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Assessing Wastewater Treatment Plant in Northern Jordan: Coefficient of Reliability Analysis for Effluent Concentrations

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Abstract

This article presents a study on the daily reliability analysis of a full-scale activated sludge wastewater treatment plant located in Northern Jordan. The coefficient of reliability (COR) is calculated to assess the performance of the plant in regard of wastewater concentrations of COD, BOD_5, and TSS. The results indicate that the global effluent performances for COD, BOD_5, and TSS comply with Jordanian standards. However, the BOD_5 performance is found to be below the quality level due to issues in the ventilation basin and exceeding treatment capacity, while the TSS performance is affected by problems in the grit chamber and variations in influent quality and quantity. The study fills a research gap by focusing on the reliability of wastewater treatment plants using activated sludge technology and utilizes a probabilistic model proposed by Niku *et al.,* (1979) to evaluate the reliability. The findings provide valuable insights into the daily variability of the treatment plant and suggest measures for improving reliability and overall efficiency

Paper type: Research paper

Keywords: Analysis of COD; BOD_5, TSS, effluent cluster, investigation of wastewater plant, reliability, treatment of Wastewater.

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Introduction

Reliability and resilience analysis of wastewater treatment systems ensures their efficient and sustainable operation. However, there is a research gap in understanding the specific reliability of wastewater treatment plants (WWTP) utilizing activated sludge technology. This article aims to bridge that gap by providing a comprehensive overview of the diverse techniques, performances, results, and methods used in the field of reliability and resilience analysis of wastewater treatment systems. Over the past four decades, scholars and researchers have conducted numerous studies aiming to thoroughly study the reliability of maintaining high sustainability and efficiency of WWT by different approaches and methodologies. For example, in 1979, Niku *et al.,* introduced a mathematical model to assess the coefficient of reliability (COR) in wastewater treatment systems, which laid the foundation for subsequent reliability analysis studies. Their model provided insights into evaluating treatment process performance. In contrast, in 1982, Pearson *et al.,* focused on studying the reliability analysis of a specific wastewater treatment plant using fault tree analysis.

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They identified critical failure modes and proposed strategies to enhance system reliability. This approach emphasized the importance of addressing potential failure points. Moreover, recognizing the need for resilient wastewater treatment systems, Smith *et al.,* introduced the concept of resilience analysis in 1990. Their framework evaluated a system's ability to withstand disturbances and recover quickly by considering factors like redundancy, flexibility, and adaptability. Additionally, Helsel and Hirsch (1990) developed a statistical approach to evaluate the reliability of water quality data in wastewater treatment systems. Their study addressed uncertainties associated with data variability and measurement errors, providing insights into the reliability of data used in analysis and decision-making.

Whereas, Chen and Hwang employed reliability block diagrams (RBDs) in 1995 to analyze the reliability of a wastewater treatment plant. Their study assessed the impact of component failures on system performance and identified critical components for maintenance and improvement. Likewise, Eisenberg *et al.,* proposed a method in 2001 to evaluate inherent and mechanical reliability in water and wastewater treatment systems. Their approach emphasized reliability assessment and establishing minimum reliability requirements, contributing to reliable operational standards.

However, In 2003, Liu *et al.,* explored the use of Markov models to assess the reliability and availability of wastewater treatment processes. Their study provided insights into system performance under different conditions and the influence of operational and maintenance strategies. Furthermore, to study the impact of climate change on the reliability and resilience of WWT systems, Wang *et al.,* in 2008 proposed an investigation that considered changing weather patterns, sea-level rise, and increased storm intensity, highlighting the need for adaptation measures. Subsequently, Oliviera and Von Sperling (2008) explored the relationship between the coefficient of reliability (COR), coefficient of variation (CV), and high-reliability levels in wastewater treatment systems. Their study shed light on treatment process reliability and influencing factors.

In addition, Zhang *et al.,* Developed a Performance Evaluation Framework for the Reliability and Resilience of Decentralized Wastewater Treatment Systems (2012), where they combined several measures of performance to get a complete rating of treatment performance, resource recovery, and environmental impact. Similarly, Ren *et al.,* performed a 2014 reliability analysis of a wastewater treatment anaerobic digestion process. Such programs evaluated probabilities of failure of critical components and suggested reliability improvement procedures that could be employed for the system. Then, Ayodele *et al.,* performed a maintenance reliability analysis on a membrane bioreactor system in 2015 for wastewater treatment They showed, through the studying, that the risk of failure for membrane modules was quantified and the important parts as components and factors that affected reliability and performance of the system also evident in the analysis.

In 2016, Li *et al.*, conducted a comparative analysis of reliability analysis methods, including fault tree analysis, event tree analysis, and failure mode and effects analysis. They compared the strengths and limitations of these methods in wastewater treatment systems. After that, Wu *et al.,* utilized Bayesian networks in 2017 for reliability analysis of a wastewater treatment plant. They assessed reliability by considering probabilistic and causal relationships among system components and identified critical factors affecting performance. Moreover, Wang and Chen (2019) utilized system dynamics modelling to help the resilience of wastewater treatment systems. In their research, they took into account feedback loops and dynamic interactions in resilience analysis, most likely under shifting conditions and disturbances.

In addition, another study by Wu *et al.,* in 2019 paid more attention to employing a reliability-centered maintenance approach in wastewater treatment systems. They developed maintenance strategies based on criticality analysis and condition-based monitoring to optimize system reliability and minimize downtime. Loureiro *et al.,* (2020) also explored the resilience of wastewater treatment systems to natural disasters. The study took into account the effects of floods, earthquakes, and hurricanes on system performance and suggested strategies for improving resilience. However, Velez *et al.,* (2021) examined the effect of ageing infrastructure on the reliability and resilience of wastewater treatment systems. They emphasized proactive maintenance and infrastructure renewal for long-term system performance. Accordingly, Zhou *et al.,* (2022) developed a multi-objective optimization model for scheming reliable and resilient wastewater treatment systems. Their study integrated reliability, cost, and environmental performance criteria to identify optimal design configurations. Finally, Zhang *et al.,* (2023) conducted a comprehensive review of resilience assessment methods in wastewater treatment systems. Their analysis compared various approaches, such as mathematical modelling, simulation, and multi-criteria decision-making, providing recommendations for future research.

All these research articles, collectively demonstrate the evolution of techniques, performances, results, and methods used in the field of reliability and resilience analysis of wastewater treatment systems. From mathematical models and fault tree analysis to system dynamics modelling, climate change impact assessments, and resilience evaluation methods, these studies have significantly contributed to enhancing our understanding of system vulnerabilities, identifying critical components, and developing strategies for improving reliability and resilience. Utmost, reliability is of crucial aspect in demonstrating the effectiveness of WWTPs operation, as it directly influences the system's ability to consistently meet prescribed standards. In the situation of WWTPs, reliability represents the consistent performance of the system, ensuring it reliably encounters release threshold requirements and adheres to environmental conventions. To assess and forecast the likelihood of unwanted events, reliability-engineering ethics are applied, enabling a comprehensive valuation of the system's risk elements. Statistical analysis of influent and effluent data plays a crucial role in defining the reliability of WWTPs. By examining performance indicators derived from these data, such as pollutant concentrations and treatment effectiveness, the reliability of the system can be measured. Informed resolutions regarding target discharge levels can then be made based on a conventional probability of consistently attaining these criteria. A WWTP can be well-thought-of and very reliable when it consistently functions as predictable, without breaking environmental rules or discharge thresholds.

The current study aims at a practical implication for plant workers, environmental organizations, and legislators, highlighting the importance of AI traceability. By conducting a full reliability investigation of the Wadi Arab WWTP. The Wadi Arab WWTP is situated in the Middle East, in Jordan and functions as the principal point of this study, aiding a comprehensive examination of the reliability of a WWTP employing initiated sludge technology. By applying the probabilistic model, the authors aim to quantify the reliability of the system and estimate its ability to unfailingly meet discharge threshold requirements. The results of this study will add to a deep understanding of the elements influencing reliability in WWTPs, with particular emphasis on employing activated sludge technology. Valuable understandings can be attained regarding the factors that affect system performance and reliability. These understandings can lead to the optimization of effective strategies, enhancement of conservation practices, and implementation of risk management measures to ensure the constant and dependable operation of the WWTP. Besides, the findings and methodology presented in this study can be applied to other WWTPs that employ activated sludge technology, thus advancing our understanding of reliability in wastewater treatment processes.

1 Materials and Methods:

An inclusive knowledge of a wastewater treatment plant's (WWTP) process behaviour forms the groundwork for evaluating its reliability and performance. The WWTP must be intended to effectively treat incoming wastewater and guarantee that the quality of the treated effluent remains below a predetermined threshold to meet discharge standards. Specifying this threshold involves employing a probabilistic analysis method developed by Niku *et al.,* (1979), which found a link between the usual concentration of an explicit constraint and the required verge value. This method has gained wide recognition as a standard practice, evident from its frequent citation in textbooks and utilization by numerous researchers over the past 25 years. When the discharged effluent exceeds the prescribed standards, it indicates a failure in the treatment plant process, as modelled by Niku *et al.,* (1979) through a simple equation:

$$F = Ce > Cs \tag{1}$$

where F represents the failure, Ce indicates the selected treated sewage quality parameter concentration, and Cs denotes the concentration requirement for the selected treated sewage quality consideration set by controlling criteria. Reliability, within the context of wastewater treatment plants, pertains to the probability of achieving the desired performance or ensuring that the treated effluent meets established discharge standards. Niku *et al.,* (1979) define the reliability of a WWTP based on the percentage of time during which the selected effluent quality parameters remain below the set discharge threshold. Technical reliability, therefore, can be understood as the "probability of success" or the "probability of adequate performance."

$$R = 1 - P(F) \tag{2}$$

where R refer to reliability, and P(F) indicates the probability of failure. Using equation 1, the value of ERE can be calculated as:

$$R = 1 - P(Ce > Cs) \tag{3}$$

Having the capacity to anticipate the reliability of a wastewater treatment plant (WWTP) holds paramount significance and hinges upon comprehending the probability distribution function of the quality parameters of the treated effluent. Once this distribution is understood, it enables the calculation of the proportion of time that a specific concentration has surpassed in the past. By maintaining consistent process settings and controlling parameters, this information can be utilized to predict the future performance of the WWTP. The threshold (m_x) set for an average constituent concentration of a given treated wastewater standard parameter can be derived from the equation:

$$m_x = COR * C_s \tag{4}$$

Here, m_x represents the average concentration of the constituent, and COR denotes the reliability coefficient. Niku *et al.,* (1979) put forward a mathematical model for calculating the coefficient of reliability (COR), which can be expressed as follows:

$$COR = (CV_X^2 + 1)^{1/2} \times e^{\left[-Z_{1-\alpha}\left(lnCV_X^2+1\right)^{1/2}\right]} \qquad (5)$$

Where in this context, the symbol CV_x denotes the coefficient of variation, which is calculated by dividing the standard deviation of the selected treated effluent quality parameter concentration (referred to as parameter X) by its mean value; $Z_{1-\alpha}$ denotes the normalized Standard Variate Derived from Standard Normal Tables, Representing the Probability of Non-Exceedance at a Confidence Level of $1-\alpha$). Here, α represents the significance level.

This information enables the calculation of reliability indices and facilitates the evaluation of the WWTP's daily performance in terms of its ability to meet the prescribed discharge standards. The findings from the study provide valuable insights into the daily variability of the treatment plant and the impact of different parameters on its performance. Consequently, plant operators can make informed decisions to enhance the reliability and overall efficiency of the WWTP.

1.1 Studied area specifications

The Wadi Arab wastewater treatment plant is situated approximately 1 km north of Dewqara in the Wadi Arab Valley, with coordinates at latitude 32° 37’ N, and 35° 44’ E. Its altitude ranges from (150 to 190) meters above sea level. This plant is a fundamental part of the "Wastewater Collection and Treatment Systems in the Greater Irbid Area" project, which includes two main phases: the Wadi Arab Sewage System for South-West and North-East Irbid, Swam village, and the Wadi Hassn Sewage System for Al-Nuayyima, Shatana, and Kitm village. The construction of the third project area, the Wadi Shalala Sewage System, is planned for a later stage. The catchment areas of the Wadi Arab Sewage System include Irbid South-West, Irbid North-East, Zabdat, Swam, and a part of Central Irbid. In the subsequent stage, the project will also encompass Baytras and Natfa. Wastewater from North-East Irbid is naturally drained to the North-East Pumping Station and then pumped to Hakama junction, from where it flows by gravity into the existing system. The cured sewage from the Wadi Arab wastewater treatment plant submit to dilution with fresh water and is successively reused for farming purposes in the Jordan Valley. **Figure 1** illustrates the general layouts of the Wadi Arab wastewater plant, while **Table 1** provides the fundamental design data for the Wadi Arab WWTP.

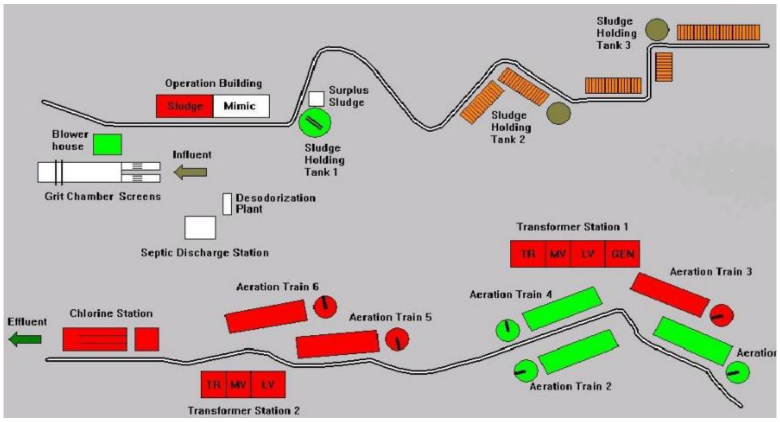

Fig. 1 Wadi Arab wastewater plant: Overview of Facility Layouts(16).

Table 1 Basic design data of the Wadi Arab WWTP.

Criterion	2010	2020
Population	202,000	311,000
Daily flow Qd (m^3/day)	20,800	35,100
Peak factor	1.8	1.7
Hourly flow Qh (m^3/h)	1,560	2,490
Max. inflow Qmax (m^3/h)	2,950	2,950
BOD load unsettled kg (BOD/day)	12,120	18,660
Suspended solids kg (SS/day)	12,120	18,660

2 Results and Discussion

2.1. Investigating the probability likelihood function for designated cured sewage quality factors

2.1.1. Applying initial statistics for verifying data distribution

The evaluation of treated effluent quality from the Wadi Arab WWTP focused on three parameters: COD, BOD_5, and TSS, which are commonly used indicators for WWTP discharges. To determine the probability distribution laws for these parameters, a preliminary analysis was conducted to verify the data distribution. This verification process involved applying the reliability model developed by Niku *et al.,* (1979), which assumes a lognormal distribution. **Table 2** presents the statistical parameters for the concentration of COD, BOD_5, and TSS in the effluent from the Wadi Arab WWTP for the year 2018.

Table 2 Statistical parameters of effluent COD, BOD_5, and TSS concentration at WWTP (2018).

Parameter	COD (mg O_2/l)	BOD_5 (mg O_2/l)	TSS (mg/l)
Average	69.6319	38.0613	30.319
Standard deviation	15.1213	12.5893	13.6945
Coeff. of variation (%)	21.7161	33.0763	45.168
Minimum	39.0	20.0	9.0
Maximum	150.0	100.0	81.0
Range	111.0	80.0	72.0
Stnd. skewness	8.93422	10.3319	6.25216
Stnd. kurtosis	14.7161	15.2426	5.76459

Evaluating Data Regularity using Skewness and Kurtosis Coefficients, Table 2 displays the skewness and kurtosis coefficients employed to assess the consistency of the treated effluent data derived from the Wadi Arab WWTP. This evaluation methodology is backed by various studies, such as Hirsch (1992 and 1990), D'Agostino *et al.,* (1990 and 1986), and Pearson *et al.,* (1977) providing further support for its validity. The skewness coefficient measures the degree of asymmetry in a distribution, where a value near zero suggests a symmetrical distribution and a positive value indicates a right-skewed distribution. Conversely, the kurtosis coefficient trials the extent of flatness or curvature in a distribution, with a kurtosis significance of 3 indicating a normal distribution.

2.1.2. Investigating probability distribution laws for tracking treated effluent quality parameters' concentrations

Figures 2-4 illustrate the historical data from 2018, displaying histograms, and PDFs of the effluent COD, BOD_5, and TSS concentrations from the Wadi Arab WWTP. The data exhibits a general asymmetry and left-skewness, which aligns with the findings presented in Table 1 (Standard Skewness). To determine the appropriate distribution laws for the COD, BOD_5, and TSS effluent concentrations, normal, lognormal, and gamma distribution laws were analyzed.

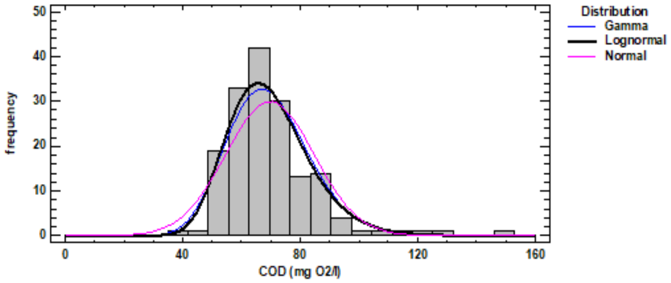

Fig. 2 Analysis of effluent COD concentration: Histogram and Probability Density Function (PDF).

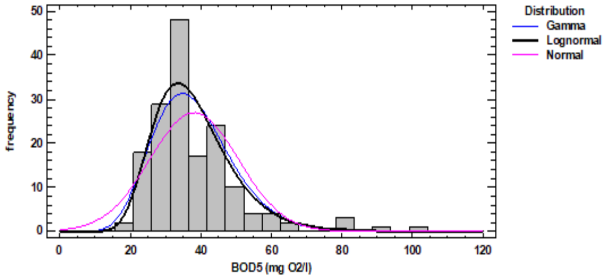

Fig. 3 Analysis of effluent BOD_5 concentration.

Using several statistical tests, including Kolmogorov-Smirnov Cramer-Von Mises, Anderson Darling, and Watson tests will help lead to the goodness-of-fit of these distribution laws. STAT-GRAPHICS was used for conducting these tests. To generate plots of the COD, BOD_5, and TSS effluent concentrations for the Wadi Arab WWTP, Centurion XVI.I. Additionally, MINITAB 19 was utilized, as depicted in **Figures (5-7)**.

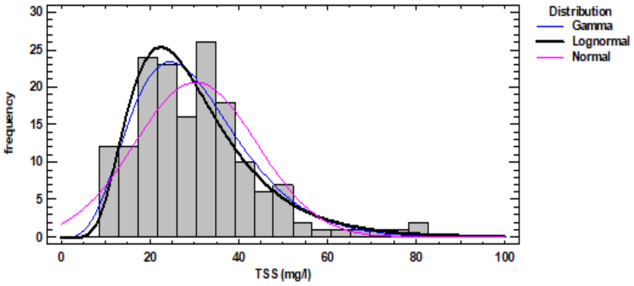

Fig. 4 Analysis of waste TSS concentration.

In choosing the Kolmogorov-Smirnov test and due to its higher power for normal and lognormal distributions preference was given over the Chi- squared test. The works of D'Agostino *et al.*, (1986) and Wondruff *et al.,*(1988), support this choice. Depending on the study's findings, the effluent parameters (COD, BOD_5, and TSS) displayed the best fit with a lognormal distribution. This determination was made after transforming the data into logarithmic values and confirming the normality of the transformed dataset using the Shapiro-Wilk test. This result is consistent with earlier research on WWTP effluent concentrations, which has also identified the lognormal distribution as an appropriate fit done by USEPA, 1991; Marvin *et al.,*1989; Ossenbruggen *et al.*, 1987; Sperling *et al.*, 1983; Schroeder *et al.*, 1981; Culp *et al.*, 1980; Forsythe *et al.,* 1976; and Cohen *et al.,*1975. The lognormal and normal distributions are extensively recognized as appropriate choices for modelling water quality data (Ward *et al.,* 1981), further supporting the suitability of the lognormal distribution for investigating BOD_5, COD, and TSS concentrations in this research.

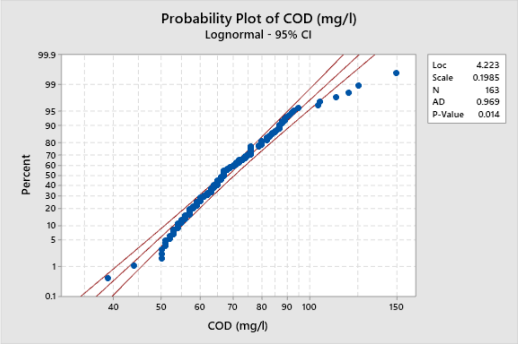

Fig. 5 Lognormal probability plot of effluent COD concentration: Wadi Arab WWTP (2018).

2.2 Utilizing COR calculation in the assessment of Wadi Arab WWTP

In the context of the year 2018, an assessment was conducted on the treated effluent quality parameters by calculating the coefficient of variation (CV). Additionally, the coefficient of reliability (COR) was determined at a confidence level of 95% ($\alpha = 5\%$) using the standard normal distribution's cumulative probability (Z-distribution) and equation 5.

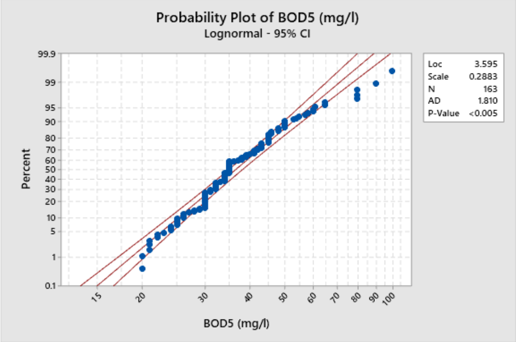

Fig. 6 Lognormal probability plot of effluent BOD_5 concentration: Wadi Arab WWTP (2018).

Table 3 showcases a range of COR values corresponding to different levels of reliability and CV, as established by Oliviera and Von Sperling (2008). Visualizing the relationship between COR and CV, **Figure 8**, illustrates that a lower confidence threshold leads to higher CV values for a specific target COR, while a higher CV yields higher COR values for a lower confidence threshold. In essence, decreasing the confidence threshold necessitates increased precision in measuring the effluent parameters, thus resulting in higher CV values.

This underscores the significance of selecting an appropriate confidence threshold based on the desired level of precision and the required accuracy in effluent parameter measurements. **Figure 9** aids in comprehending the trade-off between precision and accuracy when assessing effluent parameters.

These computations were performed using the NORMSDIST function in Excel, with the results also available in statistical textbooks. The resulting COR values, based on arbitrary CV_x values, are presented in Table 3.

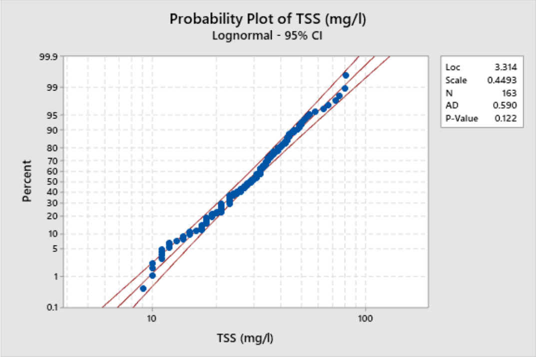

Fig. 7 Lognormal probability plot of effluent TSS concentration: Wadi Arab WWTP (2018).

Table 4 presents the mean values of CV, COR for COD, COR for BOD_5, and COR for TSS concentrations at the WWTP with a 95% confidence threshold in 2018. The majority of CV values for effluent concentrations in Table 4 were found to be below 1, indicating a high degree of precision in these parameters. However, for a reliability level of 95%, higher CV values correspond to lower COR value and lower average effluent concentrations (m_x).

Notably, all parameters (COD, BOD_5, and TSS) exhibit the lowest COR values, suggesting a lower degree of accuracy. This implies that the results may exhibit a higher degree of variability and potentially be less reliable. Consequently, **Table 4** underscores the importance of maintaining a balance between precision and accuracy in the measurement of effluent parameters.

Table 3 Exploring COR Values in Relation to CV.

Reliability	CV_x							
level	0	0.2	0.4	0.6	0.8	1	1.2	1.4
90%	1	0.79	0.66	0.57	0.52	0.49	0.47	0.45
95%	1	0.74	0.57	0.47	0.4	0.36	0.33	0.31
99%	1	0.64	0.44	0.32	0.25	0.2	0.17	0.15

Table 4 Mean values of CV, COR for COD, COR for BOD_5, & COR for TSS concentration with 95% confidence threshold at WWTP (2018).

Year	COD (mg/l)		BOD_5 (mg/l)		TSS (mg/l)	
	CV_COD	COR	CV_BOD_5	COR	CV_TSS	COR
2018	0.2171	0.72	0.3307	0.65	0.4516	0.54

To clarify, it should be noted that COR is articulated grounded on the properties of the sewage concentration values rather than the logarithmic values. The application of COR calculation, along with considering CV values and confidence thresholds, allows for the evaluation of the reliability and precision of measured effluent parameters. Balancing precision and accuracy is crucial to ensure accurate and reliable monitoring of effluent quality.

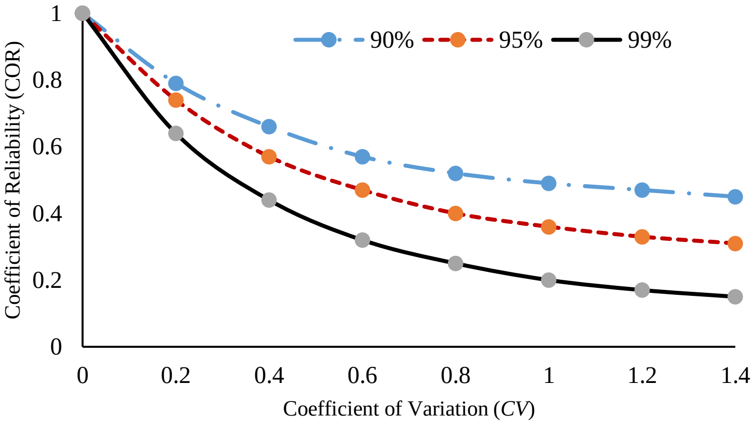

Fig. 8 Exploring the interplay of COR, CV, and reliability levels.

2.2.1 employing active strategies for superior performance

The notional framework serves as the basis for determining operational limitations (m_x) for monitored parameters to assess the quality of treated effluent. These limitations are derived using equation 4, with the variable (C_s). Values obtained from the Jordanian standards. **Table 5** presents the Jordanian standards for treated wastewater.

Table 5 Jordanian standards for treated wastewater.95% threshold at WWTP (2018).

Parameter	Value
CsCOD	100 mg/l
CsBOD_5	30 mg/l
CsTSS	30 mg/l

The outcomes of the numerical calculations are displayed in **Table 6**. The table presents the average values of operational guidelines (m_x) for COD, BOD_5, and TSS concentrations at the WWTP for the year 2018. It is important to note that the method employed to establish operational limits results in more stringent thresholds compared to existing regulations. Consequently, the design and operation of the plant should aim to maintain the average concentration of each parameter below the established limits, considering both the variability of actual concentrations (represented by the coefficient of variation) and the chosen confidence threshold used to calculate the CV. Therefore, even if the legal limit remains the same (e.g., 40 mg/l for both COD and BOD_5), the operational limit may differ.

Table 6 Jordanian standards for treated wastewater.95% threshold at WWTP (2018).

Parameters		Year of 2018
COD (mg O_2/l)	CV	0.2171
	COR	0.72
	$m_x = COR * C_s$	72
BOD_5 (mg O_2/l)	CV	0.3307
	COR	0.65
	$m_x = COR * C_s$	19.5
TSS (mg/l)	CV	0.4516
	COR	0.54
	$m_x = COR * C_s$	16.2

This underscores the significance of incorporating reliability when setting operational guidelines to ensure that the treated effluent meets specific quality standards.

2.3. Evaluation of Adherence to Discharge Standards

2.3.1. Analysis of the reliability level at Wadi Arab WWTP

The operators of the WWTP are striving to incorporate a daily assessment of the plant's reliability using the probabilistic method proposed by Niku *et al.,* (1979). The primary focus is on evaluating the reliability of the activated sludge treatment process and its influence on the discharge quality parameters, namely COD, BOD_5, and TSS. A comprehensive analysis of the operational data from the plant was conducted to gather all the necessary information.

To ascertain the suitable level of reliability for the considered factors, the daily effluent concentrations from the WWTP are compared to the range of average concentrations based on different reliability levels. This comparison allows for an assessment of the plant's performance and the reliability of the effluent quality. The calculation results of the daily reliability level for effluent COD, BOD_5, and TSS at the Wadi Arab WWTP are depicted in the accompanying figures**, Figures (9-11)**.

It is noteworthy that there is variability in the dependability of the Wadi Arab WWTP, which can be attributed to various factors impacting the performance of the wastewater treatment processes. These factors include oscillations in flow patterns and their characteristics, inherent variability in the operation of wastewater treatment processes, disruptions caused by mechanical breakdowns, and the experience level of the operators in wastewater treatment plants, mainly in developing nations.

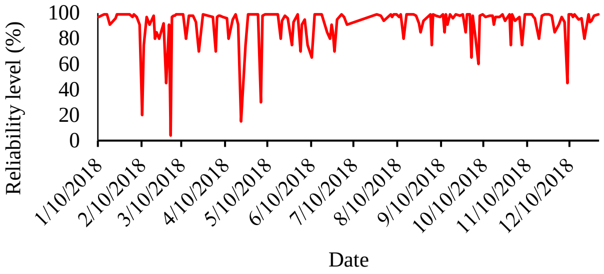

Fig. 9 Assessing the Reliability Level of Effluent COD at Wadi Arab WWTP (2018)

2.3.2. Evaluation of critical components in the Wadi Arab WWTP: a comprehensive analysis

Multiple factors that influence the plant's performance have been observed to affect the reliability level variation in the Wadi Arab WWTP. These factors involve instabilities in flow patterns, essential variability in wastewater treatment processes, mechanical failures, and operator inexperience. The considerable variability in TSS reliability can be mainly recognized due to subjects related to the grit chamber. With one of the three chambers nonoperational, the residence time for soluble solids is reduced, leading to insufficient settling time and compromising the effectiveness of TSS removal. The United States Environmental Protection Agency (USEPA) has developed a critical component analysis approach for assessing the reliability, maintainability, and availability of critical components in wastewater treatment plants. Additionally as mentioned before, Niku *et al.,*(1981) proposed a numerical and economic resolution model to make such determinations. Their approach focuses on minimizing the total costs associated with treatment plants, including construction, operation, and the cost of failure multiplied by its probability of occurrence. This framework ensures cost effectiveness while maintaining an optimal level of reliability.

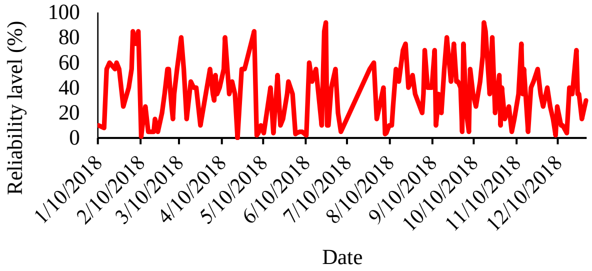

Fig. 10 Examining the Reliability Level of Effluent BOD_5 at Wadi Arab WWTP (2018).

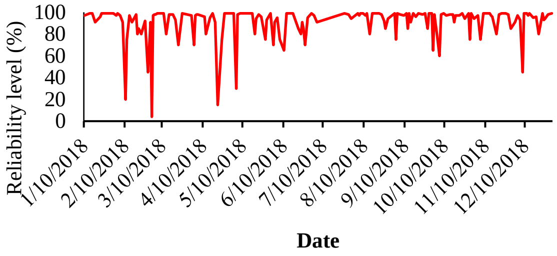

Fig. 11 Examining the Reliability Level of Effluent TSS at Wadi Arab WWTP (2018).

Conclusions

The variability in the reliability level of the Wadi Arab WWTP arises from various factors that affect the plant's performance. These factors incorporate fluctuations in flow patterns, essential variability in wastewater treatment processes, mechanical failures, and limited operator experience. The notable variability in the reliability level of TSS primarily stems from issues related to the grit chamber. The nonoperational status of one of the three chambers reduces the residence time for soluble solids, resulting in inadequate settling time. As a consequence, the effectiveness of TSS removal is compromised. The USEPA has developed a critical component analysis approach to assess the reliability, maintainability, and availability of crucial components in wastewater treatment plants. This approach serves as a valuable tool for design engineers and plant operators, facilitating the selection of new equipment and improving overall plant performance. This approach is a valuable tool for design engineers and plant operators in equipment selection and overall plant performance enhancement. Śliz (2024) proved that the determination of technological reliability and removal efficiency of certain contaminants is an important tool in assessing wastewater treatment plants' performance. In wastewater management, Eisenberge *et al.*, (2001) have suggested a technique to assess both inherent and mechanical reliability. They stress the prominence of reliability assessment and advocate for the establishment of a minimum reliability requirement to control an acceptable level of failure probability.Niku *et al.,* (1981) employ statistical and economic decision theory to make such determinations. Their approach emphasizes minimizing the total costs associated with treatment plants, including construction, operation, and the cost of failure multiplied by its probability of occurrence. This framework ensures cost-effectiveness while maintaining an optimal level of reliability.

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Nomenclature

α	=Significance level	[-]
BOD_5	=Biochemical Oxygen Demand (5-day)	[mg O_2/L]
Ce	=Concentration of treated effluent quality parameter	[mg/L]
COD	=Chemical Oxygen Demand	[mg O_2/L]
COR	=Coefficient of Reliability	[-]
CV	=Coefficient of Variation	[-]
Cs	=Concentration requirement set by controlling criteria	[mg/L]
F	=Failure	[-]
P(F)	=Probability of failure	[-]
m_x	=Average concentration of the constituent	[mg/L]
R	=Reliability	[-]
TSS	=Total Suspended Solids	[mg/L]
$Z\_(1-\alpha)$	=Normalized Standard Variate	[-]

References

Ayodele, O. B., Y. Cao, and M. Qiu "Reliability analysis of a membrane bioreactor system in wastewater treatment", *Desalination and Water Treatment*, **57**, 11983-11994, (2015).

Chen, C. H., and R. T., Hwang "Reliability analysis of a wastewater treatment plant", *Water Sci. and Tech.*, **31**, 163-170, (1995).

Cohen, A. I., Bar-Shalom, Y. W., *et al.,* “A Quantitative Method for Effluent Compliance Monitoring Recourses Allocation”, EPA-600/5-75-015, U.S. Environmental Protection Agency,” Washington, USA, (1975).

Culp, G., Wesner, G., Williams, R., and M. V., Hughes “Wastewater Reuse and Recycling Technology”, Noyes Data Corporation, New Jersey, USA, (1980).

D'Agostino, R. B., Belanger, A., and JR., R. B. D'Agostino "A Suggestion for Using Powerful and Informative Tests of Normality", *The American Statistician*, **44**, 316-321, (1990).

D'Agostino, R. B., and M. A., Stephens “Goodness-of-fit Techniques, MARCEL DEKKER”, Inc, New York, USA, (1986).

Eisenberg, D. A., D. L., Miller, and D. R., Johnson "Evaluating inherent and mechanical reliability in water and wastewater treatment systems", *J. of Env. Eng.*, **127**, 935-941, (2001).

Eisenberge, D., Soller, J., Sakaji, R., and A., Olivier "A Methodology to Evaluate Water and Wastewater Treatment Plant Reliability", *Water Sci. and Tech.*, **43**, 91-99, (2001).

Helsel, D. R., and R. M., Hirsch "Statistical methods in water resources", Techniques of Water-Resources Investigations, Book 4, Chapter A3, (1990).

Li, Y., J. Wang, and B., Wu "Comparative analysis of reliability analysis methods in wastewater treatment systems", *Procedia Eng.*, **154**, 626-633, (2016).

Liu, S., W. Zeng, and Y., Deng "Assessing the reliability and availability of wastewater treatment processes using Markov models", *Water Sci. and Tech.*, **47**, 95-102, (2003).

Loureiro, D., T. Cortesão, R. Coelho, and E. G., Tavares "Resilience assessment of wastewater treatment systems to natural disasters", *J. of Water Proc. Eng.*, **37**, 101417, (2020).

Niku, S., and E. D., Schroeder "Stability of Activated Sludge Processes Based on Statistical Measures", *J. Water Pollution Control Federation*, **53**, 129-143, (1981).

Niku, S. *et al.*, “Performance of activated sludge process: reliability, stability and variability”, Environmental Protection Agency, EPA Grant No. R805097-01, 124p, (1981).

Niku, S., Schroeder, E. D., and F. J., Samaniego "Performance of activated sludge processes and reliability-based design", *J. Water Pollution Control Federation*, **51**, 2841-2857, (1979).

Ossenbruggen, P. J., Constantine K., Collins M. R., *et al.*, "Toward Optimum Control of the Activated Sludge Process with Reliability Analysis", *Civil Eng. Systems*, **4**, 77-86, (1987).

Pearson, C. R., J. A., Lambert, and J. E., Salmon "Reliability analysis of a specific wastewater treatment plant using fault tree analysis", *Water Sci. and Tech.*, **14**, 559-569, (1982).

Pearson, E. S., D'Augustine, R. B., and K. O., Bowman "Tests for Departure from Normality: Comparison of Powers", *Biometrika*, **N 64**, 231-246, (1977).

Ren, X., H. Liu, X. Peng, and M., Li "Reliability analysis of anaerobic digestion process in wastewater treatment", *J. of Water Proc. Eng.*, **3**, 72-78, (2014).

Śliz, P. "An analysis of the operation of the wastewater treatment plant in Nowy Sącz–tools for assessing the efficiency and reliability of operation," *Technical Transactions*, **121**, e2024004, (2024).

Smith, J. B., M. H., Brown, and J. D., Zuboy "Resilience analysis of wastewater treatment systems", *Water Sci. and Tech.*, **22**, 61-69, (1990).

USEPA. “Technical Support Document for Water Quality-based Toxics Control”, EPA 505/2690-001, U.S. Environmental Protection Agency, Washington, USA, 335, (1991).

Velez, J., C. M., Galdos, L. F. B. C., Mancini, and A. P., Braga "Assessing the impact of aging infrastructure on the reliability and resilience of wastewater treatment systems", *Res., Conservation and Recycling*, **172**, 105704, (2021).

Wang, Q., W., Chen, and L., Huang "Impact of climate change on the reliability and resilience of wastewater treatment systems", *Water Sci. and Tech.*, **58**, 1743-1750, (2008).

Wang, Z., and C., Chen "Resilience analysis of wastewater treatment systems using system dynamics modeling", *J. of Env. Manag.*, **232**, 478-487, (2019).

Wu, Y., D. Wu, S. Ni, S. Han, and Y., Wang "Reliability analysis of a wastewater treatment plant using Bayesian networks", *Water Sci. and Tech.*, **75**, 753-762, (2017).

Wu, Y., Z. Huang, Y. Zhang, and J., Chen "Reliability-centered maintenance for wastewater treatment systems", *J. of Cleaner Prod.*, **232**, 10-22, (2019).

Zhang, H., B. Zhang, W. Li, and G., Xi "A comprehensive review of resilience assessment methods in wastewater treatment systems", *Env. Sci. and Poll. Res.*, **30**, 30650-30668, (2023).

Zhang, L., X. Chen, H. Yang, and L. Yang "Performance evaluation framework for decentralized wastewater treatment systems", *J. of Env. Eng.*, **138**, 704-713, (2012).

Zhou, Z., B. Zeng, Z., Peng, Y. Shi, and H., Zheng "Optimal design of reliable and resilient wastewater treatment systems: A multi-objective optimization model", *J. of Cleaner Prod.*, **315**, 128271, (2022).