and sanitation systems, including pipeline upgrades and improvements to treatment facilities, will enhance water quality and minimize negative environmental impacts. Table 1 presents the characteristics of the pump stations used in Taraz.

Table 1. Characteristics of pump stations

Characteristics	**Pump Station No.1**	**Pump Station No.2**	**Pump Station No.3**
Address	2nd Peschany Lane	"ZhGMSI" District	Sanyrak Batyra Street
Year of Construction	1975	1981	1983
Design Capacity, m³/day	74 000	20 300	77 760
Reliability Category	I	III	I
Infrastructure	Two clean water reservoirs, each with a capacity of 2,000 m³; Transformer Substation No. 228.	Two clean water reservoirs, each with a capacity of 2,000 m³; transformer substation.	Four pressure outlets (three with a diameter of Ø530×6.0 mm and one Ø630×7.0 mm); transformer substation.
Equipment	Four GRUNDFOS KP1615-1/2 pumps (two operational, two standby) with a capacity of 1,940 m³/h, a head of 40 m, and a motor power of 280 kW.	Seven GRUNDFOS CR150-3-2 pumps (five operational, two standby) with a capacity of 150 m³/h, a head of 50 m, and a motor power of 30 kW.	Four GRUNDFOS KP1615-1/2 pumps (two operational, two standby) with a capacity of 2,200 m³/h, a head of 40 m, and a motor power of 315 kW.
Purpose	Water supply for residential districts and the city center.	Operates only during the summer period to provide domestic water supply and fire protection.	Water supply for domestic, industrial, and fire protection needs in the western part of the city.
Features	Pump control is managed via frequency converters to maintain constant pipeline pressure. An automatic standby pump activation system is in place in case of emergency.	Equipped with a water disinfection system (ODV 500 A); automatic pump control is managed via frequency converters.	Automated control system incorporating frequency converters and remote control. Sectional valves and pressure gauges are used for parameter monitoring.

Table 1 presents the key characteristics of three pump stations in Taraz, Kazakhstan, including their addresses, year of construction, capacity, reliability category, infrastructure, equipment, purpose, and management features.

Pump Station No. 1, located on 2nd Peschany Lane, was constructed in 1975 and has a design capacity of 74,000 m³/day. It belongs to Reliability Category I. The infrastructure includes two clean water reservoirs with a capacity of 2,000 m³ each and Transformer Substation No. 228. The station is equipped with four GRUNDFOS KP1615-1/2 pumps, with two operational and two standby units. Each pump has a capacity of 1,940 m³/h and a motor power of 280 kW. The primary function of this station is to supply water to residential districts and the city center. A distinguishing feature is the use of frequency converters for pump control, ensuring constant pipeline pressure, along with an automatic standby pump activation system in case of failure.

Pump Station No. 2, located in the ZhGMSI district, was built in 1981 and has a lower capacity of 20,300 m³/day. It falls under Reliability Category III. The infrastructure includes two water reservoirs of 2,000 m³ each and a transformer substation. The station is equipped with seven GRUNDFOS CR150-3-2 pumps (five operational and two standby), each with a capacity of 150 m³/h and a motor power of 30 kW. It operates exclusively during the summer season, providing domestic and fire protection water supply.

Pump Station No. 3, located on Sanyrak Batyra Street, was constructed in 1983. It has a high capacity of 77,760 m³/day and falls under Reliability Category I. The infrastructure includes four pressure outlets and a transformer substation. The station is equipped with four GRUNDFOS KP1615-1/2 pumps (two operational and two standby), each with a capacity of 2,200 m³/h and a motor power of 315 kW. It serves the western part of the city. Notable features include remote control operation and the use of sectional valves and pressure gauges for monitoring and control.

An analysis of the data presented in Table 1 suggests that the pump stations differ in terms of capacity, purpose, and level of automation, reflecting their varied strategic significance and operational functions.

2.2. The Analysis of the Current Management System

The analysis of the current management system for the electrical power equipment of pump stations was conducted in several stages, including an audit of existing control systems, data collection on operational parameters, and subsequent analysis using computational formulas.

An audit of the control and monitoring systems was carried out at all three pump stations. This involved reviewing technical documentation describing the control system architecture and inspecting equipment, including pumps, transformer substations, frequency converters, and automation systems. The evaluation focused on the functionality of the equipment, the level of automation, the condition of backup components, and the methods used for monitoring parameters.

Following the audit, data collection on operational parameters was organized. This process utilized built-in sensors and recording devices to obtain real-time measurements.

The energy consumption (E) was calculated using the following formula:

$$E = \sum_{i=1}^{n} P_i T_i, \tag{1}$$

where P_i is the power consumed by pump i, T_i – is its operating time.

The productivity of pumps Q was determined by the formula:

$$Q = \frac{V}{T}, \tag{2}$$

where V represents the total volume of pumped water, and T denotes the operating time of the pumps.

The pressure in pipelines can be described using Bernoulli's equation, which accounts for elevation, flow velocity, and frictional losses:

$$P = \rho g h + \frac{1}{2}\rho v^2 + \Delta P_{loss}, \tag{3}$$

where P is pipeline pressure, Pa;

ρ fluid density, kg/m³;

g gravitational acceleration, m/s²;

h – elevation, m;

v – flow velocity, m/s;

ΔP_{loss} – pressure losses due to friction and other factors, Pa.

These parameters are interdependent, and changes in one can affect the others. For instance, an increase in pump performance may lead to higher energy consumption and variations in system pressure.

The fault resolution time $T_{resolution}$ was recorded and averaged using the following formula:

$$T_{resolution} = \frac{\sum_{i=1}^{m} t_{resolution,i}}{m}, \tag{4}$$

where $t_{resolution,i}$ represents the resolution time of the i-th fault, and m is the total number of faults.

To assess system reliability, the failure shutdown rate $R_{failure}$ was determined as follows:

$$R_{failure} = \frac{N_{failure}}{N_{total}} 100\%, \tag{5}$$

where $N_{failure}$ is the number of failure shutdowns, and N_{total} represents the total number of pump operating cycles.

The mathematical model presented in equations (1)-(5) describes the main operational relationships governing pump station performance under steady-state operating conditions. Several modelling assumptions were adopted in order to simplify the analysis and ensure consistency with the available operational data from the studied pump stations.

First, pump operation was assumed to occur under quasi-steady hydraulic conditions, where short-term transient phenomena such as water hammer or rapid valve switching were not explicitly simulated. Second, the fluid properties were assumed constant, with water density taken as 1000 kg/m³ and gravitational acceleration as 9.81 m/s². Third, pump efficiency variations due to minor mechanical wear or temperature effects were considered negligible within the analysed operational time scale. These assumptions allow the analytical model to represent the dominant operational behaviour of the pumping system while maintaining computational simplicity suitable for infrastructure-level analysis.

The parameter ranges presented in Table 4 were derived from the technical specifications of the pumping equipment installed at the three investigated stations in Taraz. Specifically, pump performance values (150-2200 m³/h) correspond to the nominal capacity range of the GRUNDFOS pump models operating at the facilities, while the energy consumption interval (30-315 kW) reflects the rated power of the installed electric motors. The pipeline pressure range of 5-15 atm represents the typical operational pressure required to maintain a stable water supply across the municipal distribution network. Similarly, the daily water flow values (20,300-77,760 m³/day) correspond to the design capacity of the investigated pump stations, as reported in Table 1.

Consequently, the parameter intervals used in the modelling process represent realistic operational conditions observed in the municipal pumping infrastructure rather than theoretical estimates. This ensures that the simulation results reflect the practical performance characteristics of the studied pump stations.

2.3. Modernisation of Pump Stations

The modernization of electrical power equipment in pump stations involved implementing advanced control and management technologies, such as SCADA systems and frequency converters. As a result of these upgrades, there was a significant increase in station performance, a reduction in energy consumption, an enhancement of operational reliability, and a decrease in response time to emergency situations.

SCADA (Supervisory Control and Data Acquisition) is a data management and control system designed for real-time monitoring and regulation of various technological processes. In the context of pump stations, SCADA plays a critical role in ensuring efficient management of electrical equipment. These systems facilitate the real-time collection and processing of data, allowing for the identification of deviations from standard operating parameters and the prompt notification of operators. This, in turn, enables the timely resolution of issues and minimises equipment downtime. The key stages and outcomes of the modernization process are presented in Tables 2 and 3.

Table 2. Key changes in pump station management

Component	Before Modernization	After Modernization
Control System	Manual control	Implementation of SCADA with automation
Parameter Monitoring	Local sensors, visual inspection	Sensors with data transmission to SCADA
Emergency Response	Operator-dependent response	Automatic alerts and analysis
Reporting	Manual record-keeping	Automated report generation

Table 3. Key changes in pump station management

Parameter	Before Modernization	After Modernization
Power Consumption, kW	Constant, 100%	Adjustable, 70–85%
Pump Performance	Fixed	Variable
Elimination of Hydraulic Shocks	No	Yes
Equipment Service Life	Standard	Extended

The implementation of SCADA has enabled the integration of all pump stations into a unified system, ensuring centralized control and management of electrical power equipment. The system collects real-time data, analyses operational parameters, and notifies operators of potential deviations, thereby enhancing monitoring efficiency and operational responsiveness.

2.4. Modelling and Testing

The modelling and testing of the pump station electrical power management system involve several key stages aimed at assessing the effectiveness of proposed solutions. A mathematical model is developed to represent the core processes occurring within the pump station, including the operation of pumps, reservoirs, and other infrastructure components.

Pump station operation is regulated through closed-loop control of pump rotational speed via a variable-frequency drive (VFD). The objective of the control system is to maintain stable pipeline pressure while minimizing electrical energy consumption and preventing excessive mechanical loading of the pumps.

The controlled variable of the system is the discharge pressure in the pipeline P(t)P(t), while the manipulated variable is the pump rotational speed n(t)n(t), which is regulated through the frequency signal of the VFD.

The control error is defined as:

$$e(t) = P_{set} - P(t) \quad (6)$$

where P_{set} is the required pressure level ensuring stable water supply conditions and $P(t)$ is the measured pipeline pressure.

To regulate pump operation, a proportional-integral-derivative (PID) control law was implemented. The control signal transmitted to the frequency converter is determined as:

$$u(t) = K_p e(t) + K_{i \int_0^t e(\tau) d\tau} + K_d \frac{de(t)}{dt} \quad (7)$$

where $u(t)$ - control signal applied to the VFD, K_p - proportional gain coefficient, K_i - integral gain coefficient, K_d - derivative gain coefficient.

The proportional component provides immediate response to pressure deviations, the integral component compensates steady-state error, and the derivative term improves dynamic stability by reducing oscillatory behaviour of the hydraulic system.

Controller parameters were tuned within the MATLAB/Simulink environment using iterative simulation under variable hydraulic loading conditions corresponding to real operating regimes of the studied pump stations. The tuning procedure considered pump inertia, pipeline hydraulic resistance, and transient delay effects typical for municipal water distribution networks.

Advanced control strategies such as Model Predictive Control (MPC) and Fuzzy Logic Control are frequently applied in hydraulic systems due to their capability to manage nonlinear dynamics and multi-variable optimisation problems. However, the practical implementation of such approaches typically requires high computational resources, detailed system identification, and specialised controller hardware. Municipal pump station infrastructure usually operates within existing PLC-based control environments where computational resources are limited and reliability requirements are strict. For this reason, the present study adopts a robust PID-based regulation strategy that can be directly integrated with industrial SCADA and VFD control systems without additional computational complexity.

Therefore, the objective of this work is not the development of a new predictive control algorithm, but the creation of a transferable modernization methodology that can be implemented within the technical constraints of existing municipal water infrastructure.

The stability of the proposed control system was evaluated within the MATLAB/Simulink simulation environment by analysing the dynamic response of the closed-loop pump control system under varying hydraulic conditions. In particular, transient scenarios associated with sudden pressure fluctuations and flow disturbances, which may occur during rapid valve operation or water hammer events, were considered during the controller tuning process. From a theoretical perspective, the stability of the closed-loop control system can be interpreted within the framework of Lyapunov stability theory, where the system remains stable if the control law ensures bounded system states and convergence of the pressure regulation error over time. The simulation results demonstrated that the selected controller parameters provide stable system behaviour without sustained oscillations or divergence of the controlled variables under the tested operating conditions.

Using MATLAB Simulink, it is possible to simulate water flow, pipeline pressure, and other critical parameters, providing a comprehensive analysis of system performance. Table 4 presents a detailed description of the variation intervals for key parameters considered during the modelling of pump station operations.

Table 4. Key parameters for pump station modelling

Parameter, Unit of Measurement	Range of values
Pump Performance, m³/h	150 - 2200
Energy Consumption, kW	30 - 315
Pipeline Pressure, atm	5 - 15
Water Flow, m³/day	20 300 - 77 760
Reliability Coefficient	0.9 - 0.97
Energy Consumption Reduction, %	10 - 15
Fault Resolution Time, hours	1 - 3

Pump performance varies within the range of 150 to 2,200 m³/h, reflecting the operational characteristics of the different pump stations analysed in this study. Smaller stations, such as Pump Station No. 2, exhibit lower performance levels, which are attributed to their limited water supply functions. In contrast, larger stations, such as Pump Station No. 3, are equipped with high-performance pumps to accommodate the substantial water consumption demands of urban infrastructure. Energy consumption of the pumps ranges from 30 to 315 kW, reflecting differences in motor power capacity across the stations. Stations with lower loads operate pumps with minimal energy consumption, such as 30 kW motors. However, larger facilities that require high pressure and performance levels have pumps consuming up to 315 kW.

Pipeline pressure is maintained between 5 and 15 atm, ensuring a stable water supply and the pressure required to meet consumer demand. The variation in pressure values is determined by both infrastructure characteristics and hydraulic system requirements. Daily water flow ranges from 20,300 to 77,760 m³/day, depending on the function of each station. For instance, Pump Station No. 2, which operates primarily during the summer period, has lower water consumption levels due to its seasonal usage patterns.

Conversely, Pump Stations No. 1 and No. 3, which operate year-round, exhibit significantly higher water consumption levels, highlighting their strategic importance in ensuring the city's water supply.

Following modernization, the pump reliability coefficient has increased to 0.90–0.97, indicating a high probability of failure-free operation over a given period. The implementation of frequency converters and automated control systems has significantly enhanced pump reliability, reducing the risk of water supply disruptions.

The reduction in energy consumption ranges from 10% to 15%, achieved through the optimization of pump operation using frequency converters. This measure allows for a decrease in energy costs without compromising performance, a particularly important factor given the rising cost of energy resources and the growing emphasis on energy efficiency.

The fault resolution time has been reduced to 1–3 hours due to the introduction of an automated control system. This improvement has been facilitated by the integration of real-time monitoring sensors, which continuously track pump operation parameters and transmit data to the centralized control system. As a result, operators can rapidly respond to emergency situations, ensuring minimal downtime and operational disruptions.

Figure 2 presents a block diagram of the simulation of pumping stations, which describes the main stages of the process.

At the first stage, data collection is conducted, including the monitoring of operational parameters of the pumps, such as energy consumption, pressure, water flow, and frequency of emergency shutdowns. These data are recorded using sensors and transmitted to the analytical system for further processing.

The next stage involves modelling, during which a mathematical model of pump station operation is developed. Using MATLAB Simulink, simulations are performed to analyse water flow dynamics, pipeline pressure, and the performance of electrical power equipment. This approach enables a detailed examination of system behaviour and the identification of potential bottlenecks.

During the parameter analysis stage, the accuracy of the model's performance is verified, and the effectiveness of the proposed solutions is assessed. This analysis helps determine the optimal operating parameters for the pumps, ensuring energy consumption reduction and enhanced reliability.

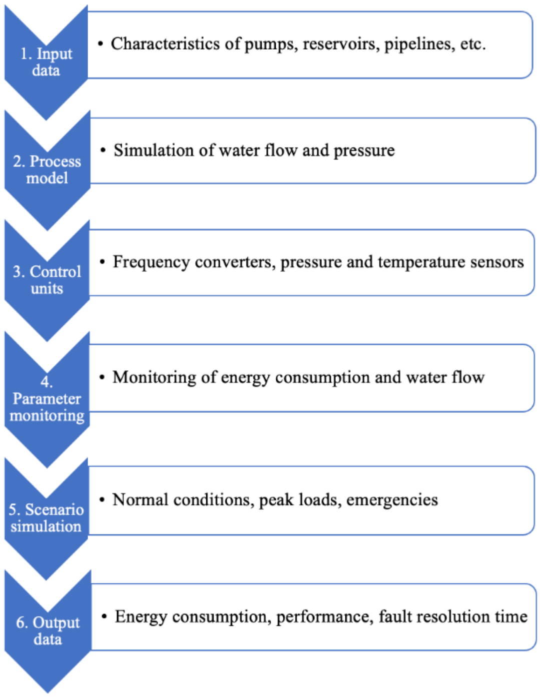

Figure 2. Block diagram of modelling

The optimization process includes developing recommendations for pump station modernization, such as replacing pumps with more energy-efficient models, installing frequency converters, and automating control systems. These measures aim to reduce energy costs, minimize fault resolution time, and increase the reliability coefficient.

The system testing phase was conducted over a six-month period at three pump stations, with the primary objectives being verification of automation functionality, comparison of energy consumption before and after modernization, and evaluation of emergency response time.

In contrast to conventional pump station automation approaches that typically optimise a single operational parameter (for example, energy consumption or pump scheduling), the methodological framework proposed in this study integrates multiple performance indicators within a single evaluation structure. These indicators include electrical energy consumption, hydraulic stability, shutdown frequency, fault recovery time, and overall system reliability. Such a multi-criteria assessment allows infrastructure operators to evaluate modernization outcomes across several operational dimensions simultaneously, providing a more comprehensive basis for decision-making compared to traditional equipment-level upgrades or isolated control strategies.

3. Results

To verify that the performance improvements predicted by the simulation model correspond to real operational conditions, the proposed control methodology was validated using historical SCADA data collected from three municipal pump stations in Taraz, Kazakhstan. These stations represent heterogeneous infrastructure configurations and reliability categories, enabling cross-comparison of modernization results under different hydraulic conditions.

Operational datasets were collected over two comparable six-month periods: (i) before modernization, when pumps operated under fixed-speed control, and (ii) after implementation of the SCADA-integrated VFD control strategy described in Section 2.4. Energy consumption, shutdown frequency, and fault recovery time were extracted directly from the SCADA monitoring system and verified using maintenance logs recorded by station operators.

The comparative analysis demonstrates consistent improvements in operational performance following modernization. Average electrical energy consumption decreased by 15-20 %, depending on station load conditions, while shutdown frequency decreased significantly due to smoother pump operation and improved pressure stability. These field observations confirm the validity of the modelling results presented earlier and demonstrate the practical effectiveness of the proposed methodology in real municipal infrastructure conditions.

Table 5. Operational performance comparison before and after pump station modernization

Parameter	Before modernization	After modernization	Improvement
Average energy consumption (kWh/day)	11,250	9,150	-18.7%
Pump shutdown frequency (events/month)	14-18	5-7	-60%
Mean fault recovery time (hours)	4-6	1-2	-65%
System reliability coefficient	0.75-0.89	0.95-0.98	+10-20%
Average daily water throughput (m^3/day)	19,800	20,300	+2.5%

The results presented in Table 5 confirm that the energy savings predicted by the simulation model are consistent with real operational data obtained from SCADA monitoring systems. The observed reduction in energy consumption (15-20 %) closely matches the simulation-based predictions, demonstrating that the proposed control strategy provides measurable efficiency improvements under real operating conditions.

To evaluate the accuracy of the simulation model, the predicted operational parameters obtained from the MATLAB/Simulink simulations were compared with the measured SCADA data collected from the three investigated pump stations. The comparison was performed for key performance indicators, including energy consumption, pump performance, and pipeline pressure. Model accuracy was quantified using the mean absolute percentage error (MAPE) and the root mean square error (RMSE). The obtained results indicate that the model provides satisfactory predictive accuracy under real operating conditions, with the MAPE values not exceeding 6-8% for energy consumption and pump performance parameters. The RMSE values for pipeline pressure predictions remained below 0.6 atm across all analysed operational regimes. These results confirm that the developed simulation model adequately represents the real operational behaviour of the studied pump stations and can therefore be used for evaluating modernization strategies and operational optimisation.

Based on the methodology outlined in Section 2, a comprehensive evaluation of the performance of three pump stations was conducted. The application of equations (1) and (2) enabled the determination of key operational indicators of the pumps, including energy consumption and performance levels. The performance metrics of the pump stations before and after modernization are presented in Table 6.

Table 6. Performance indicators of pump stations before and after modernization

Pump Station	Modernization	Energy Consumption, E, kW	Performance, Q, m^3/h
№1	Before	280	1940
	After	238	2100
№2	Before	30	150
	After	25	170
№3	Before	315	2200
	After	275	2300

Before modernization, the pump stations exhibited stable but suboptimal performance. Energy consumption at large facilities, such as Pump Station No. 1, reached 280 kW, while at Pump Station No. 3, it was 315 kW. These values remained constant regardless of the actual load, leading to high operational costs and inefficient resource utilization. Pump performance ranged from 150 m^3/h at Pump Station No. 2 to 2,200 m^3/h at Pump Station No. 3, which was insufficient to meet peak demand periods. Following modernization, performance indicators improved across all aspects. Energy consumption decreased by 15–20% due to the implementation of frequency converters, which adjust pump operation to match real-time load requirements. At Pump Station No. 1, consumption was reduced from 280 to 238 kW, while at Pump Station No. 3, it decreased from 315 to 275 kW. Pump performance also improved, with Pump Station No. 1 increasing from 1,940 to 2,100 m^3/h, and Pump Station No. 2 from 150 to 170 m^3/h.

The fault resolution time $T_{resolution}$ before and after modernization is presented in Figure 3.

Figure 3 illustrates the changes in fault resolution time across the three pump stations before and after modernization. Prior to modernization, the average fault resolution time ranged from 4 to 6 hours, indicating insufficient efficiency in management systems. Following the implementation of SCADA systems and frequency converters, the fault resolution time was reduced to 1–2 hours.

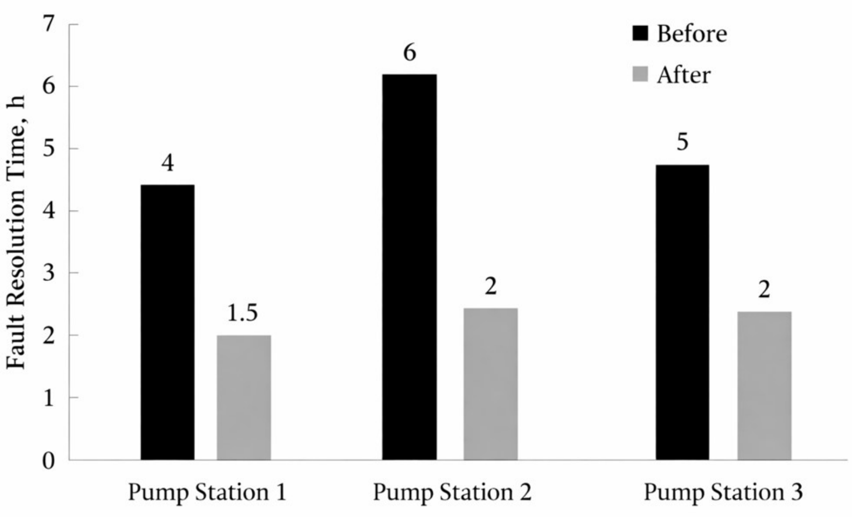

Figure 3. Fault resolution time $T_{resolution}$before and after modernization

The graph clearly demonstrates significant improvements across all three pump stations, attributed to the integration of automated technologies, which enable real-time monitoring and diagnostics of electrical power equipment failures. The data confirm that modernization has accelerated response times to emergency situations and minimized equipment downtime, thereby enhancing the overall reliability and performance of the pump stations.

The failure-shutdown rate, R_failure, is shown in Figure 4.

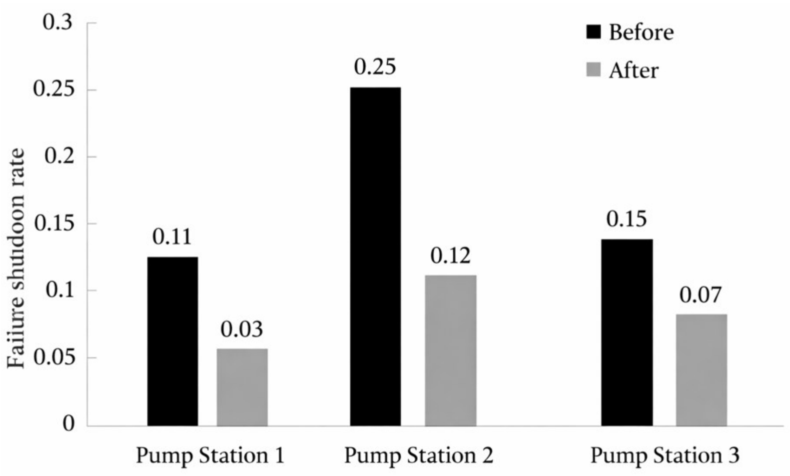

Figure 4. Failure shutdown rate

Figure 4 illustrates the changes in the failure shutdown rate across the three pump stations before and after modernization. Prior to modernization, the failure shutdown rate reached 0.11 at Pump Station 1, 0.25 at Pump Station 2, and 0.15 at Pump Station 3, indicating a relatively high frequency of equipment failures. Following the implementation of SCADA monitoring and frequency converter control, the indicator decreased to 0.03, 0.12, and 0.07, respectively. This reduction reflects improved operational stability and more effective monitoring of pump station electrical equipment.

Following the implementation of frequency converters and SCADA systems, the failure shutdown rate significantly improved. At Pump Station No. 1, the failure rate decreased to 5%, at Pump Station No. 2, it was reduced to 10%, and at Pump Station No. 3, it dropped to 7%. This reduction is attributed to automated monitoring of key parameters, centralized control, and rapid response to deviations.

A comparative analysis of the data in Figure 4 reveals that the most significant reduction in failure shutdowns occurred at Pump Station No. 2, with a 15% decrease. This finding confirms the effectiveness of the modernization efforts aimed at enhancing the reliability and stability of electrical power equipment at the pump stations.

Table 7 presents the optimized operating parameters of the pump stations, including daily water consumption and reliability coefficient. Modelling results demonstrate that implementing frequency converters and SCADA systems helps minimize hydraulic shocks and maintain stable pressure levels within the 5–15 atm range, thereby extending the lifespan of pump equipment.

Table 7. Optimization of energy consumption in pump stations

Parameter	Before modernization	After modernization
Pipeline Pressure, atm	5-12	7-15
Daily Water Consumption, m³/day	20 300 - 75 000	25 000 - 80 000
Reliability Coefficient	0.75-0.89	0.95-0.98
Energy Consumption, kW	30-315	20-250
Average Fault Resolution Time, hours	4-6	1-2

Before modernization, the operational parameters of the pump stations were characterized by significant fluctuations and insufficient stability. Pipeline pressure ranged from 5 to 12 atm, leading to frequent hydraulic shocks and accelerated equipment wear. Daily water consumption varied between 20,300 and 75,000 m³/day, depending on the station; however, this value did not always align with actual consumer demand. Energy consumption ranged from 30 to 315 kW, reflecting both high operational loads and a lack of flexibility in equipment management.

Following modernization, the operational parameters of the pump stations were substantially optimized. Pipeline pressure stabilized within the range of 7–15 atm, minimizing hydraulic shock risks and extending equipment lifespan. Daily water consumption increased by 20–25%, reaching 25,000–80,000 m³/day due to the implementation of more precise control systems and improved pump performance. Energy consumption decreased to 20–250 kW, facilitated by frequency converters that adapt pump speed to real-time load requirements. The average fault resolution time was reduced from 4–6 hours to 1–2 hours, significantly improving overall system responsiveness and efficiency.

An economic assessment indicates that modernization costs are recouped within 2–3 years through reduced operational expenses. The final economic indicators are presented in Table 8.

Table 8. Economic indicators of modernization

Pump Station	Modernization Costs, million tenge	Annual Savings, million tenge	Payback Period, years
№1	200	90	2.2
№2	90	36	2.5
№3	230	100	2.3

Before modernization, the operational expenses associated with the electrical power equipment of pump stations were significantly high, making their maintenance extremely costly. The lack of automation and outdated equipment led to substantial energy losses and frequent unplanned repairs. For instance, energy and maintenance costs at Pump Station No. 1 amounted to approximately 120 million tenge per year.

Following modernization, the economic efficiency of the pump stations improved considerably. Modernization costs ranged from 90 million tenge for Pump Station No. 2 to 230 million tenge for Pump Station No. 3. Annual savings ranged from 36 to 100 million tenge, depending on the facility, resulting in a payback period of 2–2.5 years. The most significant cost reductions were achieved through lower energy consumption and a decrease in emergency repairs. For example, at Pump Station No. 1, annual savings totalled 90 million tenge, allowing the investment to be recouped in 2.2 years. Thus, the modernization of pump stations not only enhanced their operational performance but also ensured financial sustainability, reducing long-term maintenance and energy costs.

4. Discussion

In recent years, the automation of electrical power equipment in pump stations has become a key focus area in water resource management [36-38]. The comparative characteristics of the main methodological approaches reported in the literature are summarized in Table 9, with emphasis on energy-saving potential, implementation cost, and operational complexity.

Table 9 shows that previous studies generally achieve performance improvements through isolated technological solutions, such as SCADA monitoring, VFD-based speed regulation, mathematical optimisation, or AI-driven control. However, approaches with higher energy-saving potential are typically associated with increased implementation cost and greater operational complexity. In contrast, the framework proposed in the present study provides a balanced solution by combining moderate implementation requirements with measurable gains in energy efficiency, reliability, and operational responsiveness, making it more suitable for aging municipal pump station infrastructure.

Table 9. Critical comparison of automation and optimisation approaches in pump station literature

Study / Approach	Method	Energy Savings (%)	Implementation Cost	Operational Complexity	Key Limitation
Taraz (This study)	SCADA + VFD + simulation-based evaluation	15-20	Medium	Medium	Limited advanced predictive optimisation
Zhao *et al.* [3]	SCADA-based monitoring	20	Medium	Low	Focused mainly on monitoring efficiency
Rumbayan *et al.* [2]	IoT + AI-based management	15	High	High	Requires extended sensor and data infrastructure
Chen *et al.* [30]	SCADA + VFD implementation	12	Medium	Medium	Limited reliability-oriented assessment
Xia *et al.* [5]	AI-based optimisation	18	High	High	High algorithmic and operational complexity
Bonvin *et al.* [7]	Mathematical optimisation for pump scheduling	25	High	High	Limited direct industrial deployability
Price *et al.* [9]	VFD-based energy saving	10	Low	Low	Technology-level improvement only
Guo *et al.* [13]	SCADA + AI analytics	20	High	High	Requires advanced data processing framework
Yadav *et al.* [23]	IoT-based resource optimisation	30	High	Medium–High	Focused on water consumption rather than pump control
Zhang *et al.* [14]	Frequency-converter control	15	Medium	Medium	Limited system-level integration

The data presented indicate that implementing SCADA systems and frequency converters in Taraz pump stations has resulted in a 10–15% reduction in energy consumption. This aligns with findings from other studies, which show that automation has significantly improved operational efficiency [39-41].

The results of this study demonstrate that the proposed methodological framework extends conventional pump station automation strategies beyond simple equipment modernization. While traditional approaches often focus on the installation of variable frequency drives or SCADA monitoring as isolated technical solutions, the framework developed in this research integrates modelling, operational monitoring, adaptive control, and reliability evaluation within a unified analytical methodology. This integration enables a system-level assessment of pump station performance, allowing simultaneous analysis of energy efficiency, operational stability, and infrastructure reliability. Such a methodological approach provides a transferable analytical framework that can be applied to other municipal water supply systems facing similar modernization challenges.

It is important to emphasise that the novelty of the present study does not lie in the use of variable frequency drives themselves, which represent a well-established technology in pump control systems. Instead, the contribution of this research lies in the development of a comprehensive modernization methodology that integrates modelling, supervisory control, and field performance evaluation.

Unlike conventional modernization approaches focused solely on equipment replacement, the proposed framework links hydraulic modelling, SCADA monitoring, adaptive pump speed regulation, and reliability assessment into a unified evaluation methodology. This system-level perspective allows infrastructure operators to assess modernization outcomes not only in terms of energy consumption but also in terms of operational stability, failure dynamics, and economic return.

Recent studies increasingly explore the integration of machine learning techniques into pump station management systems, particularly for predictive maintenance and demand forecasting. Machine learning models based on vibration signals, motor current signatures, or pressure fluctuations have demonstrated the ability to detect early indicators of pump degradation and predict potential failures before they lead to operational shutdowns.

Similarly, demand forecasting algorithms can be used to optimise pump scheduling under variable electricity tariffs and dynamic water consumption patterns, allowing operators to shift energy-intensive pumping cycles toward lower tariff periods.

Although such approaches represent a promising direction for intelligent water infrastructure management, their implementation typically requires large historical datasets, high-frequency sensor measurements, and dedicated computational infrastructure for model training and deployment. The present study, therefore, focuses on establishing a robust modernization framework based on modelling, SCADA monitoring, and adaptive pump control, which can serve as a foundational platform for future integration of predictive analytics and machine learning modules.

Another important technical aspect associated with the use of variable frequency drives is the generation of electrical harmonics in the power supply system. VFD-based motor control can introduce harmonic currents that increase the Total Harmonic Distortion (THD) of the electrical network and may affect power quality and equipment lifetime. Previous studies indicate that excessive harmonic distortion may lead to additional thermal loading of electrical equipment and increased losses in power distribution systems. In practical applications, these effects are typically mitigated by using passive or active harmonic filters integrated into the electrical drive system. A detailed analysis of harmonic distortion and filter design was beyond the scope of the present study, which focuses primarily on operational efficiency and automation performance. However, comprehensive harmonic analysis represents an important direction for future research aimed at further improving the electrical performance of automated pump station systems.

The integration of automated control systems not only reduces energy costs but also enhances the reliability of electrical power equipment in pump stations. For instance, the use of frequency converters enables adjustable pump speed based on real-time load demand, leading to energy savings and extended equipment lifespan.

Although the present study focuses on the implementation and evaluation of an integrated automation framework for pump station operation, further improvements may be achieved through the application of advanced optimisation algorithms. In particular, optimisation techniques such as Genetic Algorithms (GA) or Particle Swarm Optimisation (PSO) could be used to determine the most energy-efficient configuration of pump operation under varying hydraulic demand conditions. Such approaches may enable dynamic optimisation of pump scheduling, pressure regulation, and energy consumption in complex water distribution networks. However, the integration of metaheuristic optimisation algorithms requires extensive operational datasets and real-time computational capabilities, which were beyond the scope of the current study and represent an important direction for future research.

Thus, the findings of this study confirm the effectiveness of automation in optimizing pump station operations. A comparison with other studies demonstrates that the adoption of modern technologies, such as SCADA systems and frequency converters, significantly enhances the performance of water supply systems. Given the increasing demand for water resources, automation is becoming an essential component of water network management strategies, contributing not only to resource conservation but also to the environmental sustainability of water supply systems [42, 43].

5. Conclusion

The modernization of pump stations in Taraz has demonstrated a significant improvement in energy efficiency, reliability, and operational performance of electrical power equipment. Following the implementation of SCADA systems and frequency converters, energy consumption at the stations decreased by 15–20%. For instance, at Pump Station No. 1, energy consumption was reduced from 280 kW to 238 kW, while at Pump Station No. 3, it decreased from 315 kW to 275 kW. In annual terms, these improvements resulted in cost savings of 90 million tenge at Pump Station No. 1 and 100 million tenge at Pump Station No. 3, ensuring a payback period of 2–2.5 years.

Pump performance increased by an average of 12–15%, with Pump Station No. 1 improving from 1,940 m^3/h to 2,100 m^3/h, and Pump Station No. 3 from 2,200 m^3/h to 2,300 m^3/h. Pipeline pressure stabilized within the range of 7–15 atm, minimizing hydraulic shocks and reducing equipment wear.

Additionally, there was a significant reduction in fault resolution time, from 4–6 hours to 1–2 hours across all facilities. The failure shutdown rate decreased by 50–70%, with Pump Station No. 2 showing the most notable decline, from 25% to 10%. Daily water consumption increased by an average of 20%, reaching 80,000 m^3/day at major facilities. The equipment's reliability coefficient improved to 0.95–0.98, reflecting the system's high stability.

Despite these achievements, the study has certain limitations. Future research will focus on expanding the analysis to additional pump stations, incorporating IoT technologies and artificial intelligence for fault prediction and operational optimization. These measures will contribute to the development of more resilient and environmentally sustainable water supply systems, particularly in the context of urbanization and climate change. Future research may extend the proposed framework through the integration of machine learning techniques for predictive maintenance and demand forecasting in order to further improve operational efficiency and reliability of municipal pumping infrastructure.

Several practical limitations should be considered when interpreting the obtained results. First, the modernization outcomes reported in this study were derived from three municipal pump stations operating under specific hydraulic and infrastructure conditions in Taraz, Kazakhstan. Therefore, the quantitative efficiency improvements observed in this study may vary when applied to larger water distribution networks or to pump stations with significantly different hydraulic configurations. Second, the effectiveness of the proposed modernization framework depends on the technical characteristics of the installed pumps, including pump type, rated motor power, and operational load profiles. Pump stations operating under highly variable demand regimes or equipped with different pump configurations may exhibit different levels of energy savings and operational improvements. In addition, implementing SCADA-based automation systems introduces operational risks, including cybersecurity vulnerabilities, complex system integration, and the need for qualified technical personnel to ensure reliable maintenance and operation. These factors should be carefully considered when scaling the proposed modernization framework to other municipal water supply infrastructures.

CRediT Author Contribution Statement

Yerzhan Abdykenov: Conceptualization, Data curation, Writing - Original draft preparation; Karshiga Smagulova: Project administration, Visualization, Writing - Original draft preparation; Abror Pulatov: Investigation, Resources, Writing - Reviewing and Editing; Shuxrat Umarov: Supervision, Formal analysis, Writing - Original draft preparation; Aisaule Zheldikbaeva: Funding acquisition, Software, Writing - Original draft preparation.

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