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RESEARCH ARTICLE

Comparison of passive and manual chlorination in small piped water networks in rural Ghana: Technical performance, ease-of-use, and cost

Caroline Delaire[1]*, **Katherine Marshall**[1], **Michal Usowicz**[1], **Tom Mahin**[1], **Daniel Kwaah**[2], **Bashiru Yachori**[2], **Bastian Schnabel**[1], **Ranjiv Khush**[1], **Rachel Peletz**[1]

1 The Aquaya Institute, Larkspur, California, United States of America, **2** The Aquaya Institute, Accra, Ghana

* caroline@aquaya.org

Abstract

Chlorination is the most common water treatment method globally and leads to proven health benefits. Yet, many rural water supplies in low-income settings are unchlorinated, exposing consumers to waterborne diseases. Insufficient technical and financial capacity of water suppliers in low-resource settings are common barriers to more widespread chlorination. We conducted a case study of two approaches to chlorinate small piped water supplies − passive (inline) chlorination and manual chlorination− and compared their technical performance, ease-of-use, and costs in rural Ghana. Based on 685 water quality measurements across two piped networks over three months, both methods provided adequate free chlorine residuals (i.e., 0.2–2.0 mg/L) most of the time (71% for manual chlorination and 86% for passive chlorination). Follow-up measurements five months later revealed a decline in chlorine levels with the manual approach (47% in the target range) and an increase with the passive (inline) approach (100% in the target range). We observed large fluctuations in chlorine levels over time, particularly with inline chlorination, that pH, temperature, conductivity, and turbidity variations did not fully explain. Temporal changes in chlorine demand and/or inconsistently implemented protocols possibly contributed to these fluctuations. Inline chlorination scored higher for ease-of-use (85%) than manual chlorination (70%) but was less financially viable: it represented an 11% increase in operational expenses, compared to 4% for manual chlorination. Initial equipment and installation cost approximately 6,000 USD for inline chlorination and about 260 USD for manual chlorination. Our results highlight the tradeoffs between passive (inline) and manual chlorination. Although less favorable for ease-of-use, manual chlorination is more viable financially and can achieve comparable performance with strict dosing protocol adherence, suggesting this approach deserves similar consideration as passive chlorination when evaluating options for low-resource settings. Both methods are susceptible to changes in operator behaviors and require external oversight plus support for troubleshooting and recalibration.

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Introduction

Chlorination is the most commonly used approach to disinfect drinking water globally [1]. Chlorine inactivates many microbial contaminants present in water, leading to substantial reductions in diarrhea and child mortality [2, 3]. One approach widely-promoted in low- and middle-income countries, called point-of-use (POU) chlorination, relies on households to chlorinate their own drinking water. Despite the wide availability of chlorine products, their ease-of-use, and low cost [4], POU chlorination initiatives in many low-resource settings have failed to achieve high levels of sustained adoption [5–9]. The taste and smell of chlorine in water, the time required for daily water treatment, personal motivation, and behavior change are considerable barriers to POU chlorination, often resulting in a decline of this practice over time [5, 10, 11]. In addition, POU chlorination adds a financial burden on low-income households who often have limited ability and willingness to pay for preventative health measures [10, 12, 13]. Disinfecting drinking water before it reaches the consumer, therefore, may be a more viable strategy to protect public health [10, 14, 15].

Rural water suppliers in low-income countries, however, struggle to perform centralized chlorination consistently. In a recent global assessment, only 55% of service providers reported regularly treating the water they supplied [16]. Further, analyses by Bain et al., [17] and Cherukumilli et al., [18] showed that piped supplies in rural areas often have microbial contamination, and more so than those in urban areas. Specifically, an estimated 57% of rural piped water users (or 22% of all rural inhabitants) in low- and middle-income countries in 2020 received contaminated drinking water [18], indicating lack or ineffectiveness of treatment practices. Relatedly, the World Health Organization (WHO) emphasized that maintaining water safety is particularly challenging for small-scale water supply systems in rural areas [19]. For example, Momba et al., [20] described the lack of proper chlorine dosing procedures and chlorine monitoring programs as one of the critical weaknesses of rural water supplies in South Africa. The authors highlighted that these problems are linked to the inadequate training of water treatment plant staff [20]. Similarly, the WHO concluded that the 2015–2016 cholera outbreak in Tanzania was caused by water suppliers lacking the capacity to chlorinate and conduct regular water quality assessments [21]. Supplying water intermittently, a common practice in many rural piped networks, exacerbates the challenges of applying adequate chlorination [22]. Given these challenges, identifying viable methods for centralized chlorination of water supplies in low-resource, rural settings is important to guide future investments.

Two approaches to centralized chlorination of water supplies merit further investigation: passive and manual chlorination. Passive (inline) chlorinators are increasingly viewed as a promising option for such contexts [23]. While gas or liquid chlorine injectors are common in large water utilities [24, 25], low-cost, low-tech designs more suitable to low-resource settings, such as tablet erosion chlorinators, have emerged. Several organizations operating or supporting piped water supplies in rural areas of low- and middle-income countries use inline chlorinators (e.g., Safe Water Network, Water Mission, Water4, EOS International), but rigorous evidence on the performance of these devices in the field is scarce. One study in rural Nepal reported on the effectiveness and costs of two inline chlorinators for piped supplies, showing that these devices can improve water quality in this setting when an NGO provides external support [26]. Similarly, a study in rural Honduras found that piped water supplies equipped with passive chlorinators could achieve adequate water treatment in the majority of cases, particularly when receiving regular technical assistance from a local NGO [27]. Several other studies in Central America reported on inline chlorination in rural, piped water networks, but they provided limited to no longitudinal performance data and no or partial information on costs [28–33].

Manual chlorination is an alternative approach where an operator manually adds solid or liquid chlorine to a central water storage tank. In the case of solid chlorine, this approach does not use any container to hold the tablets but is conceptually similar to "pot" chlorination, a strategy that aims at slowly dissolving solid chlorine directly into a well or water reservoir [4, 34, 35]. Close to no information is available on manual chlorination of piped water supplies. Bänziger et al., [36], in Nepal is the only study of which we are aware examining the benefits of passive (inline) chlorination compared to manual chlorination in rural piped networks. Because it requires close to no hardware, manual chlorination may be more affordable and suitable in rural settings with weak supply chains for chlorination hardware and equipment.

The practicality and trade-offs of passive (inline) and manual chlorination in rural, low-resource settings are presently under-documented. This study aimed to compare these two approaches in the context of small, community-managed piped water supplies in rural Ghana. We implemented the two chlorination methods at two different water supply facilities located in the district of Asutifi North, in southern Ghana. Our objectives were to evaluate: i) technical performance (whether the two methods could produce adequate free chlorine residuals (FCR) levels in drinking water), ii) ease-of-use (whether local water supply operators could easily perform the two methods with their current technical capacity), and iii) costs (how the capital investment and operational costs of chlorination compare to existing expenditures).

Materials and methods

Study locations

We conducted this study in Asutifi North District, located in the Ahafo Region in southern Ghana. The district is primarily rural and is inhabited by approximately 73,000 people. The main economic activities in the district are agriculture and gold mining [37, 38]. Prior studies found that piped water supplies in the district regularly tested positive for indicators of fecal contamination [37, 39], indicating that chlorination practices were inadequate to ensure water safety.

This study took place at two piped water supply facilities owned by the Asutifi North District Assembly (local government), from now on referred to as water supply facility 1 (WSF1) and water supply facility 2 (WSF2). WSF1 consisted of three boreholes, each with a submersible pump, that all supplied the same concrete storage tank (120 m^3 capacity) (Fig 1). The three boreholes operated on an alternating schedule, with one or two pumping at any point in time, such that the storage tank typically received water continuously throughout the day, barring power outages. Water flowed by gravity to approximately 10,000 people via 17 public standpipes and 451 private connections, covering an area of approximately 4.3 km^2. The distribution system was typically shut off eight hours per day during the night. WSF1 was built in 2012, i.e., nine years before the start of this study. WSF1 had ten permanent staff, including one manager (holding a bachelor's degree) and one operator (with no primary education) who performed chlorination tasks. Other staff were not directly involved in chlorination and included two technicians, one accountant, three revenue collectors, and two security officers.

WSF2 was smaller and less complex than WSF1. It consisted of only one borehole with a submersible pump that supplied one storage tank (100 m^3 capacity) (Fig 1) approximately 12 hours per day. WSF2 also relied on gravity flow and served approximately 5,000 people via eight public standpipes and 264 private household connections, covering an area of approximately 0.5 km^2. The distribution network received water approximately 12 hours per day. WSF2 was built in 2005, i.e., 16 years prior to this study. WSF2 had five permanent staff, including one manager (holding a bachelor's degree), one operator (with no primary education), and one revenue collector (with secondary education) who performed chlorination

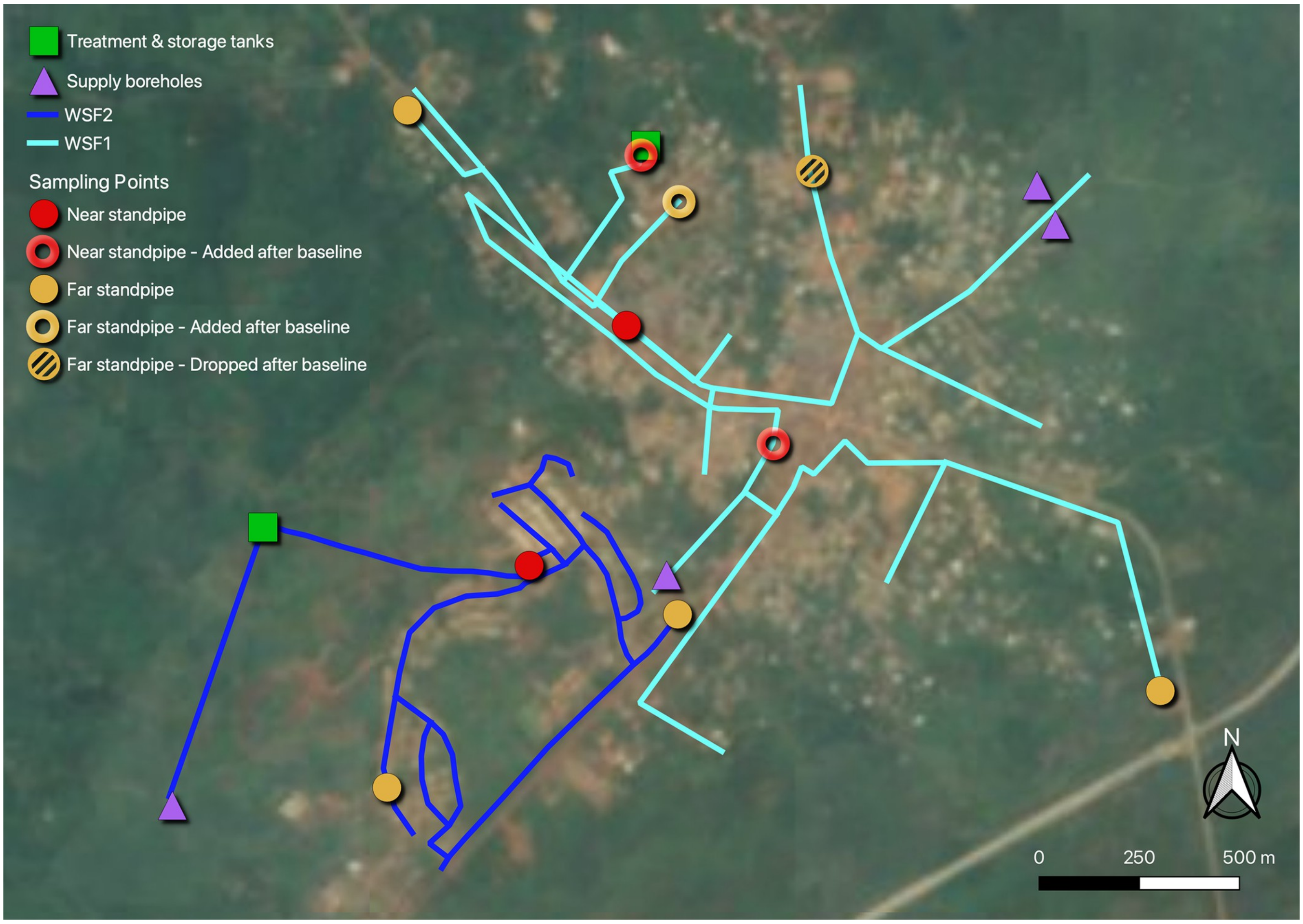

Fig 1. Map of the two water supply facilities participating in this study and their respective sampling points. Sentinel-2 cloudless - https://s2maps.eu by EOX IT Services GmbH (Contains modified Copernicus Sentinel data 2016 & 2017). Transmissions pipes between supply boreholes and the storage tank at WSF1 are not displayed.

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tasks. The other staff—one accountant and another revenue collector—were not directly involved in chlorination. Both distribution systems consisted mainly of PVC plastic pipes and, to a smaller extent, of ductile iron pipes (limited to the few meters around the storage tanks and borehole wellhead).

Study design

Our case study evaluated manual chlorination in WSF1 and passive (inline) chlorination in WSF2 (Fig 2). At WSF1, we trained the operator and the technicians to drop chlorine tablets directly into the storage tank (with no dosing apparatus). The tablets then dissolved slowly within the storage tank. At WSF2, we installed erosion inline chlorinators developed and patented by Water Mission (North Charleston, SC, USA) [40]. The function and design of Water Mission's erosion chlorinator (Model EC 75–85 AV1) are very similar to that of a T-shaped chlorinator (e.g., [41]) with the exception that water flows vertically into the chlorine chamber, hitting the tablets perpendicularly in Water Mission's device (Fig A in S1 Text) as opposed to water flowing horizontally over the chlorine tablets, as in T-shaped chlorinators. Among existing inline chlorination technologies, we chose one manufactured by Water Mission because

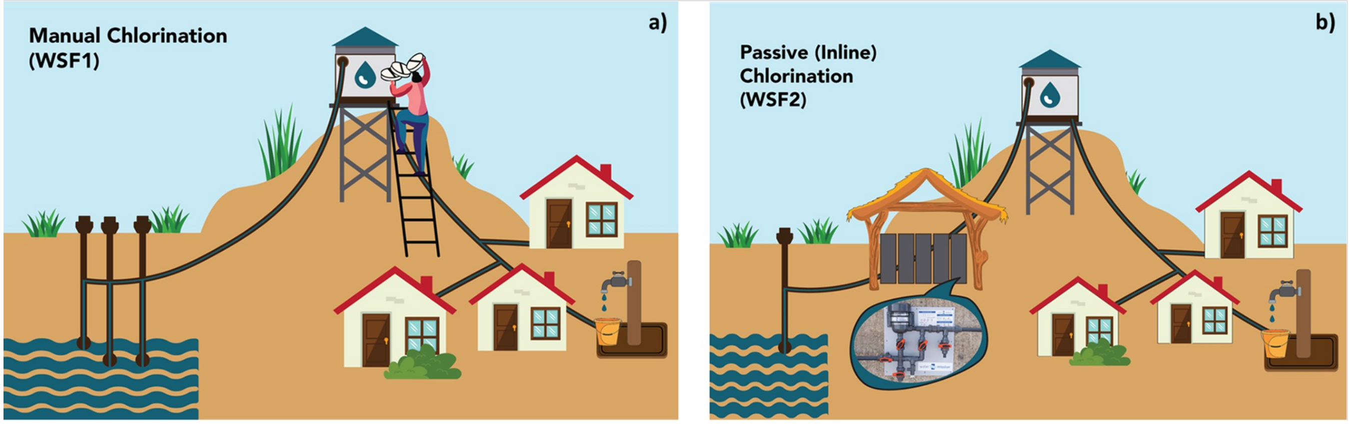

Fig 2. Illustrations of two chlorination approaches evaluated in this study: a) manual chlorination and b) passive (inline) chlorination. The photo in panel b was republished from [40] under a CC BY license with permission from Water Mission, original copyright 2021.

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Safe Water Network, a social enterprise operating in nearby communities, had experience with this technology and could provide technical support to the operator over the long term. We installed four erosion chlorinators in parallel before the storage tank. Both approaches (manual and inline chlorination) relied on the same 3-inch calcium hypochlorite tablets, which operators knew how to procure locally. We chose WSF2 to introduce passive chlorination for practical reasons: with a single borehole, WSF2 had a single flow rate, which made the chlorinators much easier to operate. At WSF1, the three boreholes working on alternating schedules led to fluctuating flow rates into the storage tank, which would have required the operator to adjust valve settings on the chlorinators frequently, increasing the risk of errors.

Before this study, both WSF1 and WSF2 occasionally performed manual chlorination, though inconsistently. Operators had received little to no training on chlorination and had no equipment to measure chlorine residuals.

The case study comprised five phases (Fig 3). First, we mapped the two distribution networks to identify adequate sampling locations (Fig 1). Second, we collected baseline data over 14 days to understand the effectiveness of the water supply facilities' prior chlorination practices. Third, we introduced the new manual chlorination protocol (at WSF1) and passive (inline) chlorinators (at WSF2). We fine-tuned them over two weeks to achieve a target concentration of 0.2–2 mg/L throughout the distribution network. For manual chlorination, fine-tuning meant identifying the adequate quantity and frequency of chlorine addition through trial and error, as described in the Supporting Information (Annex A in S1 Text). For inline chlorination, it meant identifying the adequate valve-settings, which relied on a similar trial and error process. Fourth, we conducted a three-month performance evaluation. During this period, we also collected data on the ease-of-use and costs. Fifth, five months later, we collected follow-up data for approximately one week to assess whether performance had changed over time in the researchers' absence. We collected baseline data in April 2021 (dry season), conducted the evaluation in November 2021-February 2022 (mostly dry season, though November was the end of the rainy season), and collected follow-up data in July 2022 (rainy season).

Water quality measurements

Sampling points. We sampled four standpipes at WSF1 and three at WSF2 during the baseline phase. After baseline, we added two additional sampling points at WSF1 (total of six) to better capture potential areas of water stagnation within the distribution network. We also

April 2021 — **Preparatory phase**
- Mapping of piped distribution networks and selection of sampling locations

April 2021 — **Baseline phase**
- WSF1: 95 free chlorine measurements across four sampling locations
- WSF2: 68 free chlorine measurements across three sampling locations
- Measurements once or twice daily for 14 days

May-Oct 2021 — **Start-up phase**
- Agreements with local authorities
- Procurement and installation of equipment
- Calibration of chlorine dosage

Nov 2021-Feb 2022 — **Evaluation phase**
- WSF1: 435 free chlorine measurements across six sampling locations
- WSF2: 250 free chlorine measurements across three sampling locations
- Measurements twice a day for one month, then once a day for two months
- Phone calls to water supply operators three times a week and three in-person observation visits.
- Focus group discussion with water supply operators
- Detailed cost analysis

July 2022 — **Follow-up phase**
- WSF1: 15 free chlorine measurements across two sampling locations
- WSF2: 11 free chlorine measurements across three sampling locations
- Measurements daily or every other day for approximately one week

Fig 3. Timeline of study activities.

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replaced one baseline sampling point that no longer reliably received water. Overall, our sampling points included two types of standpipes: i) standpipes located close to the storage tanks (three at WSF1 and one at WSF2) to detect potential chlorine overdoses, from now on referred to as 'near standpipes'; and ii) standpipes located in dead-ends of the distribution network or in locations where the water may stagnate (three at WSF1 and two at WSF2) to capture the lowest FCR levels in the network, from now on referred to as 'far standpipes' (Fig 1). During the follow-up phase, we sampled only a subset of standpipes at WSF1 (one near and one far) and all three standpipes at WSF2. We manually measured hydraulic distances (i.e., the approximate length of the path that water follows through the pipes) between sampling points and the storage tank with an odometer (Cablematic, Barcelona, Spain).

Sample sizes. At baseline (before introducing new chlorination methods), we collected 163 free chlorine residual measurements (95 at WSF1 and 68 at WSF2). We sampled each selected standpipe one to two times per day for fourteen consecutive days. If three successive tests at the standpipe closest to the storage tank showed undetectable FCR and if the operator reported no changes in his chlorination procedure, we only collected one sample per day; otherwise, we collected two samples per day. During the evaluation (after introducing new chlorination methods), we collected a total of 685 free chlorine residual measurements (435 at WSF1 and 250 at WSF2). We sampled each selected standpipe twice per day in the first month and once per day in the following two months, on weekdays only.

The above sampling plan was determined a priori. The resulting sample sizes allowed determining the proportion of samples with adequate free chlorine residuals with margins of error of: i) 10% at baseline and 5% during the evaluation for WSF1, ii) 12% at baseline and 6% during the evaluation for WSF2, with a 95% confidence level. The margin of error was calculated as follows:

$$Margin\ of\ Error = Z\sqrt{\frac{p(1-p)}{n}}$$

Where Z is the critical value of a normal distribution (1.96 for a 95% confidence interval), p is the population proportion with an adequate FCR level (estimated to be 50% to be conservative), and n is the sample size [42].

Sample sizes were smaller at follow-up due to resource constraints and because this phase was not the study's primary focus. We measured free chlorine residual daily or every other day for approximately one week, totaling 26 free chlorine residual measurements (15 at WSF1 and 11 at WSF2).

Water quality sampling and analysis. We flushed standpipes for one minute minimum to discard water sitting in the standpipe. We collected water directly into test vials previously rinsed with distilled water. We performed all free chlorine tests onsite using the Hach DR300 Pocket Colorimeter (Loveland, CO, USA) with the N,N-diethyl-p-phenylenediamine (DPD) method. We read chlorine concentrations one minute after adding DPD reagents. We used low-range Hach reagents (for free chlorine residuals under 2.00 mg/L). The detection limit was 0.05 mg/L.

Manganese in higher oxidation states (III to VII) can interfere with DPD measurements and cause false positive readings [43, 44]. We, therefore, sent source water samples from the two water supply facilities to the national government Water Research Institute in Accra to have them analyzed for manganese. In addition to FCR, we measured pH, conductivity, turbidity, and temperature to help interpret fluctuations in chlorine levels. We measured these parameters onsite using the Hach Pocket Pro + Multi 2 for pH, conductivity, and temperature; and the Hach 2100Q Turbidity Meter for turbidity (Loveland, CO, USA).

We recorded onsite water quality measurements in the mobile CommCare application developed by Dimagi, Inc. We processed and analyzed data (see S1 Data) in Microsoft Excel and R. We compared FCR levels between baseline, evaluation, and follow-up, between near and far taps, and between the two chlorination approaches using Wilcoxon rank sum tests. To gain insight into the factors driving FCR variability, we also analyzed whether FCR levels correlated with pH, turbidity, conductivity, temperature, distance to the storage tank, and time of day using multivariable linear regressions with standard errors clustered by standpipe.

Ease-of-use analysis. To assess the difficulty level for operators to implement the two chlorination methods, we defined eleven ease-of-use metrics organized into three categories: hardware, consumables, and operations (Table 1). We identified these metrics based on our prior experience with technology deployments in low-resource settings. We scored each metric on a three-point scale using observation and monitoring data collected throughout the evaluation via phone calls, in-person visits, and a focus group discussion. We contacted operators thrice weekly at scheduled times (e.g., Monday, Wednesday, and Friday). We asked about relevant operations since the last call (e.g., turning pumps or valves on/off, refilling chlorine supplies, etc.) using a standard script (Annex B in S1 Text). We also conducted three in-person visits during the first, sixth, and twelfth week of the evaluation to watch operators implementing the chlorination protocol (see checklist in Annex C in S1 Text). Finally, we directed a focus group discussion with the operators and managers of the two water supply facilities to collect their feedback on both chlorination approaches (see questionnaire in Annex D in S1 Text). All these data collection procedures were performed in the local language, Twi, and documented with detailed notes in English. Based on this information, two co-authors independently scored the ease-of-use metrics and reconciled any discrepancies. They used the following approach for scoring: a score of 3 indicated that they did not observe any specific issue relative to the specific metric; a score of 2 that they observed issues but that those could be resolved given the operators' capacity level; and a score of 1 that they observed problems that would be difficult to address given the operators' capacity level.

Cost analysis. We assessed two types of costs: upfront capital costs (CAPEX) and ongoing operational costs (OPEX). CAPEX included hardware, installation, and calibration expenses

Table 1. Eleven ease-of-use metrics and corresponding scores.

Metric	Definition	Manual chlorination		Passive (inline) chlorination	
		Scores	Justification	Scores	Justification
1. Hardware					
1.1 Sturdiness	Whether the hardware is robust and sturdy	NA	NA	3	
1.2 Regular maintenance	Whether the water supply facility can easily procure replacement parts locally and perform routine maintenance	NA	NA	2	The gasket that needs to be replaced annually is available in Ghana and easy to change but may be difficult to source in rural areas
1.3 Long-term replacement	Whether the water supply facility can easily replace the whole hardware at the end of its lifetime	NA	NA	2	The chlorinators have to be procured from the United States
2. Consumables					
2.1 Procurement	Whether the water supply facility can easily procure chlorine tablets locally	3		3	
2.2 Storage	Whether chlorine tablets are stored in a way that preserves them	2	Chlorine tablets sometimes stored at the top of the storage tank in direct sunlight, for convenience	3	
3. Operations					
3.1 Knowledge of procedure	Whether operators were able to perform routine chlorination tasks without technical mistakes during our shadowing visits	3		3	
3.2 Error proofness	How insensitive the chlorination process is to operators' inadvertent errors	2	Chlorination does not take place if operator is unable or forgets to perform dosing	2	There is a risk that the operator offsets the valve after daily drainage, forgets to perform daily drainage, or forgets to replenish chlorine tablets once they have all eroded.
3.3 Troubleshooting ability	Ease of troubleshooting once an error has occurred	2	If the operator overdoses the storage tank, either the storage tank or the entire network may need to be shut off and drained	3	
3.4 Operator safety	Whether routine chlorination tasks pose any risk to operators' safety	2	Risk of injury while climbing up the storage tank	3	
3.5 Operator time	Whether chlorination requires minimal time on top of the operator's routine tasks	2	Visiting the storage tank every three days is not part of the operator's routine tasks and chlorination thus requires additional travel and time	3	
3.6 Recalibration	Whether operators can easily adjust the chlorine dose in response to changes in production volumes	1	Adjusting the frequency and dose of tablet addition to the storage tank through trial and error may be beyond operators' capacity	1	Adjusting the valve position through trial and error may be beyond operators' capacity
TOTAL SCORE		17/24 (71%)		28/33 (85%)	

A score of 3 indicates that we observed no issues; a score of 2 indicates that we observed issues but that those can be resolved given the operators' capacity level; a score of 1 indicates that we observed problems that are difficult to address given the operators' capacity level. We provided a justification for every score different from 3.

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(Table A in S1 Text). OPEX included parts and consumables, ground transport for routine operations, and electricity consumption (Table A in S1 Text). We did not include staff time in OPEX because operators were already employed and paid full-time by the two water supply facilities and could fit the additional activities into their schedules. We relied on our own expenditures to estimate CAPEX, since we supported hardware installation and calibration. OPEX estimates corresponded to the following chlorine dosing and testing schedule: three tablets every three days at WSF1 (as determined during calibration), average of two tablets every three days at WSF2 (based on reported dosing during the evaluation), and two weekly chlorine tests at each facility (as recommended by the research team). We compared CAPEX and OPEX estimates with water supply facilities' average monthly revenue and expenses computed over the ten months preceding our study (January-October 2021). We applied a currency exchange rate of $1 = GHS 6.15 (January 2022, oanda.com).

Concerning energy consumption, we expected that inline chlorinators at WSF2 would cause a pressure loss and increase the energy required to pump water in the storage tank [45]. We estimated the incremental energy requirements by comparing electricity consumption per m^3 of water distributed (kWh/m^3) before and after installing the chlorinators using 19 months of data (January 2021 to July 2022). Our estimates are approximate because record periods for electricity consumption and water distribution did not match exactly. We chose this approach rather than simply reporting electricity expenses because these were not directly proportional to consumption due to fluctuating prices, making the interpretation difficult. For the cost analysis, we applied the January 2022 electricity price to our estimate of additional energy requirements (in kWh/m^3).

Ethical considerations. This study emerged at the official written request of the Asutifi North District Assembly, following a water quality testing program implemented by the Aquaya Institute, called the Water Quality Assurance Fund [46]. The research protocol was approved by the Council for Scientific and Industrial Research (CSIR) in Ghana (protocol number CSIR/IRB/AL/VOL1-036 in 2021). We obtained written consent from all study participants, including standpipe caretakers and water supply facility staff. All land accessed was public land administered by the District Assembly of Asutifi North.

Results and discussion

Chlorination performance

Comparison with baseline and between chlorination approaches. At baseline, before implementation of the new chlorination methods, FCR levels were below the WHO-recommended minimum value of 0.2 mg/L in 94% of samples at WSF1 and 84% at WSF2 (Fig 4, Table B in S1 Text). Median FCR concentrations were 0.05 mg/L at WSF1 and 0.07 mg/L at WSF2 (Table B in S1 Text). At baseline, standpipes located near the storage tank had slightly higher FCRs ($p<0.01$), though still lower than 0.2 mg/L most (70%) of the time (Table B in S1 Text). Although operators of both water supply facilities reported practicing some level of manual chlorination before our intervention, these data indicate that their dosing protocols were largely ineffective due to limited technical capacity. Most importantly, they lacked the equipment to make their own chlorine measurements, which means that they could not check whether the dose and frequency of chlorine dosing they applied were adequate.

After introducing the new chlorination methods, chlorine levels increased substantially in both piped water networks (Fig 4, Table C in S1 Text). WSF1, which performed manual chlorination, saw median FCR levels increase from 0.05 mg/L to 0.26 mg/L. Passive, inline chlorinators at WSF2 led to similar improvements, from 0.07 mg/L to 0.42 mg/L (Table C in S1 Text). These increases in FCR levels were statistically significant ($p<0.001$) overall and at every sampling point. Most samples (71% of samples at WSF1 and 86% at WSF2) were within 0.2–2.0 mg/L, the range recommended by WHO (Table C in S1 Text). The remainder were primarily between 0.1 and 0.2 mg/L. Fewer than 4% of samples were below 0.1 mg/L FCR, and none had more than 2 mg/L (Table C in S1 Text).

One of the three boreholes supplying WSF1 had manganese levels up to 0.26 mg/L. The other two boreholes supplying WSF1 and the borehole supplying WSF2 had no detectable manganese (<0.01 mg/L). Although manganese may have interfered with the DPD chlorine

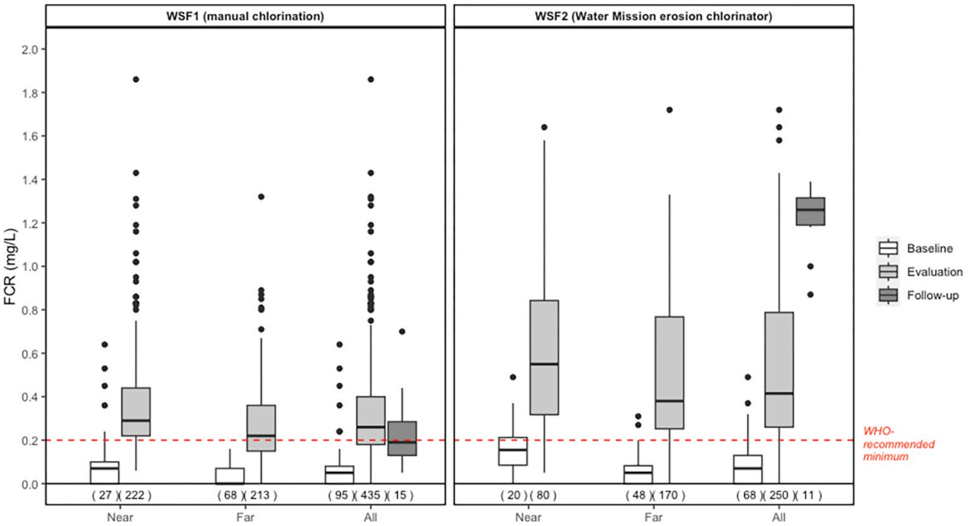

Fig 4. Boxplots of free chlorine residual (FCR) levels at WSF1 (manual chlorination) and WSF2 (Water Mission erosion chlorinator) over the 2-week baseline, the 3-month evaluation period, and during follow-up spot-checks five months later. Plots display FCR levels at "near", "far", and all sampling points. Whiskers extend to 1.5 times the interquartile range.

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measurement method at WSF1, we estimated that the interference would inflate FCR measurements by 0.1 mg/L at most [47]. As the three supply boreholes each provided water on alternating schedules, manganese levels in the network likely fluctuated over time. Therefore, we did not apply a uniform correction factor to our FCR measurements in WSF1. However, manganese interference applied to both the baseline and evaluation measurements and would not affect the above comparison substantially.

Passive (inline) chlorination with the Water Mission erosion chlorinator (WSF2) generally resulted in higher FCR levels than manual chlorination (WSF1) (Fig 4, Table C in S1 Text). The mean and median were both approximately 0.2 mg/L higher at WSF2 compared to WSF1 ($p<0.001$). However, the water supply network relying on passive chlorinators also experienced greater variability in FCR concentrations: the interquartile range was at 0.26–0.79 mg/L at WSF2 compared to the narrower 0.18–0.40 mg/L at WSF1 (Table C in S1 Text). Greater variability at WSF2 could not be explained by network size, as it covered a geographic area eight times smaller than WSF1 and water therefore travelled over shorter distances (Fig 2). Additionally, chlorine levels were comparable over time; we did not observe a temporal trend during our three-month evaluation (Fig B in S1 Text).

Prior studies evaluating other passive chlorinators in rural water supply facilities reported similar variability in FCR levels to what we observed with the Water Mission chlorinator. Henderson et al., [30] found that inline tablet erosion chlorinators (n = 5) and hypochlorinators (n = 8) installed at 13 facilities in Honduras produced free chlorine ranging from 0 to 2.2 mg/L as indicated by weekly measurements over six months. In one water supply facility with an inline tablet erosion chlorinator in Panama, Orner et al., [31] observed free chlorine levels between 0 and 0.4 mg/L in three sets of week-long daily measurements. In Nepal, Crider et al., [26] reported levels ranging from 0 to >1.6 mg/L for two tablet erosion chlorinators (Aquatabs Flo and PurAll 100) installed at six piped systems over one year. One recent study in rural Honduras documenting the performance of two erosion chlorinators (CTI 8 and Clorador ADEC) over nine years found free chlorine residuals ranging from 0 to 2.8 mg/L [27]. These studies, however, generally recorded lower proportions of samples exceeding 0.2 mg/L free chlorine (15% in Panama, 30% and 77% in Honduras, 64–80% in Nepal) compared to what we obtained with the Water Mission chlorinator in this study (86%).

Examining variability. In both water supply networks, mean FCR was 0.1 mg/L higher at standpipes located closer to the storage tank compared to standpipes situated further in the network or at dead ends (Table C in S1 Text, $p<0.05$). However, the variability of FCR levels over the entire period was larger than that (e.g., the interquartile range was approximately 0.2 mg/L wide at WSF1 and 0.5 mg/L wide at WSF2, Table C in S1 Text), largely masking this spatial trend (Fig 4). Further, FCR was not always higher at near standpipes: that was the case on only 70% of days (or 30% of days if considering differences of 0.1 mg/L or greater) in both water supply networks. Mean FCR levels at individual standpipes were not correlated with their hydraulic distance from the storage tank ($p>0.05$), though we note that our sampling locations may have been too few (six at WSF1, three at WSF2) to detect such correlations. Other studies reported that FCR levels generally decrease across a distribution network due to reactions occurring near pipe walls and within the bulk water [48–50]. However, water age is not a simple function of hydraulic distance; pressure, topography, and network configuration can cause water to stagnate in certain areas and/or fail to reach certain sections, blurring the relationship between FCR levels and distance.

The two facilities displayed different correlations between FCR levels and physicochemical characteristics. At WSF1, higher FCR levels correlated with higher conductivity ($p<0.001$) and turbidity ($p = 0.006$) (Table D in S1 Text). These correlations reflect that adding calcium hypochlorite increases conductivity, oxidizes manganese, and can favor the precipitation of calcium carbonate. Manganese oxide and calcium carbonate precipitates, both of which we occasionally observed when collecting samples at WSF1, likely caused the higher turbidity. At WSF2, higher FCR levels correlated with higher temperature ($p<0.001$), lower pH ($p = 0.05$), and shorter hydraulic distances ($p<0.001$) (Table D in S1 Text). Higher temperatures typically lead to lower pH values [51], explaining part of this trend. However, these conditions promote chlorine decay and often correlate with lower FCR levels, as opposed to higher levels, which suggests that other effects dominated in this case. Warmer temperatures likely caused faster erosion of chlorine tablets, as mentioned in the manufacturer's manual [52], leading to higher FCR concentrations. That more rapid erosion of tablets prevailed over faster chlorine decay is plausible in a small piped system such as WSF2, where water has a relatively short residence time. We could not elucidate why the two water supply facilities experienced different correlations. This may have been due to differences in the facilities' sizes, configurations, pumping schedules, physical integrity, or source water characteristics beyond those we measured. Further, in both facilities, the physicochemical characteristics tested could not account for the high variability in FCR concentrations, as indicated by R^2 values smaller than 0.1 in multivariate regressions (Table D in S1 Text).

The factors driving FCR variability in our study remain unclear. We found associations between FCR and physicochemical parameters (temperature, conductivity, turbidity, pH) and a trend of higher FCR levels closer to the storage tank, but these factors did not fully account for the variability we observed. Operators' potential inconsistent adherence to chlorination protocols may have caused some of the fluctuations. For the manual approach, operator delays in adding the next chlorine dose would result in a temporary decline in FCR concentrations. For the inline approach, forgetting to open the chlorinator's drain valve while intake pumps are off for half the day would lead water to sit in prolonged contact with chlorine tablets and could result in substantially higher chlorine loading. Other possible sources of variability in FCR levels include poor mixing and variable residence time in the storage tank [53], as well as fluctuations in dissolved organic matter content or other types of chlorine demand [54–57]. Prior work on passive chlorinators suggests that multiple conditions (flow patterns, water velocity, and number of tablets in the chlorinator) can affect chlorine concentrations, while manual chlorination may be subject to fewer influences [58, 59], possibly explaining the higher FCR variability at WSF2.

Finally, we note that spatiotemporal variability in chlorine levels is not uncommon in piped water systems, including in higher-resource settings [49, 60–62]. Difficulty in managing chlorine levels far from treatment plants is one of the reasons why some water systems switch to chloramination (reducing disinfection byproducts being the other main motivation) [63].

Insights from follow-up measurements. Follow-up measurements five months later revealed lower chlorine levels at WSF1 compared to the three-month evaluation period (mean went from 0.33 mg/L to 0.24 mg/L, $p = 0.03$) and higher levels at WSF2 (mean went from 0.53 mg/L to 1.22 mg/L, $p<0.001$) (Fig 4, Tables C-E in S1 Text). At WSF1, which implemented manual chlorination, 47% of measurements were within the WHO-recommended range of 0.2–2.0 mg/L at follow-up compared to 71% during the evaluation period (Tables C-E in S1 Text). Despite this decrease, the vast majority of measurements (93%) still had detectable chlorine (Table E in S1 Text), indicating that the operator was still performing chlorination, though less effectively. The follow-up measurements occurred in the rainy season, during which source water quality and production volumes may have changed relative to the dry season evaluation period, resulting in a need to adjust chlorine dosing. It is also possible that the operator did not maintain strict adherence to the dosing protocol and reduced the dose or frequency of chlorine addition, leading to a decline in FCR concentrations. Though sample sizes at follow-up were considerably smaller, these findings suggest that the performance of manual chlorination may decline over time, possibly as operators adhere more loosely to protocols or are unable to recalibrate chlorine dosage in the absence of external support. At WSF2, which implemented passive (inline) chlorination, 100% of free chlorine measurements were within 0.2–2.0 mg/L (Table E in S1 Text). WSF2 experienced an even larger drift in chlorine levels, though in this case, it impacted the percentage of samples in the desired range favorably. The operator of WSF2 reported increasing the frequency at which he replenished the erosion chlorinator with new chlorine tablets (i.e., not waiting until tablets were fully dissolved before replacing them) and also forgetting to drain the chlorinator when pumps were off, which likely explains the higher chlorine levels.

In both water supply facilities, follow-up measurements revealed a drift in FCR levels when the research team was no longer providing close oversight. Though in this case these drifts led to higher technical performance (i.e., a higher proportion of samples in the target FCR range) for the passive (inline) approach and to a decline in performance for the manual approach, it is important to note that they may have resulted in different outcomes in other circumstances. For example, in the case of manual chlorination, a change in pumping schedules or reductions in chlorine demand of source water could lead to higher FCR levels, even if the operator does not adhere strictly to the chlorination frequency or dose. In the case of inline chlorination, the repeated failure to open the chlorinator's drain valve when pumps are off could lead to exceeding the target FCR range and therefore lower technical performance. The primary insight from these follow-up measurements is therefore that both methods are vulnerable to the operator's lack of adherence to protocols and inability to adjust them when needed.

Ease-of-use. Passive (inline) chlorination received a higher ease-of-use score (85%, 28/33) than manual chlorination (71%, 17/24) (Table 1). More specifically, passive chlorination outperformed manual chlorination in four out of eleven metrics: storage of consumables (metric 2.2), troubleshooting ability (metric 3.3), operator safety (metric 3.4), and operator time (metric 3.5) (Table 1). Concerning consumables (metric 2.2), the operator of WSF1 sometimes stored the bag of chlorine tablets at the top of the storage tank in direct sunlight (to avoid climbing the ladder with consumables every time), which could lead to degradation. In contrast, chlorine tablets at WSF2 (implementing passive chlorination) were stored in a dark room. Rectifying an accidental chlorine overdose (metric 3.3) would be easier with the passive chlorinators, as the valves allow immediate dose adjustments. With manual chlorination, it could require shutting off the distribution system to drain an overdosed storage tank. With respect to operator safety (metric 3.4), we noted a risk of accidents when climbing up to the top of the storage tank repeatedly. At WSF1, the ladder was relatively safe, but this may not be the case in all rural water supply facilities. Beyond safety, driving to and climbing the storage tank every few days was time-consuming and sometimes conflicted with the operator's other priorities (metric 3.5).

Both chlorination approaches received the lowest score for the metric "recalibration" (3.6, Table 1). In both cases, establishing the proper chlorine dosage through trial and error required substantial technical inputs from our research team at the onset. For manual chlorination, this entailed identifying the number of chlorine tablets to add to the storage tank and the frequency (Annex A in S1 Text). For inline chlorination, it meant fine-tuning valve settings on each of the four chlorinators until they delivered the desired dose. With their current technical capacity levels, the two water supply facilities would likely struggle to recalibrate dosage if production volumes changed in the future. The inability to recalibrate dosage may have explained the drifts in chlorine levels that we observed in our follow-up measurements five months after the evaluation. Additionally, both approaches received a medium score for error proofness (metric 3.2, Table 1). For manual chlorination, this was because the operator reported forgetting to dose the storage tank on several instances or mistakenly applying a different chlorine dose than that identified during calibration (i.e., three tablets every three days). For the passive chlorinator, this was because the operator could mistakenly offset the position of a valve after daily drainage, forget to perform daily drainage, or forget to top up chlorine tablets. Overall, our evaluation revealed that "passive" (inline) chlorination was similarly prone to human error as manual chlorination. Finally, the passive chlorinator received medium scores for hardware maintenance (metric 1.2) and replacement (metric 1.3), as spare parts (e.g., gaskets) can be difficult to source in Ghana, and the main hardware must be procured overseas.

Overall, both chlorination approaches scored relatively high (>70%), and all of the issues flagged above could be resolved with external support (e.g., training, improvement of health & safety measures, strengthening of supply chains, and help with recalibrations). Prior studies similarly highlighted the importance of external support (e.g., NGO, manufacturer, technical expert) to ensure the proper operation and maintenance of passive chlorination devices [26, 27, 64, 65] or the proper implementation of manual chlorination [36]. In our study, external support was most critical at the onset to determine appropriate dosing frequencies (for manual calibration) and valve settings (for passive chlorination). Similarly, Dossegger et al., [66] found that achieving adequate chlorine dosage using five different inline technologies (chlorine dosing bucket, T-chlorinator, AkvoTur, AquatabsFlo, and MSR Venturi) was challenging. While we did not observe any chlorine supply issues during our study, other studies in Nepal, Uganda, and Haiti reported procurement issues for chlorine tablets or hardware [26, 64, 66]. After evaluating 79 passive inline chlorinators after three years in Haiti, Rayner et al. [64] found that none of the water suppliers had any chlorination tablets in stock because they did not know how to procure them. It is, therefore, essential to only implement or promote passive chlorination devices in contexts where consumables are locally available and affordable, either through market supply chains or through long-term NGO support.

Costs. Our cost estimates are presented in Table 2. CAPEX for manual chlorination was minimal (259 USD) relative to WSF1's existing expenses (averaging 2,486 USD per month before chlorination). Monthly OPEX for manual chlorination at WSF1 amounted to 96 USD,

Table 2. Estimated costs of manual and passive (inline) chlorination at the two water supply facilities, including initial capital expenditures (CAPEX) and ongoing operational expenditures (OPEX).

	WSF1 (manual chlorination)	WSF2 (passive, inline chlorination)
Average monthly revenue*	2,289 USD	1,232 USD
Average monthly expenses* (OPEX prior to chlorination)	2,486 USD	1,221 USD
Average monthly production*	5,307 m^3	2,255 m^3
CAPEX for chlorination	**259 USD**	**6,017 USD**
Chlorinators and test kits (+ shipping and taxes)	100 USD	4,433 USD
Installation/calibration	13 USD	1,577 USD
Personal protective equipment	146 USD	7 USD
Monthly OPEX for chlorination	**96 USD**	**129 USD**
Chlorine tablets	76 USD	49 USD
Reagents for chlorine tests	<1 USD	<1 USD
Transport to storage tank	11 USD	-
Transport for chlorine tests	9 USD	9 USD
Electricity**	-	70 USD
Replacement gasket	-	<1 USD
OPEX/m^3	0.02 USD/m^3	0.06 USD/m^3
% increase in OPEX	4%	11%

* Before the study: January-October 2021

** Estimated increase in electricity expenses to overcome the pressure loss introduced by passive chlorinators

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corresponding to a 4% increase in WSF1's operational expenses. CAPEX for inline chlorination amounted to 6,017 USD, equivalent to approximately five months of the facility's expenses (averaging 1,221 USD per month before chlorination). Monthly OPEX for passive chlorination at WSF2 amounted to 129 USD, an 11% increment to WSF2's total operational expenses, primarily driven by the estimated increase in electricity requirements to overcome the pressure loss caused by chlorinators. In contrast, manual chlorination caused no changes in electricity consumption at WSF1. Overall, manual chlorination was considerably more affordable than passive (inline) chlorination in the context of rural Ghana. Considering that water supply facilities in this setting were already struggling to cover their operating costs through revenue (Table 2), passive chlorination may not be financially sustainable without tariff increases and/or external subsidies.

Our OPEX estimates for Water Mission's passive (inline) chlorinators were consistent with those reported for alternative technologies in the literature: we found that inline chlorination amounted to approximately 0.06 USD per m^3, while Dossegger et al., [66] reported 0.02–1.07 USD per m^3 in Uganda across five inline technologies (chlorine dosing bucket, T-chlorinator, AkvoTur, AquatabsFlo, and MSR Venturi) and Crider et al., [26] reported 0.06–0.09 USD/m^3 in Nepal for PurAll 100 and Aquatabs Flo. In our study, energy requirements to overcome pressure loss represented half of the chlorinators' OPEX (0.03 USD/m^3). According to the manufacturer, at WSF2's flow rate (135 liters per minute), the chlorinators introduce a pressure loss of approximately six psi, resulting in a head loss of approximately four meters, which is not negligible compared to the storage height (approximately 45 meters). It is, therefore, not surprising that WSF2 experienced an estimated 15% increase in energy consumption from 0.98 kWh/m^3 before to 1.13 kWh/m^3 after the installation of chlorinators. Prior studies on facility-level passive chlorination did not report associated pressure losses or energy expenses, possibly because many of these studies took place in gravity-flow facilities with no energy expenses and no easy way to measure pressure losses (e.g., see [23]). In situations like ours where water was pumped into the storage tank, installing chlorinators upstream of the storage tank resulted in electricity costs that we encourage future studies to document. In contrast, seating chlorinators after the storage tank would result in no additional energy expenses but it may not provide optimal chlorine mixing and contact time and may reduce pressure in the distribution network.

Limitations

Our study had several limitations. First, we only evaluated one of each type of chlorination approach, and each chlorination approach at a different water supply facility. Although the two facilities had similar technical, human, and financial characteristics, they were not identical, and their differences may have confounded the comparison to some extent. However, we note that the differences in FCR variability between the two systems were the opposite of what we would have expected solely based on their characteristics: WSF1, with manual chlorination, was larger in size and supplied by three boreholes (instead of one at WSF2), both of which could introduce variability in chlorine levels. In contrast, chlorine levels were notably more variable at WSF2, which implemented passive chlorinators. Second, it is likely that our daily measurements and regular check-ins with operators influenced their adherence to routine chlorination tasks. In fact, when measuring chlorine levels again five months later, we observed drifts in chlorine concentrations (downwards in one case, upwards in the other), possibly due to looser adherence to, or changes in, protocols. Third, the small number of sampling points may have limited our ability to identify factors driving FCR variability in the network, particularly hydraulic distance. Fourth, ease-of-use metrics were all weighted equally, and their scoring was prone to the researchers' subjectivity (although based on notes from phone calls, observation visits, and a focus group discussion). Finally, the electricity costs of passive chlorination were difficult to estimate due to complex electricity pricing. Therefore, the electricity requirements reported above should be interpreted as estimates, merely indicating that passive chlorination was not energy-free in our study setting.

Conclusion

We compared the performance, ease-of-use, and costs of manual and passive (inline) chlorination at two piped water supply facilities in rural Ghana. Both chlorination approaches produced adequate free chlorine residuals (i.e., 0.2–2.0 mg/L) most of the time, though passive chlorinators produced higher levels on average and a higher percentage of samples in the target FCR range. The water supply facility with passive chlorinators also experienced the largest variability in chlorine levels, which could not be entirely explained by variations in physicochemical parameters or network size. Passive (inline) chlorination received a higher ease-of-use score than manual chlorination, but it was substantially more expensive and, therefore, less financially viable in this context. Increased electricity requirements (estimated at +15%) to overcome the pressure loss caused by the chlorinators represented half of the operational expenses for passive chlorination. For water supply facilities already struggling to recover their operating expenses through revenue, passive chlorination before the storage tank may be financially unrealistic unless they receive external funding or switch to solar power to reduce electricity expenses. Manual chlorination is more viable financially and can achieve comparable performance if dosing protocols are adhered to. Both manual and passive chlorination may be impractical at specific water supply facilities: manual chlorination requires a safe access point for the operator to drop tablets into the storage tank, which may not always exist, while passive chlorinators are ill-suited for facilities with variable flow rates. Finally, given the current limited technical capacity of water supply operators in this context, we assessed that both chlorination approaches would require external oversight to remain successful in the long run, as they both involve manual steps prone to human error and require recalibration of dosing protocols in response to changes in production volumes or source water quality.

Manual chlorination remains under-documented in the literature. Passive (inline) chlorinators adapted to low-resource contexts receive substantially more attention, but their benefits and trade-offs compared to the more rudimentary, manual approach are poorly understood. This comparative case study in rural Ghana sought to address this knowledge gap. Our findings suggest that manual chlorination is not an intrinsically inferior approach, as its ability to achieve free chlorine residual levels within the WHO-recommended range can be similar to inline chlorination under certain circumstances. Additionally, we found that operator adherence to protocols can influence the technical performance of both methods. In addition to providing one data point from a specific setting, this study proposed a multi-dimension evaluation framework (considering technical performance, ease-of-use, and costs) allowing others to replicate similar comparisons in different settings. The most appropriate approach will likely vary between settings. Replicating this comparison in other contexts would allow for a more granular understanding of the practicalities of implementing both methods.

Supporting information

S1 Text. Supplementary tables, figures, data collection tools, and protocol for manual chlorination.
(DOCX)

S1 Data. Water quality and spatiotemporal parameters. The data analysis script is available on GitHub (https://github.com/CarolineDelaire/chlorination-comparison-analysis-code.git).
(XLSX)

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Author Contributions

Conceptualization: Caroline Delaire, Ranjiv Khush, Rachel Peletz.

Data curation: Katherine Marshall, Michal Usowicz, Daniel Kwaah, Bashiru Yachori.

Formal analysis: Caroline Delaire, Katherine Marshall, Michal Usowicz, Bastian Schnabel.

Funding acquisition: Ranjiv Khush, Rachel Peletz.

Investigation: Michal Usowicz, Tom Mahin, Daniel Kwaah, Bashiru Yachori.

Methodology: Caroline Delaire, Michal Usowicz, Tom Mahin.

Project administration: Caroline Delaire, Michal Usowicz, Bashiru Yachori.

Resources: Michal Usowicz, Bashiru Yachori.

Supervision: Caroline Delaire, Rachel Peletz.

Validation: Caroline Delaire, Katherine Marshall, Tom Mahin.

Visualization: Caroline Delaire, Katherine Marshall.

Writing – original draft: Caroline Delaire, Katherine Marshall, Bastian Schnabel.

Writing – review & editing: Caroline Delaire, Katherine Marshall, Michal Usowicz, Tom Mahin, Daniel Kwaah, Bashiru Yachori, Bastian Schnabel, Ranjiv Khush, Rachel Peletz.

References

1. World Health Organization, editor. Guidelines for drinking-water quality [Internet]. 4th ed. Geneva: World Health Organization; 2011. 541 p. Available from: https://iris.who.int/handle/10665/44584
2. Cutler D, Miller G. The Role of Public Health Improvements in Health Advances: The Twentieth-Century United States. Demography. 2005 Feb 1; 42(1):1–22. https://doi.org/10.1353/dem.2005.0002 PMID: 15782893
3. Kremer M, Luby S, Maertens R, Tan B, Więcek W. Water Treatment and Child Mortality: A Meta-analysis and Cost-effectiveness Analysis [Internet]. Cambridge, MA: National Bureau of Economic Research; 2023 [cited 2023 Jan 9]. Report No.: 30835. Available from: https://www.ssrn.com/abstract=4071953
4. Branz A, Levine M, Lehmann L, Bastable A, Imran Ali S, Kadir K, et al. Chlorination of Drinking Water in Emergencies: A Review of Knowledge to Develop Recommendations for Implementation and Research Needed. Waterlines. 2017; 36(1):37.
5. Crider YS, Tsuchiya M, Mukundwa M, Ray I, Pickering AJ. Adoption of Point-of-Use Chlorination for Household Drinking Water Treatment: A Systematic Review. Environ Health Perspect. 2023 Jan; 131 (1):016001. https://doi.org/10.1289/EHP10839 PMID: 36715546
6. Luby SP, Keswick BH, Hoekstra RM, Mendoza C, Chiller TM. Difficulties in Bringing Point-of-Use Water Treatment to Scale in Rural Guatemala. Am J Trop Med Hyg. 2008 Mar 1; 78(3):382–7. PMID: 18337330
7. Luoto J, Najnin N, Mahmud M, Albert J, Islam MS, Luby S, et al. What Point-of-Use Water Treatment Products Do Consumers Use? Evidence from a Randomized Controlled Trial among the Urban Poor in Bangladesh. Herrmann JL, editor. PLoS ONE. 2011 Oct 20; 6(10):e26132. https://doi.org/10.1371/journal.pone.0026132 PMID: 22028817
8. Null C, Stewart CP, Pickering AJ, Dentz HN, Arnold BF, Arnold CD, et al. Effects of Water Quality, Sanitation, Handwashing, and Nutritional Interventions on Diarrhoea and Child Growth in Rural Kenya: A Cluster-Randomised Controlled Trial. The Lancet Global Health. 2018 Mar; 6(3):e316–29. https://doi.org/10.1016/S2214-109X(18)30005-6 PMID: 29396219
9. Rosa G, Clasen T. Estimating the Scope of Household Water Treatment in Low- and Medium-Income Countries. The American Journal of Tropical Medicine and Hygiene. 2010 Feb 1; 82(2):289–300. https://doi.org/10.4269/ajtmh.2010.09-0382 PMID: 20134007
10. Amrose S, Burt Z, Ray I. Safe Drinking Water for Low-Income Regions. Annu Rev Environ Resour. 2015 Nov 4; 40(1):203–31.
11. Ojomo E, Elliott M, Goodyear L, Forson M, Bartram J. Sustainability and scale-up of household water treatment and safe storage practices: Enablers and barriers to effective implementation. International Journal of Hygiene and Environmental Health. 2015 Nov; 218(8):704–13. https://doi.org/10.1016/j.ijheh.2015.03.002 PMID: 25865927
12. Ahuja A, Kremer M, Zwane AP. Providing Safe Water: Evidence from Randomized Evaluations. Annu Rev Resour Econ. 2010 Oct 10; 2(1):237–56.
13. Daniel D, Marks SJ, Pande S, Rietveld L. Socio-environmental drivers of sustainable adoption of household water treatment in developing countries. npj Clean Water. 2018 Dec; 1(1):12.
14. Ray I, Smith KR. Towards safe drinking water and clean cooking for all. The Lancet Global Health. 2021 Mar; 9(3):e361–5. https://doi.org/10.1016/S2214-109X(20)30476-9 PMID: 33444550
15. Sharma Waddington H, Masset E, Bick S, Cairncross S. Impact on childhood mortality of interventions to improve drinking water, sanitation, and hygiene (WASH) to households: Systematic review and meta-analysis. Thorley J, editor. PLoS Med. 2023 Apr 20; 20(4):e1004215. https://doi.org/10.1371/journal.pmed.1004215 PMID: 37079510

16. Nilsson K, Hope R, McNicholl D, Nowicki S, Charles K. Global prospects to deliver safe drinking water services for 100 million rural people by 2030. Oxford, UK: University of Oxford and RWSN; 2021 p. 68. Report No.: REACH working papaer 12.

17. Bain R, Johnston R, Khan S, Hancioglu A, Slaymaker T. Monitoring Drinking Water Quality in Nationally Representative Household Surveys in Low- and Middle-Income Countries: Cross-Sectional Analysis of 27 Multiple Indicator Cluster Surveys 2014–2020. Environ Health Perspect. 2021 Sep; 129(9):097010. https://doi.org/10.1289/EHP8459 PMID: 34546076

18. Cherukumilli K, Bain R, Chen Y, Pickering AJ. Estimating the Global Target Market for Passive Chlorination. Environ Sci Technol Lett. 2023 Jan 10; 10(1):105–10.

19. World Health Organization. A Field Guide to Improving Small Drinking-Water Supplies: Water Safety Planning for Rural Communities [Internet]. World Health Organization; 2022. Available from: https://www.who.int/europe/publications/i/item/9789289058414

20. Momba M, Obi C, Thompson P. Survey of disinfection efficiency of small drinking water treatment plants: Challenges facing small water treatment plants in South Africa. WSA [Internet]. 2009 May 23 [cited 2023 Mar 28]; 35(4). Available from: http://www.ajol.info/index.php/wsa/article/view/76795

21. World Health Organization. Disease outbreak update—Cholera—Tanzania—22 April 2016. [Internet]. WHO Regional Office for Africa. 2016 [cited 2022 Aug 2]. Available from: https://www.afro.who.int/health-topics/cholera/outbreak/22-april-2016-tanzania

22. Kumpel E, Nelson KL. Intermittent Water Supply: Prevalence, Practice, and Microbial Water Quality. Environ Sci Technol. 2016 Jan 19; 50(2):542–53. https://doi.org/10.1021/acs.est.5b03973 PMID: 26670120

23. Lindmark M, Cherukumilli K, Crider YS, Marcenac P, Lozier M, Voth-Gaeddert L, et al. Passive In-Line Chlorination for Drinking Water Disinfection: A Critical Review. Environ Sci Technol. 2022 Jul 5; 56 (13):9164–81. https://doi.org/10.1021/acs.est.1c08580 PMID: 35700262

24. Cornwell Engineering Group. The 2017 Water Utility Disinfection Survey Report. American Water Works Association; 2018 Apr.

25. Patwardhan AD. Chlorination and the use of chlorinators. Bombay, India: Indian Water Works Association; 1989. (Manual of Water Supply Practices). Report No.: M3.

26. Crider YS, Sainju S, Shrestha R, Clair-Caliot G, Schertenleib A, Kunwar BM, et al. Evaluation of System-Level, Passive Chlorination in Gravity-Fed Piped Water Systems in Rural Nepal. Environ Sci Technol [Internet]. 2022 Sep 20 [cited 2022 Oct 3]; Available from: https://doi.org/10.1021/acs.est.2c03133 PMID: 36125807

27. Lindmark M, Meier W, Calix D, Just C. Performance of Community Water Board-Managed Passive In-Line Chlorinators Supported by a Circuit Rider Program in Rural Honduras. ACS EST Water. 2023 Dec 8; 3(12):4011–9. https://doi.org/10.1021/acsestwater.3c00425 PMID: 38094914

28. Brooks YM, Tenorio-Moncada EA, Gohil N, Yu Y, Estrada-Mendez MR, Bardales G, et al. Performance Evaluation of Gravity-Fed Water Treatment Systems in Rural Honduras: Verifying Robust Reduction of Turbidity and *Escherichia Coli* During Wet and Dry Weather. Am J Trop Med Hyg. 2018 Oct 3; 99 (4):881–8.

29. Compatible Technology International (CTI). Effectiveness of CTI Water Chlorinator at controlling bacterial contamination in rural Nicaragua's drinking water [Internet]. CTI + EOS International; 2015. Available from: https://www.eosinternational.org/wp-content/uploads/2022/11/2015-nicaragua-water-quality-study.pdf

30. Henderson AK, Sack RB, Toledo E. A Comparison of Two Systems for Chlorinating Water in Rural Honduras. J HEALTH POPUL NUTR. 2005; 23(3):275–81. PMID: 16262025

31. Orner KD, Calvo A, Zhang J, Mihelcic JR. Effectiveness of in-Line Chlorination in a Developing World Gravity-Flow Water Supply. Waterlines. 2017 Apr; 36(2):167–82.

32. Taflin C. A low-cost solution to rural water disinfection. IEEE Eng Med Biol Mag. 2006 May; 25(3):36–7. PMID: 16764429

33. Yoakum BA. Improving Implementation of a Regional In-Line Chlorinator in Rural Panama Through Development of a Regionally Appropriate Field Guide [Master's Thesis]. [Tampa, FL, USA]: University of South Florida; 2013.

34. Skinner B. Chlorinating Small Water Supplies a Review of Gravity-Powered and Water-Powered Chlorinators. London: Loughborough University; 2001 p. 60. (A WELL Study 511).

35. Yates T, Allen J, Joseph ML, Lantagne D. Short-term WASH interventions in emergency response: a systematic review [Internet]. London: International Initiative for Impact Evaluation (3ie); 2017 Feb p. 291 pp. Report No.: Systematic Review 33. Available from: https://www.3ieimpact.org/sites/default/files/2019-01/sr33-wash-interventions_0.pdf

36. Bänziger C, Schertenleib A, Kunwar BM, Bhatta MR, Marks SJ. Assessing Microbial Water Quality, Users' Perceptions and System Functionality Following a Combined Water Safety Intervention in Rural Nepal. Frontiers in Water. 2022 Feb 15; 3:750802.

37. Aquaya Institute. Water Supply Landscape in Asutifi North, Ghana. Aquaya Institute; 2019.

38. Asutifi North District Assembly. Water Sanitation and Hygiene (WASH) Masterplan. Kenyasi—Ghana; 2018.

39. Press-Williams J, Delaire C, Yachori B, Karon A, Paletz R, Khush R. Water Quality Testing Assuance Fund: Lessons Learned [Internet]. Aquaya Institute; 2021 May [cited 2022 Apr 29] p. 11. (Lesson Learned). Available from: https://aquaya.org/wp-content/uploads/2021_Water-Quality-Assurance-Fund-Lessons-Learned-_ResearchBrief.pdf

40. Water Mission. Erosion Chlorinator. Water Mission; https://watermission.org/wp-content/uploads/2021/03/Erosion-Chlorinator_Flyer_Final.pdf

41. Jacob F, Taflin C. The CTI 8 Chlorinator: an instrument for disenfecting drinking water in gravity fed systems. Manual of information, operation & maintenance. Minnesota, USA: Compatible Technology International; p. 24.

42. Select Statistical Services. Population Proportion–Sample Size [Internet]. 2023 [cited 2021 Mar 10]. Available from: https://select-statistics.co.uk/calculators/sample-size-calculator-population-proportion/

43. Engelhardt TL, Malkov VB. Chlorination, Chloramination and Chlorine Measurement. Loveland, Colorado, USA: Hach Company; 2015. Report No.: DOC180.53.20183.

44. Spon R. Do You Really Have a Free Chlorine Residual? Opflow. 2008 Jun; 34(6):24–7.

45. Water Mission. Erosion Chlorinator Installation and Operation Manual: Item 020030 and Item 011117. Water Mission; 2022 Mar.

46. REAL-Water. Implementation Manual: Water Quality Assurance Fund. United States Agency for International Development (USAID) Rural Evidence and Learning for Water Project.; 2023.

47. Li P, Furuta T, Kobayashi T. Micro-particles as interfering substances in colorimetric residual chlorine measurement. Ecotoxicology and Environmental Safety. 2021 Jan; 207:111279. https://doi.org/10.1016/j.ecoenv.2020.111279 PMID: 32920317

48. Al-Jasser AO. Chlorine decay in drinking-water transmission and distribution systems: Pipe service age effect. Water Research. 2007 Jan; 41(2):387–96. https://doi.org/10.1016/j.watres.2006.08.032 PMID: 17140619

49. Clark RM, Goodrich JA, Wymer LJ. Effect of the Distribution System on Drinking Water Quality. J Water SRT-Aqua. 1993; 42(1):30–8.

50. Nono D, Odirile PT, Basupi I, Parida BP. Assessment of probable causes of chlorine decay in water distribution systems of Gaborone city, Botswana. WSA [Internet]. 2019 Apr 30 [cited 2023 Mar 28];45(2 April). Available from: https://www.watersa.net/article/view/6652

51. World Health Organization. pH in Drinking-water: Revised background document for development of WHO Guidelines for Drinking-water Quality. 2007. Report No.: WHO/SDE/WSH/07.01/1.

52. Water Mission. Potable Water Chlorinator: Assembly and Operation Manual. Charleston, USA: Water Mission; 2017 Mar p. 24. Report No.: 020007.

53. Araya A, Sánchez LD. Residual chlorine behavior in a distribution network of a small water supply system. Journal of Water, Sanitation and Hygiene for Development. 2018 Jun 1; 8(2):349–58.

54. Fisher I, Kastl G, Sathasivan A, Jegatheesan V. Suitability of Chlorine Bulk Decay Models for Planning and Management of Water Distribution Systems. Critical Reviews in Environmental Science and Technology. 2011 Oct 15; 41(20):1843–82.

55. Islam R, Hossain M. Estimation of short-term chlorine demand and its correlation with available iron in drinking water. Int J Chem Stud. 2014; 2(4):55–9.

56. Warton B, Heitz A, Joll C, Kagi R. A new method for calculation of the chlorine demand of natural and treated waters. Water Research. 2006 Aug; 40(15):2877–84. https://doi.org/10.1016/j.watres.2006.05.020 PMID: 16831456

57. Yee LF, Abdullah P, Ata S, Ishak B. Dissolved Organic Matter and its Impact on the chlorine demand of treated water. The Malaysian Journal of Analytical Sciences. 2006;10(2).

58. Martin AC. Evaluation of Tablet Chlorinator for a Rural Haitian Water Treatment System—Computational Modeling and Laboratory Testing [Master's Thesis]. Clemson University; 2020.

59. Voth-Gaeddert LE. Inline Chlorinator for Potable Water Systems in Low-Resource Settings. J Environ Eng. 2021; 147(7):4.

60. Abokifa AA, Yang YJ, Lo CS, Biswas P. Water quality modeling in the dead end sections of drinking water distribution networks. Water Research. 2016 Feb; 89:107–17. https://doi.org/10.1016/j.watres.2015.11.025 PMID: 26641015

61. Ardila A, Rodriguez MJ, Pelletier G. Spatiotemporal optimization of water quality degradation monitoring in water distribution systems supplied by surface sources: A chronological and critical review. Journal of Environmental Management. 2023 Jul; 337:117734. https://doi.org/10.1016/j.jenvman.2023.117734 PMID: 36996548

62. Clark RM, Grayman WM, Goodrich JA, Deininger RA, Skov K. Measuring and Modeling Chlorine Propagation in Water Distribution Systems. J Water Resour Plann Manage. 1994 Nov; 120(6):871–87.

63. Centers for Disease Control and Prevention (CDC). Water Disinfection with Chlorine and Chloramine [Internet]. 2020. Available from: https://www.cdc.gov/healthywater/drinking/public/water_disinfection.html#print

64. Rayner J, Yates T, Joseph M, Lantagne D. Sustained Effectiveness of Automatic Chlorinators Installed in Community-Scale Water Distribution Systems During an Emergency Recovery Project in Haiti. J Water Sanit Hyg Dev. 2016 Dec 1; 6(4):602–12.

65. Laauwen M, Nowicki S. Reinforcing Feedbacks for Sustainable Implementation of Rural Drinking-Water Treatment Technology. ACS EST Water. 2024 Apr 12; 4(4):1763–74. https://doi.org/10.1021/acsestwater.3c00779 PMID: 38633363

66. Dossegger L, Tournefier A, Germann L, Gartner N, Huonder T, Wanyama K, et al. Assessment of low-cost, non-electrically powered chlorination devices for gravity-driven membrane water kiosks in eastern Uganda. Waterlines. 2021; 40(2):15.