Jovana Radnovic [144]
Termoenergetski i procesni sistemi DOO, Zrenjanin/Serbia
Mića Đurđev [145]
University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin/Serbia
Ljiljana Radovanovic [146]
University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin/Serbia

SMART AND ENERGY-EFFICIENT WATER SUPPLY PLANNING FOR SOCIETY 5.0: A TAGUCHI OPTIMIZATION APPROACH

DOI: 10.5937/PIM26500R

Abstract:

The increasing demand for energy-efficient and sustainable water supply systems requires the development of effective analytical and optimization approaches. This study presents a methodology for evaluating and minimizing energy consumption in pumping systems using Taguchi design and regression analysis. A Taguchi L9 experimental design was applied to investigate the influence of key operational parameters, including flow rate, pump head, and efficiency, on pumping power. The signal-to-noise (S/N) ratio analysis, based on the "smaller-is-better" criterion, was used to identify the optimal conditions for minimizing energy consumption. In addition, regression analysis was conducted to quantify the relationship between the input parameters and pumping power. The results indicate that flow rate and pump head are the most influential factors, while pump efficiency has a significant inverse effect on energy consumption. The developed regression model demonstrates high predictive accuracy, with a coefficient of determination exceeding 99%. The findings confirm consistency with fundamental hydraulic principles and highlight the importance of parameter optimization in improving energy efficiency. The proposed approach provides a simple and effective framework for supporting smart decision-making in modern water supply systems.

Keywords: *Energy efficiency, Pumping systems, Taguchi method, Regression analysis, Water supply systems, Parameter optimization*

Introduction

The global transition toward Society 5.0 emphasizes a human-centric approach where advanced technologies are integrated to solve complex social and industrial challenges [3]. Among these challenges, the sustainable management of urban infrastructure, particularly water supply systems, remains a critical priority, as integrating AI is essential

[144] jovana.radnovic, ORCiD: 0009-0005-3498-1171
[145] mica.djurdjev@tfzr.rs, ORCiD: 0000-0002-1825-2754
[146] ljiljana.radovanovic@tfzr.rs, ORCiD: 0000-0002-5234-4820

for future sustainable urban development [3]. As urbanization increases and energy resources become more constrained, the necessity for smart, energy-efficient planning in water distribution networks has never been more vital, especially with the increasing shift toward IoT-based monitoring in smart cities [1].

Water supply systems are among the largest consumers of electricity in municipal infrastructure, primarily due to the continuous operation of high-capacity pumping stations. Optimizing the energy consumption of these systems is not only an economic requirement for reducing operational costs [7], but also an environmental necessity in the context of reducing carbon footprints. Traditional optimization methods often require extensive and costly experimental trials; therefore, the application of statistical tools has become a more efficient alternative.

This paper focuses on the evaluation and optimization of pumping system parameters—specifically flow rate, pump head, and efficiency—to minimize total power consumption. By employing the Taguchi experimental design (L9 orthogonal array), the study aims to identify the sensitivity of each operational factor, as this method remains a robust tool for analyzing hydraulic systems with minimal experimental trials [2]. Furthermore, regression analysis is utilized to develop a high-precision predictive model, enabling smart decision-making within the framework of modern water infrastructure [4]. Recent research confirms that regression models based on operational data achieve high predictive accuracy for energy demand forecasting [4]. Through this integrated approach, the study contributes to the broader goals of Society 5.0 by balancing technological efficiency with sustainable resource management [3], aligning with the future of digital twin-driven energy management [5].

1. Taguchi method

The Taguchi method is a statistical design-of-experiments approach used for robust parameter design and process optimization. Its main advantage is the ability to evaluate the influence of several input parameters with a reduced number of experimental trials. Instead of testing all possible factor combinations, the method uses predefined orthogonal arrays that provide balanced and systematic experimental conditions [6], [7], [8].

In this paper, the Taguchi method was applied to investigate the effects of flow rate Q, pump head H, and pump efficiency η on pumping power P.

Since three factors were considered at three levels each, the L9 orthogonal array was selected.

This design enables the analysis of nine experimental combinations instead of 27 combinations required by a full factorial design.

A key element of the Taguchi method is the signal-to-noise (S/N) ratio, which combines the average response and its variability into a single performance indicator. Since the aim of this study is to minimize energy consumption, the "smaller-is-better" criterion was used [9].

2. Application of the Taguchi Method to the Pumping System Example

The proposed methodology was applied to a simplified water supply pumping system in order to evaluate the influence of flow rate Q, pump head H, and pump efficiency η on the required pumping power P. These parameters represent the main operational variables that determine energy demand in pumping stations. In practical water distribution systems, flow rate is related to water demand, pump head is associated with elevation differences and hydraulic losses, while pump efficiency reflects the operating condition and performance of the selected pump [10], [11].

The pumping power was calculated using the fundamental hydraulic power equation:

$$P = \frac{\rho g Q H}{1000\eta}$$

where P is the required pump power in kW, ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), Q is the flow rate in m^3/s, H is the pump head in m, and η is the pump efficiency. According to this relationship, power consumption increases proportionally with flow rate and pump head, while higher efficiency reduces the required input power.

The experimental matrix was formed using the Taguchi L9 orthogonal array. Three factors were examined at three levels: flow rate Q=0.05, 0.08, 0.10 m^3/s, pump head H = 20, 30, 40 m, and pump efficiency η = 0.65, 0.75, 0.85. The obtained power values ranged from 15.09 kW to 52.32 kW, confirming that the selected parameter intervals produce significant changes in energy demand. The calculated power values for all nine experimental runs are presented in Table 1.

Table 1: *Taguchi L_9 experimental matrix and calculated pumping power*

Run	Flow Rate, [m^3/s]	Pump Head, H [m]	Efficiency, η [-]	Power, P [kW]
1	0.05	20	0.65	15.09
2	0.05	30	0.75	19.62
3	0.05	40	0.85	23.08
4	0.08	20	0.75	20.93
5	0.08	30	0.85	27.70
6	0.08	40	0.65	48.30
7	0.10	20	0.85	23.08
8	0.10	30	0.65	45.28
9	0.10	40	0.75	52.32

As shown in Table 1, the lowest power consumption was obtained in Run 1, where the flow rate and pump head were at their lowest levels. The highest power consumption was obtained in Run 9, where both flow rate and pump head were at high levels. The power values range from 15.09 kW to 52.32 kW, confirming that the selected operating parameters produce significant differences in energy demand.

The signal-to-noise (S/N) ratio analysis was performed using the "smaller-is-better" criterion, because the objective of the optimization was to minimize pumping power. The response table for S/N ratios is presented in Table 2.

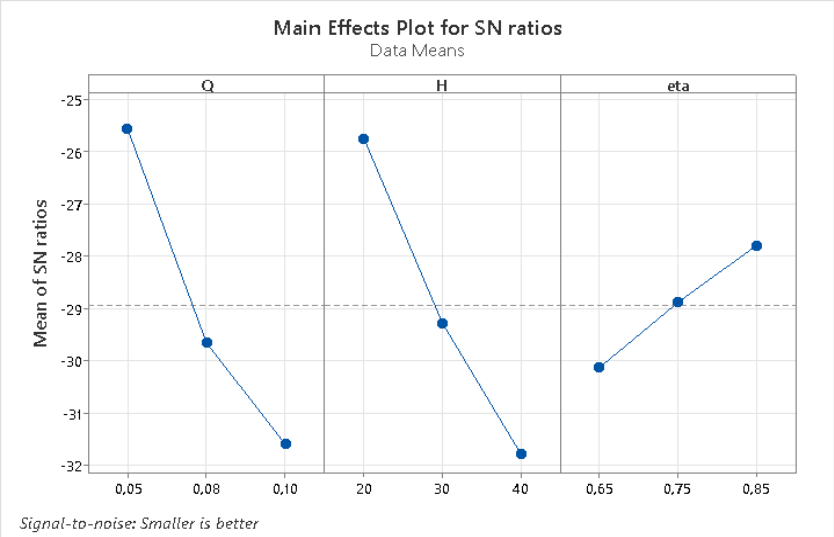
Table 2: *Response table for signal-to-noise ratios*

Level	Q	H	η
1	-25,56	-25,75	-30,12
2	-29,65	-29,27	-28,88
3	-31,59	-31,77	-27,79
Delta	6,02	6,02	2,33
Rank	1	2	3

The results in Table 2 show that flow rate Q and pump head H have the strongest influence on power consumption. Both factors have the same delta value of 6.02, indicating that their contribution to the variation of energy consumption is dominant. Pump efficiency η has a lower Delta

value of 2.33, but its influence is still important because increasing efficiency directly reduces the required pumping power.

The main effects plot for S/N ratios, shown by *Picture 1*, confirms this trend. The steepest changes are observed for flow rate and pump head, while the curve for efficiency shows a smaller but consistent influence. Since the "smaller-is-better" criterion was used, the optimal level for each factor is selected based on the highest S/N ratio.



Picture 1. *Main effects plot for S/N ratios*

Based on the S/N ratio analysis, the optimal factor combination for minimizing energy consumption corresponds to the lowest flow rate, the lowest pump head, and the highest efficiency:

$$Q = 0.05\ m^3/s,\ H = 20\ m,\ \eta = 0.85$$

This combination corresponds to the lowest flow rate, the lowest pump head, and the highest pump efficiency. However, in real water supply systems, operating conditions must also satisfy water demand, pressure requirements, and reliability constraints. Therefore, this result should be interpreted as an energy-efficiency reference point rather than as a universal operating condition.

In addition to Taguchi analysis, regression modeling was performed in order to quantify the relationship between the input parameters and pumping power. The obtained regression equation is:

$$P = 9.57 + 420.5Q + 1.0766H - 58.00\eta$$

The regression coefficients are presented in Table 3. The results in Table 3 show that all three investigated parameters have statistically significant effects on pumping power, since their p-values are lower than 0.05.

Table 3: *Regression coefficients for pumping power model*

Term	Coef	SE Coef	T-Value	P-Value
Constant	9,57	4,27	2,24	0,075
Q	420,5	19,6	21,46	0,000
H	1,0766	0,0493	21,84	0,000
η	-58,00	4,93	-11,77	0,000

The positive coefficients of Q and H indicate that increasing flow rate and pump head increases power consumption. The negative coefficient of η confirms that higher pump efficiency reduces the required power. The quality of the regression model is summarized in Table 4. As shown in Table 4, the regression model demonstrates very high predictive accuracy. The coefficient of determination is R^2= 99.54%, which means that almost all variation in pumping power is explained by the selected input parameters. The adjusted R^2=99.26% and predicted R^2=98.10% further confirm the reliability of the model and its ability to predict power consumption for similar operating conditions.

The analysis of variance is presented in Table 5.

Table 4: *Model summary*

S	R-sq	R-sq(adj)	R-sq(pred)
1,20755	99,54%	99,26%	98,10%

Table 5: *Analysis of variance for the regression model*

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	1569,05	523,017	358,68	0,000
Q	1	671,78	671,776	460,70	0,000
H	1	695,42	695,421	476,91	0,000
η	1	201,85	201,853	138,43	0,000
Error	5	7,29	1,458		
Total	8	1576,34			

The ANOVA results in Table 5 confirm that the regression model was statistically significant. The regression p-value is 0.000, indicating that the model reliably explains the variation in pumping power. Among the individual factors, pump head H has the highest adjusted sum of squares, followed by flow rate Q, while pump efficiency η has a smaller but still statistically significant contribution. This is consistent with both the Taguchi analysis and the physical interpretation of the pumping process. The diagnostic plots provide additional verification of the regression model. The Pareto chart of standardized effects confirms that Q, H, and η are significant predictors of power consumption. The normal probability plot and residual plots indicate that the residuals are acceptably distributed and that no major violation of regression assumptions is observed.

Overall, the combination of Taguchi sensitivity analysis and regression modeling provides a reliable framework for evaluating and optimizing energy performance in pumping systems. Taguchi analysis identifies the relative importance and optimal levels of the investigated factors, while regression analysis provides a predictive equation that can be used for estimating power demand under different operating conditions. This integrated approach supports smart and energy-efficient water supply planning by enabling faster decision-making, reduced experimental effort, and improved operational efficiency.

CONCLUSION

This study presented an approach for evaluating and minimizing energy consumption in water supply pumping systems using the Taguchi method and regression analysis.

The analysis focused on three key operating parameters: flow rate, pump head, and pump efficiency.

The Taguchi L9 orthogonal array enabled the investigation of three factors at three levels using only nine experimental combinations. The S/N ratio analysis based on the “smaller-is-better” criterion showed that flow rate and pump head are the dominant factors affecting pumping power, while pump efficiency has a significant inverse effect.

The obtained results confirmed that increasing flow rate and pump head leads to higher power consumption, whereas increasing pump efficiency reduces energy demand. Regression analysis additionally confirmed the relationship between the input parameters and pumping power. The developed model showed high predictive accuracy, with R^2 = 99.54%, adjusted R^2 = 99.26%, and predicted R^2 = 98.10%. The ANOVA results

confirmed that all investigated parameters have statistically significant effects on power consumption. The proposed methodology provides a practical framework for supporting smart and energy-efficient water supply planning. It can help identify energy-saving operating conditions, reduce operational costs, and contribute to sustainable infrastructure management within the concept of Society 5.0.

REFERENCES

[1] Aziz, M. A., et al. (2023). IoT-Based Smart Water Management Systems: A Review of Energy Efficiency and Sustainability. *Sustainability*, *15*(4), 3125.

[2] Gupta, S., & Kumar, P. (2024). Optimization of Pumping Stations Using Taguchi Method and Metaheuristic Algorithms. *Journal of Cleaner Production*, *410,* 137250.

[3] Kim, J. H., & Park, S. Y. (2022). Society 5.0 and the Future of Urban Infrastructure: Integrating AI for Sustainable Water Supply. *Technological Forecasting and Social Change*, *178,* 121564.

[4] Sharma, R., & Vasant, P. (2023). Machine Learning and Regression Analysis in Pumping System Performance Optimization. *Energy Informatics*, *6*(1), 12-28.

[5] Zhang, L., et al. (2024). Digital Twin-Driven Energy Management for Smart Water Distribution Networks. *Applied Energy*, *355*, 122290.

[6] Taguchi, G. (1986). *Introduction to Quality Engineering: Designing Quality into Products and Processes*. Tokyo: Asian Productivity Organization.

[7] Roy, R. K. (2010). *A Primer on the Taguchi Method*. 2nd ed. Dearborn, Michigan: Society of Manufacturing Engineers.

[8] Kacker, R. N., Lagergren, E. S., and Filliben, J. J. (1991). Taguchi's Orthogonal Arrays Are Classical Designs of Experiments. *Journal of Research of the National Institute of Standards and Technology*, 96(5), 577–591.

[9] Minitab. (2024). *Methods and formulas for Analyze Taguchi Design*: Retrieved May 11th 2026, from Minitab Support web site: https://support.minitab.com/en-us/minitab/help-and-how-to/statistical-modeling/doe/how-to/taguchi/analyze-taguchi-design/methods-and-formulas/methods-and-formulas/

[10] Hydraulic Institute. (2024). *Pump Fundamentals – Pump Curves*. Retrieved May 11th 2026, from Hydraulic Institute Data Tool web site:https://datatool.pumps.org/pump-fundamentals/pump-curves

[11] Grundfos. (2019). Basic Hydraulics and Pump Performance: Calculating Pump Efficiency. *Grundfos Ecademy*. Retrieved May 11th 2026, from Hydraulic Institute Data Tool web site: https://www.grundfos.com/content/dam/global/page-assets/learn/ecademy/pdfs/module-4-basic-hydraulics-calculating-efficiency-master.pdf