



Optimizing Chlorine Decay Factors in Intermittent Water Supply Using Box-Behnken Design

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Abstract

Chlorine decay in water distribution systems is a critical challenge that impacts disinfection efficiency and public health. Using the Box-Behnken Design this study systematically investigates the effects of pH, flow rate, pipe length, and stagnation time on chlorine residual loss through a controlled experimental framework and optimize them to maintain acceptable residual chlorine. Analysis of Variance (ANOVA) was performed and revealed that pH and stagnation time were the most significant factors. Lower pH less than 7 and longer stagnation of over 2 hours accelerated chlorine decay by up to 40%. Flow rate showed a secondary but notable effect, where higher velocities (1.0 L/min) reduced decay by 15 to 20%. A quadratic model ($R^2 = 0.98$) demonstrated strong predictive accuracy and revealed key interactions between initial chlorine dose and pH. At optimized conditions, a target residual chlorine level of 0.34 mg/L was achieved, balancing disinfection and operational efficiency. This study offers a vital strategy for utilities to mitigate the public health risks associated with inadequate disinfection in distribution networks.

Keywords · pH effects, flow rate, stagnation time, water distribution systems, Analysis of Variance, EPANET model.

1. Introduction

Access to safe drinking water remains a major global public health challenge. According to the World Health Organization (WHO, 2023), over 2 billion people consume water from sources contaminated with fecal matter, leading to widespread outbreaks of waterborne diseases such as cholera, typhoid, dysentery, and hepatitis A. The situation is particularly severe in sub-Saharan Africa, where only 30% of the population has access to safely managed drinking water services, compared to over 70% in high-income countries (UNICEF, 2021). Inadequate water infrastructure, urbanization pressures, and institutional

limitations exacerbate the problem across many African nations. In Tanzania, for instance, approximately one-third of the population still relies on unimproved or contaminated water sources (URT, 2022). Poor water quality is directly linked to increased morbidity and mortality. Globally, unsafe water causes more than 443,832 diarrheal deaths annually for children under 5 and an additional 50,851 children aged 5 to 9 years, with sub-Saharan Africa bearing a disproportionate share of this burden (WHO, 2023).

Various water treatment methods are employed globally to address water quality challenges, ranging from dosing with chlorine to full convention treatment. While these technologies are effective, they face

numerous implementation challenges such as high operational costs, inadequate infrastructure, and limited technical capacity in many developing countries (Momba & Thompson, 2009). Among them, conventional water treatment systems, which include multi-barrier approaches culminating in disinfection, remain the most widely adopted for large-scale water supply schemes (WHO, 2022). In Tanzania, this method is prevalent due to its proven reliability, capacity to handle large volumes, and ability to significantly reduce pathogens when properly maintained. Challenges include the formation of disinfection byproducts (DBPs), variable chlorine decay in distribution networks, and difficulties in maintaining adequate residual chlorine at distant and low-flow points in the system lead to Degradation of water quality after treatment (Deborde & von Gunten, 2008).

Chlorine is widely used as a disinfectant in water distribution systems due to its effectiveness in controlling microbial organism and preventing waterborne diseases (WHO, 2022). However, maintaining an adequate chlorine residual throughout the distribution network is challenging due to natural decay processes influenced by various physicochemical and hydraulic factors. Among these, pH, flow rate, and stagnation time play critical roles in determining chlorine decay rates (Fisher et al., 2011). Understanding how these factors interact is essential for optimizing disinfection strategies and ensuring safe drinking water quality.

The pH of water significantly affects chlorine decay by influencing the dominant chlorine species hypochlorous acid (HOCl) and hypochlorite ion (OCl⁻) which have different disinfecting efficiencies and reaction kinetics (Zhang et al., 2017). At lower pH levels (below 7.5), HOCl predominates and is more reactive with organic and inorganic compounds, leading to faster chlorine decay. Similarly at higher pH levels, OCl⁻ dominates, which is less reactive but persists longer in the system (Hua et al., 2015).

Flow dynamics, including lamina flow rate and turbulence, also influence chlorine decay by altering the contact time between chlorine and reactive substances in the water. High flow rates reduce the hydraulic residence time, potentially decreasing chlorine decay due to limited reaction time (Boccelli et al., 2003). Conversely, low flow or stagnant conditions allow prolonged interaction between chlorine and organic/inorganic matter, accelerating decay (Clark et al., 2005). Stagnation time is particularly critical in dead-end pipes or low-demand periods, where extended water age leads to significant chlorine loss, increasing the risk of microbial regrowth (Prasad et al., 2004).

Several studies have explored chlorine decay dynamics in water supply systems, focusing on factors such as water quality, pipe material, temperature, and hydraulic conditions. For instance, a study by (Fisher et al., 2012) investigated chlorine decay in continuous water supply systems, highlighting the significant impact of organic matter and pipe wall interactions on residual chlorine depletion, using a first-order decay model to predict chlorine concentrations. Similarly, (Ramos et al., 2010) examined chlorine decay in IWS systems, emphasizing the role of intermittent flow patterns and stagnation periods in accelerating chlorine loss due to increased microbial activity and sediment resuspension. Their findings underscored the need for tailored chlorination strategies in IWS systems to maintain adequate disinfectant residuals. Additionally, (Al-Araimi et al., 2019) applied response surface methodology to optimize chlorine dosing in water distribution networks, demonstrating that statistical experimental designs can effectively identify key factors influencing chlorine decay, such as pH and initial chlorine concentration.

Despite this extensive research, a critical gap remains in the multi-factor optimization of these variables under realistic, operationally relevant conditions, particularly in the context of intermittent water supply (IWS) systems common in developing nations like Tanzania. Previous studies have often

focused on individual factors or controlled laboratory settings that do not fully capture the complex, harmonious interactions between pH, flow dynamics, pipe length, and extended stagnation periods typical of IWS. This study aims to bridge this gap by systematically evaluating the combined effects of these critical variables through a controlled experimental

Morogoro Region. Morogoro Municipal is an urban area situated at the foothills of the Uluguru Mountains, approximately 190 kilometers west of Dar es Salaam (Figure 1). Bigwa Ward is one of the key administrative areas within the municipality, characterized by a mix of residential, commercial, and small-scale farming activities.

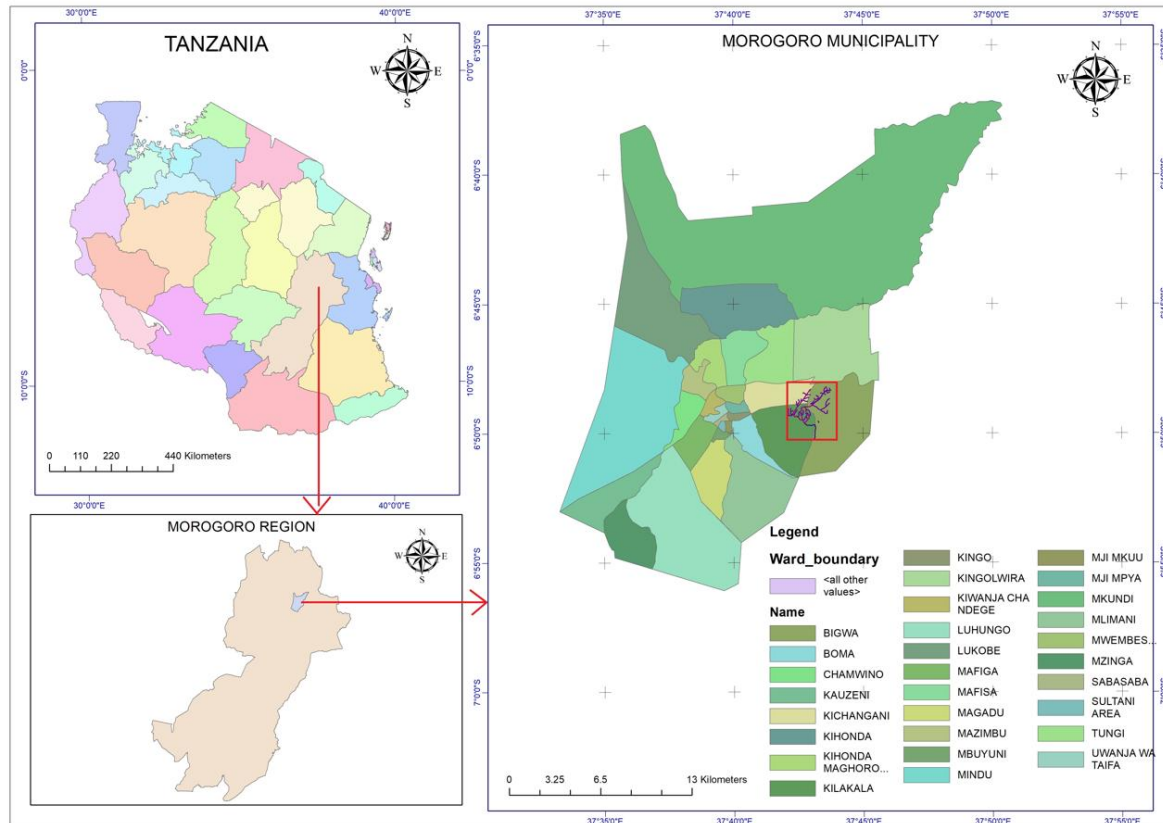


Figure 1: Location of Study area

framework using a Box-Behnken Design. The findings will provide Tanzanian water utilities, and those in similar contexts, with actionable, evidence-based insights for optimizing disinfection practices, improving residual chlorine management, and ultimately ensuring the delivery of safe drinking water despite the constraints of intermittent supply.

2. Material and Method

2.1. Study Area

The study is carried out on Bigwa water supply scheme, located in Morogoro Municipality, in

According to census (2022) the Municipality has a population of 471,409 people while population of Bigwa Ward is estimated to be 16,623 people. The area has experienced gradual urbanization, leading to increased infrastructure development and social services.

Morogoro Municipal experiences a tropical savanna climate, characterized by distinct wet and dry seasons with moderate to high temperatures ranging between 16°C and 33°C. The average annual rainfall ranges from 821 mm to 1,505 mm, with higher

precipitation in the mountainous areas of the Uluguru ranges (Ernest et al., 2017).

2.2. Water Supply Service

The existing water supply system in Bigwa is owned and operated by Morogoro Urban Water supply and Sanitation Authority (MORUWASA). The system is a gravity fed system serving communities in and around Bigwa ward Figure 1. It consists of 90 m³ water storage tank that serves as the system's hydraulic anchor and primary pressure regulation structure. From this reservoir, water flows through an extensive 24-kilometer distribution network comprising pipes of varying diameters from DN150 main transmission lines to DN50 secondary distribution lines. The system predominantly consists of PVC pipes which account to 90% of the network, with the remaining 10% consisting of HDPE pipes for specifically for secondary distribution.

The topography of area covered by supply system plays a crucial role in water distribution system hydraulic dynamics with the elevation ranging from 620m a.m.s.l to 480m a.m.s.l. The terrain consists of rolling slopes with moderate vegetation cover, typical of the eastern foothills of the Uluguru Mountains. The elevation advantage enhances water pressure in the distribution system. The source of water supply is Bigwa river originating from Uluguru mountains, water from the source undergo a treatment process that consists of Sedimentation and disinfection with chlorine.

2.3. Experimental model Setup

The experimental water supply system was designed to replicate real-world drinking water distribution system (DWDS) conditions to investigate the effects of pH, flow rate, pipe length, and stagnation time on chlorine decay. The system was modelled

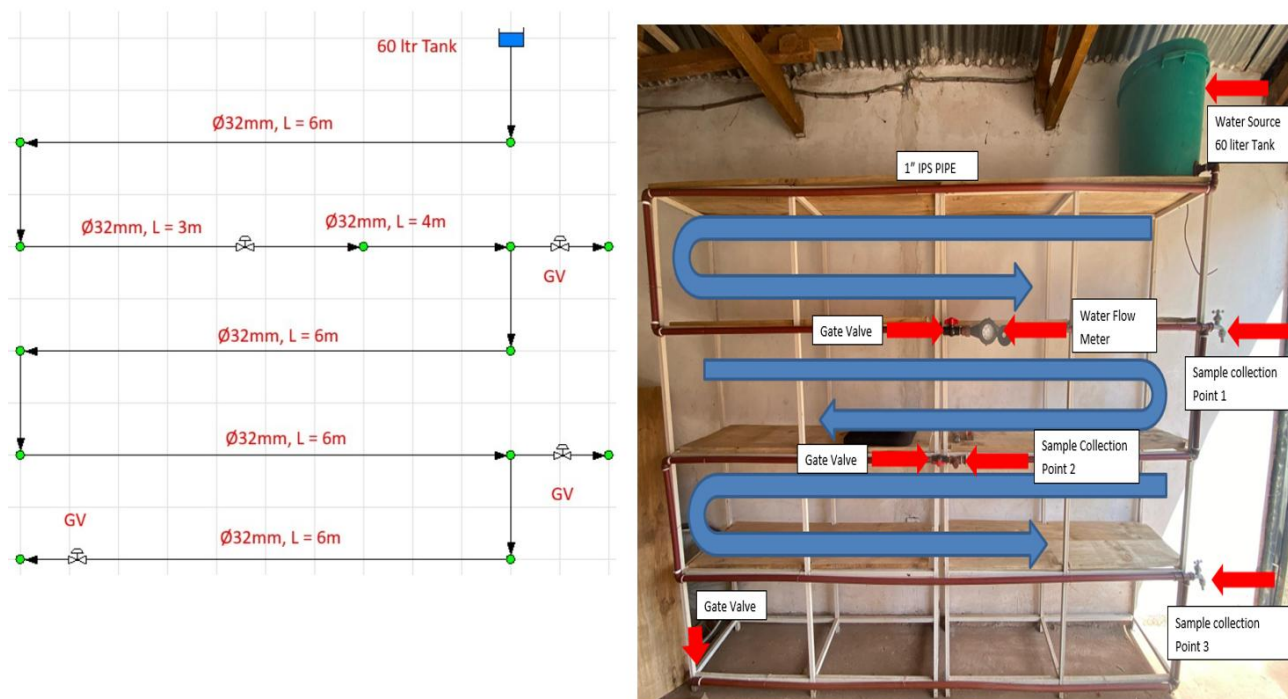


Figure 2: The laboratory experimental pipe network a) schematic diagram designed using Pipe Flow Expert software, b) Photograph of the constructed experimental pipe facility

using Pipe Flow Expert software version 7.4 and the physical pilot-scale pipe network as seen in (Figure 2) was constructed using DN32 high-density

polyethylene HDPE pipes, which are commonly used in municipal water systems due to their corrosion resistance and minimal chlorine reactivity (AWWA, 2021). The pipe segments varying lengths ranging from 10 to 30 m. A 60-liter tank was installed on top of the system to simulate supply tank feeding system by gravity. NSF single jet Plastic Water Meter of DN32 was installed in series with valve to control flow rates 0.5 to 1 L/min, DN32 Gate Valves were installed and used close and open section of the system to simulate different operational conditions, including intermittent water supply (IWS) scenarios where drain-down effects were studied. Multi-meter was used to measure pH and temperature of water, ensuring real-time data collection.

Table 1: Box-Behnken Design input parameters and levels for chlorine decay experiments

Factor	Low (−1)	Middle (0)	High (+1)
pH	4	6	8
Flow rate (m/s)	0.5	0.75	1
Stagnation (h)	1	2	3
Pipe length (m)	10	20	30

design (CCD), while still providing sufficient information for developing second-order quadratic models (Ferreira et al., 2007). This makes it useful when resources are limited. Additionally, BBD avoids combinations where all factors are simultaneously at their highest or lowest levels, which can be useful in preventing experiments that involve extreme operating conditions that may be infeasible (Montgomery, 2013). Furthermore, BBD provides good predictability within the experimental space and is well-suited for exploring optimal conditions in multi-variable systems, making it ideal for studies involving process optimization or parameter interaction analysis (Myers et al., 2016). These features make BBD a robust and cost-effective choice in many scientific and engineering research applications.

2.4. Experimental Design

To systematically evaluate the influence of key variables (pH, flow rate, stagnation time, and pipe length) on chlorine decay, a statistical experimental design was developed using Design Expert software, which facilitated the optimization of test conditions through Response Surface Methodology (RSM) (Myers et al., 2016). A Box-Behnken Design (BBD) was implemented in to evaluate the interactive effects of pH, flow rate, stagnation time and pipe length on chlorine decay (Table 1). The Box-Behnken Design (BBD) method was selected based on its advantages over other experimental design techniques, particularly in the context of response surface methodology (RSM).

In this study, a total of 46 experimental runs were proposed using the Box-Behnken Design (BBD) method to evaluate the effects of key operational parameters on residual chlorine concentration in an intermittently supplied water distribution system. All standardized measurements of the 46 experiments were performed under Morogoro Urban Water Supply and Sanitation Authority (MORUWASA) Water Quality Laboratory.

2.5. Sample Analysis

The study employed the DPD (N,N-Diethyl-p-Phenylenediamine) colorimetric method, a widely

recognized and standardized technique, to measure residual chlorine concentrations in the water samples to analyse the level of residual chlorine in the samples. Samples were collected in 500 ml sterile Polyethylene Graduated Water Sampling Containers at the end of each experimental run and analyzed immediately to prevent any decay of residual chlorine during storage. DPD reagent in powder was added to each sample, resulting in a color change to pink when chlorine was present. The absorbance of the solution was then measured using a HACH pocket colorimeter to determine the residual chlorine concentration. The pH level of each sample was determined using a calibrated HACH HQ40d multimeter. pH adjustments during experiments were for controlled lab analysis to observe how pH influence residual chlorine. The water flow rate was monitored using a mechanical NSF single jet Plastic Water Meter. The meter was installed in-line with the experimental setup, providing real-time flow data in liters per minute (L/min).

2.6. Data Analysis

Data analysis in this study was conducted using Design-Expert version 13 software, which provided a

robust platform for implementing the Box-Behnken Design (BBD) under the framework of Response Surface Methodology (RSM) to evaluate the influence of pH, flow rate, pipe length, and stagnation time on chlorine decay. Following completion and loading of the experimental results into the software, a comprehensive Analysis of Variance (ANOVA) was performed to determine the statistical significance of each individual factor and their interactions. This technique was critical for identifying the most influential parameters affecting chlorine residuals and assessing the adequacy of the developed regression model. The analysis also included computation of key statistical indicators such as the F-value, p-value, R^2 , Adjusted R^2 , and Predicted R^2 , which helped validate the model's reliability and predictive strength. Diagnostic plots such as normal probability plots and residuals versus predicted values were used to evaluate model assumptions and identify any potential anomalies in the data.

Table 2: ANOVA for Reduced Quadratic model

Source	F-value	p-value	
Model	526.63	< 0.0001	significant
A-Initial Chlorine Dose	781.42	< 0.0001	
D-pH	1368.51	< 0.0001	
E-Stagnant Time	760.33	< 0.0001	
AD	123	< 0.0001	
AE	77.64	< 0.0001	
E ²	48.85	< 0.0001	
Residual			
Lack of Fit	1.84	0.259	not significant
Pure Error			
Cor Total			

2.7. Quality Assurance and Quality Control (QA/QC)

To ensure the reliability and accuracy of the experimental results, QA/QC measures were

systematic errors, and suitable for statistical evaluation.

3. Results and discussion

3.1. Analysis of Variance (ANOVA)

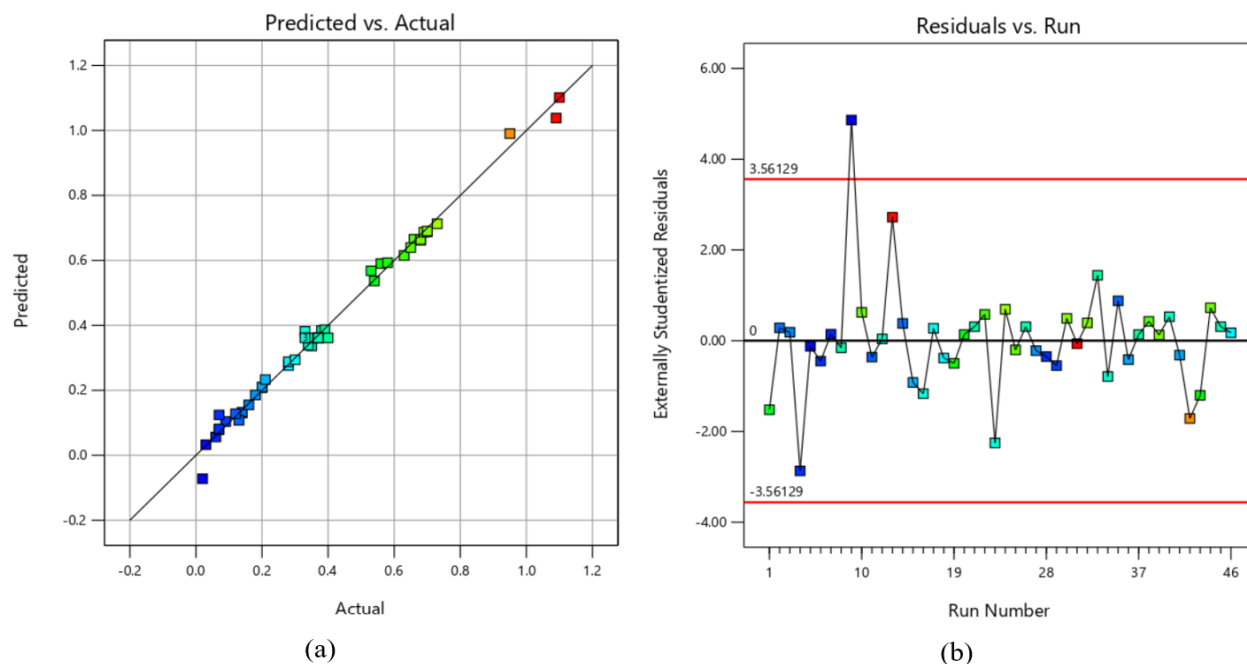


Figure 2: Model's predictions and the actual experimental values of residual chlorine and Residuals vs. Run

implemented throughout the study. The pH levels were continuously monitored using a calibrated multimeter to minimize fluctuations, and adjustments were made using standardized solutions of aluminum sulphate to maintain consistency. Flow rates were precisely controlled using manual gate valves and verified with a calibrated flow meter, ensuring repeatability across experimental runs. For residual chlorine measurements, the DPD colorimetric method was strictly followed, and samples were analyzed immediately after collection to prevent degradation. The HACH pocket colorimeter was calibrated using known standards to maintain measurement accuracy. All data were recorded in real-time and cross-checked for anomalies before being uploaded to Design Expert software for analysis. These measures ensured that the data collected were of high quality, free from

To statistically evaluate the significance of the investigated parameters (pH, flow rate, stagnation time, and pipe length) on chlorine decay, Analysis of Variance (ANOVA) was assessed. The ANOVA indicated that the individual and interactive effects of each factor by decomposing the total variability in chlorine decay rates into contributions from model terms and residual error (Montgomery, 2019). The Quadratic model fitted to the data was evaluated based on p-values (<0.05 for significance), and lack-of-fit tests to ensure model adequacy as seen in (Table 2). The results indicated that A, D, E, AD, AE, E^2 are significant model terms with $p < 0.0001$, with stagnation time and pH exhibiting a strong negative correlation with chlorine decay. Flow rate showed moderate significance. Pipe length had the least impact, suggesting its influence was secondary to chemical and hydraulic factors. Based on the analysis

the data fitted well to a quadratic regression model. The quadratic model was chosen for its ability to capture not only the main effects of individual input variables but also the interaction effects between pairs of

$$\text{Residual Chlorine} = 0.37 + 0.23*A - 0.304*D - 0.219*E - 0.185*AD - 0.14*AE + 0.069E^2.$$

3.2. Model Fit

Table 3: Residual Chlorine Response under Varying pH, low rate, pipe length, and stagnation time

Std	Run	A: Initial Chlorine Dose (mg/l)	B: Flow Rate (l/min)	C: Pipe Length (m)	D: pH	E: Stagnant Time (hr)	Actual Value of Residual Chlorine (mg/l)	Predicted Value (mg/l)
3	2	0.5	1	20	6	2	0.14	0.126
13	3	0.5	0.75	10	6	2	0.16	0.136
40	6	1.25	1	20	8	2	0.07	0.082
8	7	1.25	0.75	30	8	2	0.06	0.067
21	8	1.25	0.5	10	6	2	0.38	0.38
20	9	1.25	0.75	20	8	3	0.02	0.047
10	10	1.25	1	20	6	1	0.68	0.665
34	13	2	0.75	20	6	1	1.09	1.04
31	15	1.25	0.75	10	6	3	0.21	0.232
36	17	2	0.75	20	6	3	0.3	0.292
33	18	0.5	0.75	20	6	1	0.28	0.286
4	19	2	1	20	6	2	0.58	0.596
5	24	1.25	0.75	10	4	2	0.73	0.724
42	26	1.25	0.75	20	6	2	0.37	0.363
32	27	1.25	0.75	30	6	3	0.18	0.189
7	29	1.25	0.75	10	8	2	0.09	0.095
26	31	2	0.75	20	4	2	1.1	1.1
38	32	1.25	1	20	4	2	0.7	0.691
45	33	1.25	0.75	20	6	2	0.4	0.363
12	36	1.25	1	20	6	3	0.2	0.212
22	37	1.25	1	10	6	2	0.39	0.393
29	39	1.25	0.75	10	6	1	0.69	0.69
23	40	1.25	0.5	30	6	2	0.35	0.343
17	42	1.25	0.75	20	4	1	0.95	1.02
2	43	2	0.5	20	6	2	0.56	0.583

variables and the curvilinear (non-linear) behavior of each factor. This comprehensive approach allows the model to account for situations where the influence of a variable on residual chlorine is not constant but changes at different levels of that same variable.

The model demonstrates an excellent fit to the experimental data, as evidenced by both the Predicted vs Actual plot and the Fit Statistics (Figure 3(a)). From the Predicted vs Actual plot, data points closely align with the 45-degree reference line, indicating a high

level of agreement between the model's predictions and the actual experimental values of residual chlorine. There is no noticeable systematic deviation or wide scatter, suggesting that the model accurately captures the underlying data patterns across the range of Residual Chlorine.

$R^2 = 0.9979$ indicates that 99.79% of the variability in residual chlorine is explained by the model. Adjusted $R^2 = 0.9968$ and Predicted $R^2 = 0.9942$ are both very close. Standard Deviation = 0.0208 and C.V. % = 2.03% are both low, implying minimal residual error relative to the mean response (1.02).

On (Figure 3(b)) it was observed that most experimental results did not deviate significantly from the model's predicted values, suggesting that the model provides a reasonable fit to the data. However, one data point notably exceeds the upper control limit, indicating the presence of a potential outlier. Overall, the residual plot confirms the robustness of the regression model used in the Box-Behnken Design, with no serious violations of model assumptions except for the single outlier. This validates the reliability of the model in capturing the relationships between factors and the response variable within the experimental space.

3.3. Factors Influencing Chlorine Decay

Bigwa water supply system is operated under an intermittent water supply (IWS). The system is divided into three supply zones, with each zone receiving water on alternate days in a three-day rotation cycle. With the supply at each zone begins at 9:00AM on the day of supply. This results to residual chlorine in the distribution system to fall below 0.2 mg/l due to prolonged stagnation periods which results and increased reaction times with organic and inorganic matter in the pipes (Abokifa et al., 2016).

To achieve an acceptable residual chlorine level of above 0.2 mg/L, four key operational factors were optimized to determine the optimal operation level factor which will results to acceptable residual chlorine

level in the distribution system at all time. An initial chlorine dose of 1.5 mg/L was selected to ensure

sufficient disinfection capacity while avoiding excessive residuals that could lead to taste and odor complaints, a common concern in chlorinated drinking water (WHO, 2022). The flow rate was maintained at 0.97479 m/s, representing an optimal balance between minimizing stagnation and ensuring adequate contact time for chlorine to inactivate pathogens effectively (LeChevallier et al., 2003). A neutral pH of 7 was maintained, as this range minimizes both rapid chlorine decay at low pH and reduced disinfectant efficacy at high pH. Additionally, the stagnation time parameter of 1.67581 hours was considered to represent realistic zero-flow conditions in intermittent water supply systems. The optimization of four parameters successful resulted a residual chlorine level of 0.34 mg/L. Residual chlorine value suggests this combination of factors represents a balanced solution between disinfection efficacy, resource use, and compliance with water quality standards.

3.4. Influence of Factors Influencing Disinfection

The experimental results in (Table 3) demonstrated considerable variability in residual chlorine concentrations as influenced by initial chlorine dosage, flow rate, pipe length, pH, and stagnation time. Among the 46 experimental runs, Run No. 9 exhibited the lowest residual chlorine concentration of 0.02 mg/L, which occurred under conditions of 1.25 mg/L initial chlorine, 0.75 L/min flow rate, 20 meters pipe length, pH 8, and a 3-hour stagnation period. This sharp decay is due to the combined effects of elevated pH and extended stagnation time. At higher pH levels, hypochlorous acid (HOCl) the most effective form of chlorine dissociates into hypochlorite ions (OCl^-), which are less effective as disinfectants and degrade more rapidly (Desiderio & Nibbering, 2010). The prolonged stagnation time further enhanced chlorine decay by allowing more time for chlorine to react with pipe wall materials and organic or inorganic constituents present in the water, which is consistent with findings by (Rossman, 2000) that longer residence

time increases chlorine demand and accelerates loss. In contrast, Run No. 31 showed the highest residual chlorine concentration of 1.1 mg/L under conditions of 2 mg/L initial chlorine dose, 0.75 L/min flow rate, 20 meters pipe length, pH 4, and only 2 hours of stagnation. The low pH in this run favored the presence of HOCl, enhancing chlorine stability, while the high initial dosage and short stagnation period reduced the opportunity for decay reactions to occur. These results corroborate earlier studies by (Fisher et al., 2012), which found that low pH and high initial chlorine concentrations contribute to prolonged chlorine persistence in distribution systems. Collectively, the findings from this study emphasize that pH and stagnation time are critical parameters in chlorine decay during intermittent water supply and must be carefully controlled to ensure effective disinfection throughout the distribution network.

3.5. Influence of individual factors on Residual Chlorine

3.5.1. Impact of Initial Chlorine Dose

The analysis results in (Figure 4) indicate that the Higher initial chlorine concentrations 2.0 mg/L consistently resulted in greater residual chlorine levels ranging between 0.32 – 1.09 mg/L after 2–3 hours compared to lower doses 0.5 mg/L, which yielded 0.407–0.452 mg/L. This trend aligns with first-order decay kinetics, where higher initial concentrations provide a larger reactive mass, slowing the relative

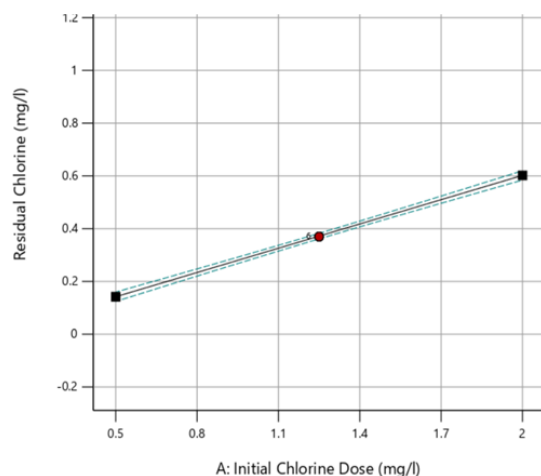


Figure 4: Residual chlorine vs Initial chlorine dose

decay rate (Fisher et al., 2011). At a mid-range dose 1.25 mg/L, residuals averaged 0.927–1.131 mg/L, demonstrating a near-linear relationship between initial and residual concentrations under controlled conditions. The near-linear progression in the graph at mid-range doses 1.1 to 1.4 mg/L yielding residuals of 0.6 to 0.8 mg/L further supports the first-order decay kinetics described in the literature, where residual chlorine scales predictably with initial concentration under controlled conditions.

3.5.2. pH Influence

The graph in (Figure 5) illustrates a clear negative correlation between pH and residual chlorine concentration, indicating that as pH increases from 4 to

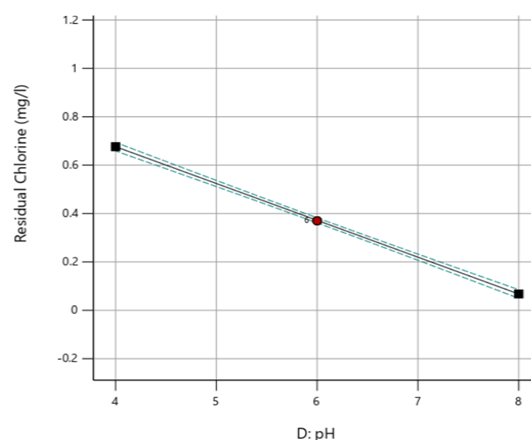


Figure 3: Residual chlorine vs pH

8, the level of residual chlorine decreases significantly. At a low pH of 4, residual chlorine concentrations are observed to be above 0.6 mg/L, while at pH 8, the concentration drops to below 0.1 mg/L. This trend confirms that chlorine is more stable and effective in slightly acidic conditions and degrades more rapidly under alkaline conditions (LeChevallier et al., 1981). The observed pattern can be attributed to chlorine speciation behaviour in which at lower pH, chlorine predominantly exists as hypochlorous acid (HOCl), a powerful and stable disinfectant. As pH increases, HOCl dissociates into hypochlorite ions (OCl^-), which are significantly less reactive and degrade more readily (Zhang et al., 2017). The observed behaviour is

consistent with the report from another study which reported that the disinfecting efficiency and persistence of chlorine significantly decline at higher pH due to the predominance of OCl^- (Hua et al., 2015).

3.5.3. Stagnation Effects

From the analysis the residual chlorine concentrations exhibit a clear dependence on stagnation time. As seen in (Figure 6), the progressive decline in disinfectant levels with increasing duration from 1 to 3 hrs, residual chlorine decreases exponentially. This behavior reflects fundamental chlorine decay kinetics, where longer contact times allow greater interaction with organic matter, pipe surfaces, and microbial communities (Boccelliet al., 2003). Field studies by (Hallam et al., 2002) have

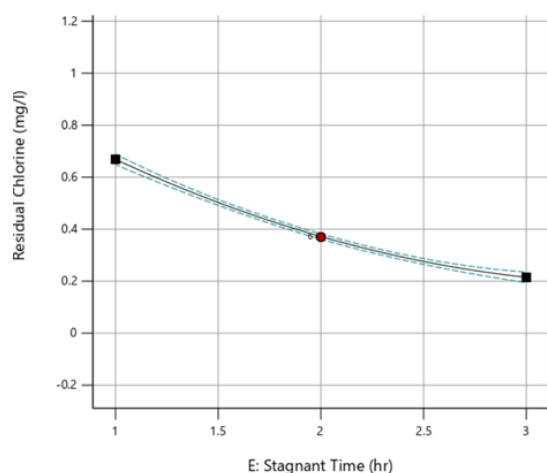


Figure 5: The relationship between residual chlorine concentration and stagnation time

documented similar patterns, with chlorine residuals decreasing 15-25% over comparable stagnation periods in operational distribution systems a range that aligns closely with the observed decay in these results.

The compounding effect of reduced flow rates on chlorine persistence becomes particularly evident when examining systems with prolonged stagnation. Data showing residual chlorine dropping from 0.58 mg/L at 1 L/min to just 0.07 mg/L at 0.5 L/min is the same as the findings from (Vasconcelos et al., 1997), who identified flow velocity as a critical determinant of disinfectant retention.

3.5.4. Pipe Length Variability

Pipe length demonstrates a measurable but secondary influence on residual chlorine levels compared to other factors like pH and stagnation. The experimental results in (Figure 7) demonstrate that the longer pipe segments (30 m) exhibited slightly reduced residual chlorine concentrations, ranging from 0.41 to 1.024 mg/L, compared to shorter pipe sections (10 m), which maintained concentrations between 0.41 and 1.637 mg/L. This was due to increased surface area contact and extended hydraulic residence time in longer pipes. The greater pipe wall interaction provides more opportunities for chlorine consumption through reactions with biofilm, corrosion products, and pipe materials (Al-Jasser, 2007). However, the relatively modest difference in residuals between pipe lengths suggests that while pipe length contributes to chlorine demand, its impact is less significant than water chemistry parameters (Boccelli et al., 2003). This hierarchy of influencing factors is consistent with distribution system studies by (Clark et al., 2005b), who found pipe length accounted for only 15-20% of total chlorine decay variance in typical operating conditions. The results emphasize that while infrastructure geometry affects disinfectant persistence, operational strategies should prioritize controlling water chemistry and flow conditions to maintain effective residual levels throughout the distribution network.

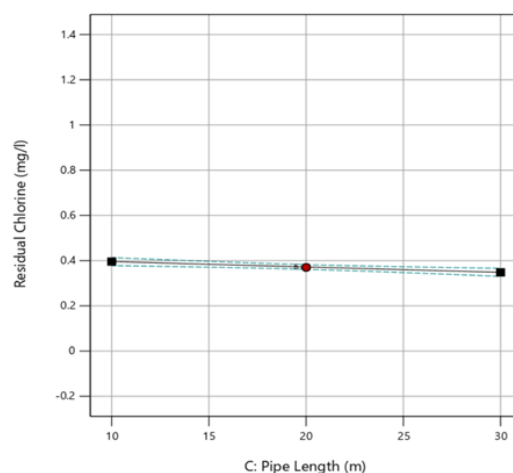


Figure 6: The effect of pipe length on Residual chlorine

3.6. Interactive Effects

3.6.1. Initial Chlorine Dose and pH

Contour plot in (Figure 8) illustrating the interaction effects of initial chlorine dose and pH on residual chlorine concentration. The plot reveals that residual chlorine concentration increases with higher initial chlorine doses and decreases with increasing pH levels. At low chlorine dosages of 0.5 mg/L and high pH above 7, the residual chlorine levels fall below 0.2 mg/L, indicating significant chlorine decay. Conversely, at higher initial doses close to 2 mg/L and lower pH values around 4 to 5, residual chlorine remains above 1.0 mg/L, reflecting minimal loss. This pattern is consistent with the chemical behavior of chlorine in water: at higher pH, chlorine predominantly

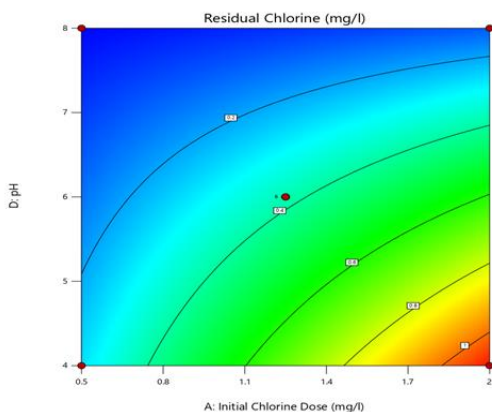


Figure 7: Interaction effects of initial chlorine dose and pH on residual chlorine concentration

exists as hypochlorite ion (OCl^-), which is less effective and more prone to decay than hypochlorous acid (HOCl), the dominant species at lower pH. The contour lines and color gradient further emphasize this trend, showing a sharp gradient of chlorine loss along the pH axis and a positive response along the dosage axis. These findings confirm that both initial chlorine concentration and pH are critical parameters influencing residual chlorine levels in distribution systems, and optimizing these variables is essential for maintaining effective disinfection, especially in systems affected by intermittent water supply.

3.6.2. Initial Chlorine Dose and Stagnation time

The interaction between initial chlorine dose and stagnation time significantly influences residual chlorine levels, as illustrated in (Figure 9). The contour plot shows that at a low initial dose of 0.5 mg/L and stagnation time of 3 hours, the residual chlorine concentration drops to approximately 0.2 mg/L, which is below the WHO recommended minimum of 0.5 mg/L for effective disinfection. In contrast, when the initial dose is increased to 2.0 mg/L and stagnation time is kept at 1 hour, the residual chlorine remains high approximately 0.9 mg/L, indicating effective persistence.

This trend highlights that higher initial chlorine doses can compensate for decay and extend disinfectant efficacy over time. However, as stagnation time increases, particularly beyond 2.5 hours, the effectiveness of even higher doses diminishes due to natural degradation mechanisms, including reactions with natural organic matter, pipe wall reactions, and thermal breakdown (Deborde & von Gunten, 2008). The observed nonlinear relationship is especially evident at lower chlorine doses, where even moderate increases in stagnation time lead to steep reductions in residual levels. This finding underscores the critical need to balance both dose and water age in distribution systems to prevent microbial regrowth and maintain water safety (WHO, 2017).

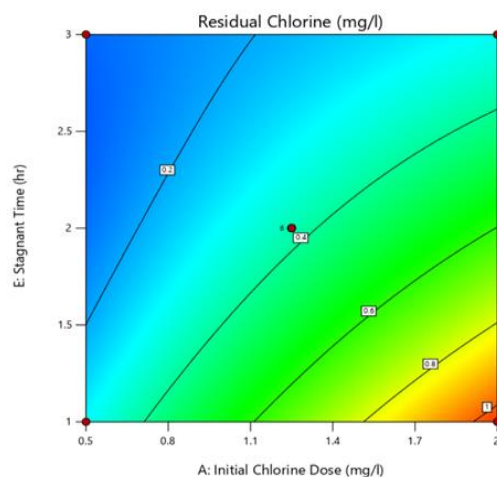


Figure 8; Interaction effects of initial chlorine dose and stagnation time on residual chlorine concentration

3.7. Factor Optimization

The optimization process was carried out to identify the most favorable conditions for minimizing chlorine

shown in (Appendix 1), indicate a marked increase in residual chlorine concentration after optimization. Before applying the optimized parameters, the system exhibited substantial chlorine decay, with residual

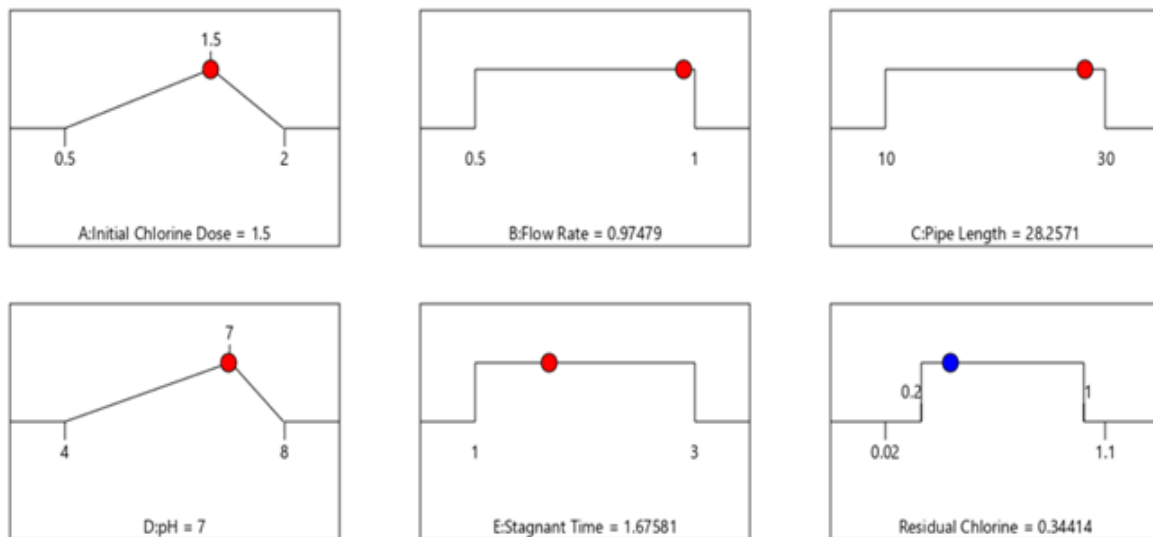


Figure 9: Optimization of operational factors

decay and maintaining effective residual levels. It aimed to maximize residual chlorine while keeping all operational parameters within practical and safe bounds. The criteria used for optimization were: maximizing the residual chlorine concentration, while setting the ranges for the input factors based on experimental limits initial chlorine.

The model predicted an optimal condition at an initial chlorine dose of 1.5 mg/L, flow rate of 0.97479 L/min, pipe length of 28.2571 m, pH of 7, and stagnation time of 1.67581 hours. Under these conditions, the model estimated a residual chlorine concentration of 0.34414 mg/L with a desirability value of 1.0 (Figure 10). This indicated a perfectly optimized solution according to the set constraints and goals. These values represent a balanced trade-off between sufficient disinfection and operational efficiency. The predicted an optimal condition were adopted on the EPANET model for Bigwa supply system, resulting to significant improvements in residual chlorine levels. The simulation results, as

levels falling below the World Health Organization's recommended minimum of 0.2 mg/L (WHO, 2017). After optimization, residual chlorine levels consistently exceeded 0.2 mg/L across the network, reaching an optimal value of approximately 0.3 mg/L. This achievement highlights the efficacy of the integrated factor adjustment approach in enhancing disinfection stability and ensuring water safety.

4. Conclusion.

This study quantitatively demonstrated that pH, stagnation time, and flow dynamics are pivotal factors governing chlorine decay in water distribution systems. The experimental results and subsequent Quadratic regression modelling revealed that low pH less than 7 and extended stagnation time more than 2 hours accelerate chlorine decay due to the dominance of reactive hypochlorite ion (OCl^-) and prolonged contact time with reactive surfaces. Conversely, higher flow rates (1.0 L/min) mitigated decay by 15–20% by reducing hydraulic residence time. The developed regression model with the predicted $R^2 = 0.98$,

provides water utilities with a practical tool to predict residual chlorine levels under varying operational conditions. utilities should integrate pH control, minimize stagnation in pipelines, and adjust flow management practices to ensure compliance with residual chlorine standards while optimizing resource use

It is important to note the study's limitations. The findings are derived from a controlled laboratory-scale setup; actual decay rates in a full-scale network with different pipe materials, ages, and biofilms may vary. Furthermore, this study did not address potential seasonal variations in water quality that could influence chlorine demand.

Future research must transition from controlled experimentation to field validation. A pivotal next step is to investigate the feasibility of real-time adaptive chlorine dosing systems for intermittent water supply settings. This should involve integrating hydraulic and water quality sensors with feedback control algorithms to dynamically adjust chlorine injection rates, providing a resilient solution for maintaining safe disinfectant residuals in the challenging and variable environments of real-world distribution networks.

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Author Contributions:

A. S. B prepared the Outline, carried out Analysis, interpreted the results, wrote the manuscript, and responded on the review and editing. G.C and M.J.N provided the review and editing of the manuscript draft in writings, Visualization and Supervision. All authors

have read and agreed to the published version of the manuscript.

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Conflict of interest:

The Authors confirm that this research was performed with no conflict of interest.

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Appendix 1

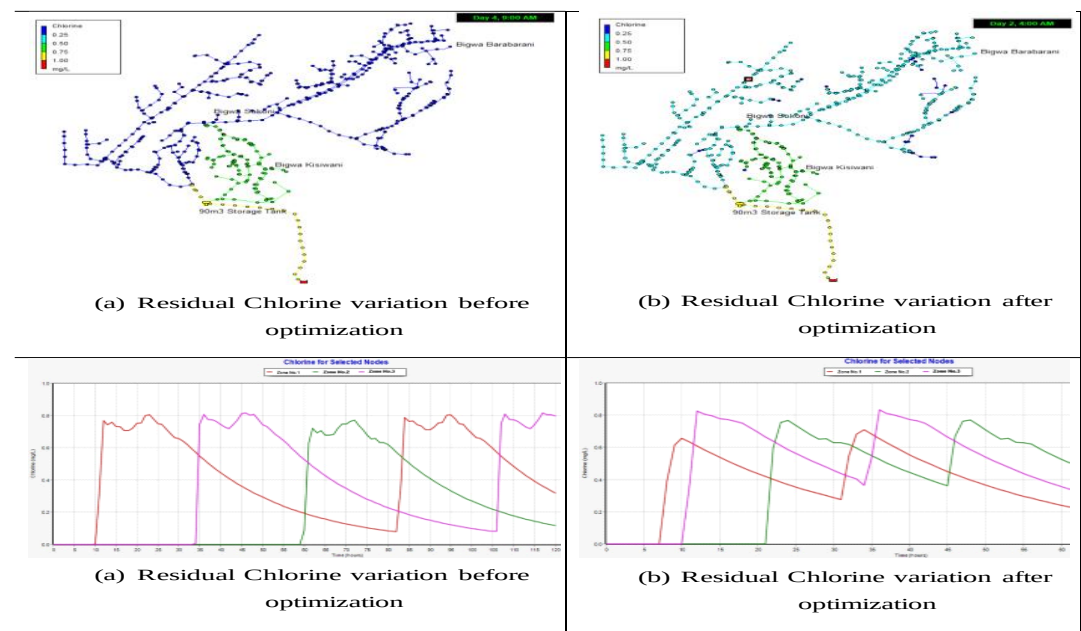


Figure 10: Optimization of four key operational