Turbidity and chlorine demand reduction using locally available physical water clarification mechanisms before household chlorination in developing countries

Nadine Kotlarz, Daniele Lantagne, Kelsey Preston and Kristen Jellison

ABSTRACT

Over 1.1 billion people in the world lack access to improved drinking water. Diarrhoeal and other waterborne diseases cause an estimated 1.9 million deaths per year. The Safe Water System (SWS) is a proven household water treatment intervention that reduces diarrhoeal disease incidence among users in developing countries. Turbid waters pose a particular challenge to implementation of SWS programmes; although research shows that a 3.75 mg l^{-1} sodium hypochlorite dose effectively treats turbid waters, users sometimes object to the strong chlorine taste and prefer to drink water that is more aesthetically pleasing. This study investigated the efficacy of three locally available water clarification mechanisms—cloth filtration, settling/decanting and sand filtration—to reduce turbidity and chlorine demand at turbidities of 10, 30, 70, 100 and 300 NTU. All three mechanisms reduced turbidity (cloth filtration −1–60%, settling/decanting 78–88% and sand filtration 57–99%). Sand filtration ($P = 0.002$) and settling/decanting ($P = 0.004$), but not cloth filtration ($P = 0.30$), were effective at reducing chlorine demand compared with controls. Recommendations for implementing organizations based on these results are discussed.

Key words | developing countries, drinking water, household water treatment, point-of-use chlorination, safe water system, water clarification

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INTRODUCTION

Point-of-use water treatment and the safe water system

An estimated 1.1 billion people lack access to improved water supplies and 2.6 billion people are without adequate sanitation (WHO/UNICEF 2004). The health consequences of inadequate water and sanitation services include an estimated 4 billion cases of diarrhoea and an estimated 1.6 million deaths each year, mostly among young children in developing countries (WHO 2002, 2004). In addition, waterborne diarrhoeal diseases lead to decreased food intake and nutrient absorption, malnutrition, reduced resistance to infection (Baqui *et al.* 1993), and impaired physical growth and cognitive development (Guerrant *et al.* 1999).

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Chlorination was first used for disinfection of public water supplies in the early 1900s and is one factor that contributed to dramatic reductions in waterborne disease in cities in the United States (Cutler & Miller 2005). Although small trials of point-of-use chlorination had been implemented in the past (Mintz *et al.* 1995), larger-scale trials began in the 1990s as part of the Pan American Health Organization (PAHO) and the US Centers for Disease Control and Prevention (CDC) response to epidemic cholera in Latin America (Tauxe *et al.* 1995). The Safe Water System (SWS) strategy devised by CDC and PAHO includes three elements: water treatment with dilute (generally 1.25%) sodium hypochlorite at the point-of-use, storage of chlorinated water in a safe container and behaviour change communication to improve hygiene and water and food handling practices. The sodium hypochlorite solution is packaged in a bottle with directions instructing users to add one full bottle cap (generally 3 ml) of the solution to clear water, or 2 caps to turbid water, in a standard sized (generally 20 l) storage container, agitate, and wait 30 minutes before drinking. Source waters treated with one or two full bottle cap(s) receive a dosage of 1.875 or 3.75 mg l^{-1} sodium hypochlorite, respectively. In five randomized, controlled trials, the SWS has resulted in reductions in diarrhoeal disease incidence ranging from 26 to 84% (Semenza *et al.* 1998; Quick *et al.* 1999, 2002; Luby *et al.* 2004; Crump *et al.* 2005; Chiller *et al.* 2006).

This well-documented reduction of diarrhoeal disease incidence among SWS users has encouraged non-governmental organizations (NGOs) and governments to broadly disseminate the programme. National, regional and local SWS projects have been implemented with NGO and government partners in over 30 countries since 1998. As access to the SWS has expanded in developing countries, where many water sources contain suspended organic material, questions have been raised about (i) the necessary sodium hypochlorite dosage for turbid waters; (ii) potential risks from trihalomethanes from direct chlorination of turbid water; (iii) user acceptability of treating turbid waters with sodium hypochlorite solution; and (iv) potential locally appropriate mitigation strategies to reduce turbidity and chlorine demand before chlorination.

Necessary sodium hypochlorite dosage in turbid waters

The CDC SWS programme aims for a free chlorine residual of less than 2.0 mg l^{-1} at 1 hour after sodium hypochlorite addition and greater than 0.2 mg l^{-1} at 24 hours after sodium hypochlorite addition. This free chlorine residual range was selected because it meets WHO and USEPA guidelines for free chlorine in drinking water (WHO 2004; USEPA 2006), because of user taste acceptability concerns above 2.0 mg l^{-1} free chlorine (Lantagne 2008), and because less than 0.2 mg l^{-1} free chlorine may not adequately protect water from recontamination.

Lantagne (2008) documented free chlorine residual levels for 24 hours after treatment with different sodium hypochlorite doses in 106 drinking water sources from 13 countries. Results were consistent among non-chlorinated source waters of turbidity less than 10 NTU or from a protected source, with 71 (86.6%) of 82 samples treated with 1.875 mg l^{-1} sodium hypochlorite meeting the CDC free chlorine residual criteria. The results of dosage testing in the 14 non-chlorinated waters from unimproved sources with turbidity between 10 and 100 NTU were not as consistent: only 5 (41.7%) of the 12 sources analysed at the 3.75 mg l^{-1} dosage had free chlorine residuals that met the criteria (Lantagne 2008). Direct chlorination was not recommended for waters over 100 NTU. Further research on dosage and chlorine demand reduction in turbid waters was recommended.

Trihalomethane formation in direct chlorination of turbid water

Pre-treatment of water using cloth filtration and settling/decanting before chlorination have been investigated as potential trihalomethane (THM) mitigation strategies. The study documented that addition of sodium hypochlorite to six source waters of turbidity 4.23–305 NTU did not lead to formation of THM levels that exceeded WHO guideline values for any of the four individual THMs or the additive total THM (TTHM) ratio guideline value (Lantagne *et al.* 2008). Neither pre-treatment procedure was effective at reducing TTHM concentrations in chlorinated water compared with chlorination-only controls. These are not unexpected results; as THM precursor compounds have been identified as primarily organic carbon particles smaller than 0.45 μm in size (Chow *et al.* 2005), it is unlikely that gross filtration mechanisms would remove such small particles. Filtration through sand was not investigated as a potential THM mitigation strategy. Further investigation of the efficacy of using locally available water clarification methods for pre-treatment was recommended.

User acceptability of turbid waters treated with sodium hypochlorite solution

Chlorine taste and odour are key concerns for user acceptability in SWS programmes. Many taste and odour concerns can be addressed by using dosage regimes that prevent overdosing (POUZN 2007). Focus groups on taste testing have found that the majority of SWS users are comfortable drinking water with a free chlorine residual of up to 2.0 mg l^{-1}; however, there is significant regional variation in the acceptable maximum residual (Lantagne 2008). The higher sodium hypochlorite dosages necessary to ensure maintenance of chlorine residual in turbid waters exacerbate the taste and odour concerns.

In addition, there is a commonly held perception that clear water is equivalent to clean, potable water (POUZN 2007). In the Population Services International (PSI) India SWS project, results from the baseline survey indicated that the majority of households agreed with the statement ‘water that looks clear is safe to drink’.

Locally available physical water clarification options

Several practical and inexpensive methods for water clarification are available to populations in developing countries who are targeted by point-of-use water treatment intervention programmes such as the SWS. This study investigated three locally available and commonly utilized physical water clarification methods–cloth filtration, settling/decanting and sand filtration–in laboratory-controlled circumstances to determine whether use of these mechanisms reduced turbidity and chlorine demand before chlorination. Investigations of chemical water clarification methods, such as the use of alum and moringa seeds, are ongoing and data is not considered herein. Even though two of these physical water clarification methods have been shown not to reduce THM formation potential, the reduction of turbidity and chlorine demand before chlorination can provide important sensory benefits that may enhance consumer acceptance of treated water and SWS programme implementation. Reduction of turbidity would cause a visual improvement in the treated water that could help encourage correct and consistent use among SWS users. Reduction of chlorine demand would allow the use of a lower dosage of sodium hypochlorite, which could increase taste acceptability and reduce the cost of treatment.

METHODS

Setting

This research was conducted in the laboratories of the Department of Civil and Environmental Engineering at Lehigh University in Bethlehem, Pennsylvania.

Study design

We analysed turbidity and chlorine demand reduction compared with controls using three different locally available water clarification options–cloth filtration, settling/decanting and sand filtration–before chlorination with a 1.875 and 3.75 mg l^{-1} dose of sodium hypochlorite in waters with turbidity of 10, 30, 70, 100 and 300 NTU (Table 1). Note that cloth filtration was tested on waters with turbidity of 10, 30, 100 and 300 NTU only.

For settling/decanting and sand filtration, fifteen 20-litre buckets of turbid water were prepared; for cloth filtration, twelve 20-l buckets were prepared (Table 1). Fresh water and river-bottom sediment obtained from Saucon Creek in Bethlehem, Pennsylvania, was mixed with purified laboratory water (Millipore Corporation,

Table 1 | Studies completed for each of three water clarification mechanisms (note buckets 7–9 were deleted for cloth filtration)

Bucket (number)	Turbidity (NTU)	Clarified	Sodium hypochlorite dosage (mg l^{-1})
1	10	Clarified	1.875
2	10	Clarified	3.75
3	10	Control	1.875
4	30	Clarified	1.875
5	30	Clarified	3.75
6	30	Control	1.875
7	70	Clarified	1.875
8	70	Clarified	3.75
9	70	Control	1.875
10	100	Clarified	1.875
11	100	Clarified	3.75
12	100	Control	1.875
13	300	Clarified	1.875
14	300	Clarified	3.75
15	300	Control	1.875

Billerica, Massachusetts) to produce water with turbidity of 10, 30, 70, 100 and 300 NTU. Turbidity was measured with a Hach (Lovely, Colorado) 2100P portable turbidimeter. Chemical characterization of the raw water and sediments were not completed because such testing is unavailable in developing countries settings and turbidity is utilized as the water quality indicator to determine chlorine dosage (Lantagne 2008). Three buckets were prepared at each of the five turbidity levels, and the water clarification mechanism was completed on two of each set of three buckets. The third bucket in each turbidity level served as a control.

For the cloth filtration testing, turbid water was poured through the cloth into a clean bucket. Locally available, tightly woven cotton cloth used for household cleaning purposes, obtained in western Kenya, was used in these tests. The cloth was rinsed with deionized water and dried between usages, although pore-size of the cloth would decrease with age and use (Colwell *et al.* 2003). Water with a turbidity of 10 and 30 NTU was filtered through two layers of the cloth. To prevent clogging, water with a turbidity of 100 and 300 NTU was filtered through one layer of the cloth. For the settling/decanting testing, the 20 litres of turbid water were allowed to stand for 24 hours. Fifteen litres of the supernatant water were then decanted into a clean bucket, taking care not to resuspend any of the settled solids.

For the sand filtration testing, a sand filter was made in a 20-litre bucket (Figure 1). The sand filter comprised a 4-inch (10 cm) layer of gravel beneath a 9-inch (23 cm) layer of sand; a layer of cotton cloth, sandwiched between two layers of wire mesh, separated the sand and gravel layers. The sand used was Pavestone Play Sand #55141, and the gravel was Vigoro Decorative Stone, All Purpose, #00017. Sieve testing on the sand found a D_{10} of 0.24 mm and a uniformity coefficient of 2.42. Both parameters are within recommended ranges for slow sand filtration (www.biosandfilter.org). Sand and gravel were chosen to be representative of what might be available to consumers in developing countries, and were rinsed with deionized water prior to usage to remove any contamination until the effluent turbidity was between 1 and 4 NTU. Approximately 1.5 inches (3.8 cm) of head space was available above the sand layer, and a spigot was installed approximately

Figure 1 | Sand filter design.

2 inches (5 cm) from the bottom of the bucket. A PVC cap, surrounded by one layer of cloth, was attached to the end of the spigot inside the bucket. Gravel and sand were washed before filter construction; rinse water for: (i) wire mesh, cloth and gravel; and (ii) sand was measured at 3 and 10 NTU, respectively. It is of note that the sand filters used in this study were simply sand filters. They were not 'biosand filters', a specific household water treatment filter that includes a biologically active 'schmutzdecke' layer to assist in removal of microbiological contaminants.

After the water was clarified, a chlorine dosage of $1.875\ mg\,l^{-1}$ and $3.75\ mg\,l^{-1}$, respectively, was added to one of the two buckets of clarified water for each turbidity value. As a control, a chlorine dosage of $1.875\ mg\,l^{-1}$ was directly added to the non-clarified turbid water in the third bucket for each turbidity value. Chlorine was added to each bucket as a 1.25% sodium hypochlorite solution (Clorox® bleach diluted in Millipore (purified) water, stabilized to pH 11.9 with sodium hydroxide to prevent degradation). Sodium hypochlorite solution was made fresh every month and chlorine concentrations were measured using Hach (Loveland, Colorado) iodimetric titration method 8209 for high-range total chlorine. The pH of the turbid water sample was approximately neutral, and thus appropriate for direct treatment with sodium hypochlorite solution.

Water testing procedures

Each water sample was analysed for turbidity before and after clarification with a Lamotte 2020 turbidimeter (Chestertown, Maryland) calibrated weekly with non-expired stock calibration solutions.

Free chlorine was measured at 1, 2, 4, 8 and 24 hours after the addition of sodium hypochlorite using a Lamotte 1200 single wavelength chlorine colorimeter and DPD-1 and DPD-3 tablets (Chestertown, Maryland). The meter was calibrated daily using non-expired stock calibration solutions at 0, 0.1, 1.0 and 2.65 $mg\,l^{-1}$ free chlorine.

Data analysis

All data was entered into Microsoft Excel and analysed using the Analysis ToolPak for statistical significance using paired t-tests for means.

RESULTS

Turbidity reduction

All turbidity samples were tested in triplicate to ensure accuracy; results were averaged for reporting purposes. The average percentage error of these samples was 2.4%, with a minimum of 0.0%, a maximum of 7.9% and a standard deviation of 1.7%.

The actual laboratory initial turbidity values were, on average, within 4.7% of the intended turbidity values of 10, 30, 70, 100 and 300 NTU. The minimum error from intended turbidity was 0.1%, the maximum error was 18.3% and the standard deviation was 4.5%. One outlier in the control buckets was discarded from this analysis.

After cloth filtration, turbidity was reduced by a minimum of −0.8% at initial turbidity of 10 NTU to a maximum of 59.8% at initial turbidity of 300 NTU (Table 2). Turbidity was reduced by a consistent 78.4–87.5% in all samples settled and decanted. After sand filtration, turbidity was reduced by a minimum of 57.0% at 10 NTU to a maximum of 98.5% at initial turbidity of 300 NTU.

The average percentage reduction in turbidity of the two buckets at each initial turbidity value using the three different clarification mechanisms is graphically displayed in Figure 2.

Chlorine demand reduction

After clarification, chlorine dosages of 1.875 and 3.75 $mg\,l^{-1}$ were added to the two buckets that had been clarified from each initial turbidity value. A chlorine dosage of 1.875 $mg\,l^{-1}$ was directly added to non-clarified water to serve as the control. A single control was deemed sufficient for each test, and as such a 3.75 $mg\,l^{-1}$ control was not conducted. Free chlorine residual was monitored for 24 hours after chlorine addition in each bucket. A representative example result from one of the individual tests, showing free chlorine decay over time in the 1.875 $mg\,l^{-1}$ dose control, the 1.875 $mg\,l^{-1}$ dose after sand filtration, and the 3.75 $mg\,l^{-1}$ dose after sand filtration at 100 NTU initial

Table 2 | Turbidity reduction using locally available water clarification mechanisms

	Average post-clarification turbidity and percentage reduction (NTU, %)									
Initial turbidity (NTU)	**10**		**30**		**70**		**100**		**300**	
Bucket number*	**1**	**2**	**4**	**5**	**7**	**8**	**10**	**11**	**13**	**14**
Cloth filtration	10.7	10.2	25.4	22.4	–	–	48.1	53.6	125.0	161.0
	−0.8%	13.4%	16.1%	28.4%			52.7%	47.5%	59.8%	46.8%
Settling/decanting	2.2	1.9	4.1	4.1	8.8	9.3	20.7	23.8	49.5	51.5
	80.4%	80.1%	87.5%	86.2%	87.5%	87.5%	79.4%	78.4%	83.3%	82.5%
Sand filtration	3.6	4.8	2.5	3.5	2.9	2.5	2.6	3.7	4.5	7.0
	67.9%	57.0%	92.0%	88.0%	95.9%	86.5%	97.5%	96.2%	98.5%	97.7%

*Bucket numbers 3, 6, 9, 12 and 15 were control buckets with no clarification method completed.

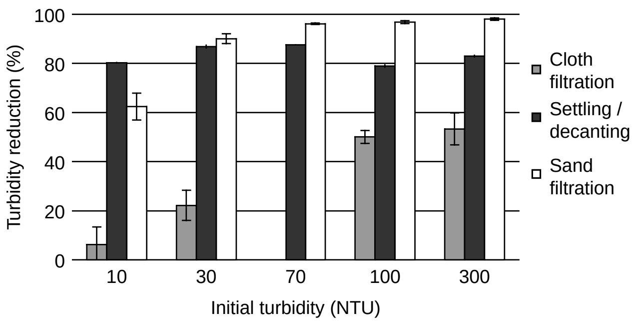

Figure 2 | Average turbidity reduction using three clarification methods (cloth filtration not tested at 70 NTU).

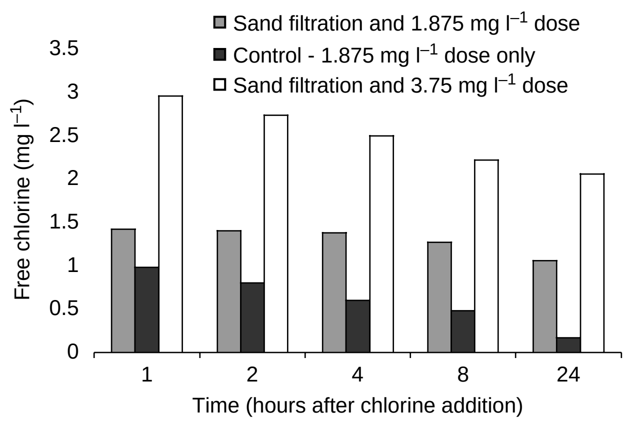

Figure 3 | Example free chlorine residual decay over time in sand filter and control water with initial turbidity of 100 NTU.

turbidity, is displayed in Figure 3. As can be seen, free chlorine residuals in both the control and the sand filtered water decayed over time.

Figure 3 is consistent with results seen in all individual tests. Thus, for further analysis in this paper, only the results from the 1.875 mg l^{-1} dosages will be used to compare control versus clarification method results. In addition, only the free chlorine residual results at 24 hours after chlorine addition will be depicted, because the goal of the CDC Safe Water System programme is to maintain a maximum of 2.0 mg l^{-1} free chlorine residual 1 hour after chlorine addition and a minimum of 0.2 mg l^{-1} free chlorine residual 24 hours after chlorine addition. Because only the 1.875 mg l^{-1} dosage will be used for further analysis, it is not possible for greater than 2.0 mg l^{-1} of free chlorine residual to be present at any point. For the complete data set, please contact the authors.

Cloth filtration

Across all initial turbidity values, free chlorine residual was not maintained ($P = 0.30$) at a higher level in water clarified with cloth filtration before chlorination than in water that was not clarified (Table 3, Figure 4).

Settling/decanting

Across all initial turbidity values, free chlorine residual was maintained at a significantly ($P = 0.005$) higher level in waters clarified with settling/decanting before chlorination than in unclarified water (Figure 4). Compared with controls, the increase in free chlorine residual level in settled/decanted water 24 hours after chlorination ranged from 0.23 mg l^{-1} at 10 NTU to 0.85 mg l^{-1} at 300 NTU (Table 3).

Sand filtration

Free chlorine residual was maintained at a significantly ($P = 0.002$) higher level in waters clarified with sand filtration before chlorination than in unclarified water across all initial turbidity values (Figure 4). Compared with controls, the increase in free chlorine residual level in sand filtered water at 24 hours after chlorination ranged from 0.41 mg l^{-1} at 10 NTU to 1.11 mg l^{-1} at 300 NTU (Table 3).

DISCUSSION

As can be seen in Figure 2, all three clarification mechanisms were effective at reducing turbidity. Sand filtration was the most effective, removing 57.0 to 98.5% of the turbidity at initial turbidity values of 10 and 300 NTU, respectively. Cloth filtration was the least effective, removing −0.8 to 59.8% of the turbidity at initial turbidity values of 10 and 300 NTU, respectively. Settling/decanting removed a consistent average of 78.4–87.5% of turbidity at all initial turbidity values. Both sand filtration and cloth filtration had increased removal efficiencies at higher initial turbidity loadings, while settling and decanting showed consistent removal efficiency across all initial turbidity values.

Table 3 | Effectiveness of three pre-chlorination clarification options at maintaining chlorine residual at 24 hours after chlorination

	Free chlorine residual ($mg\,l^{-1}$) 24 hours after chlorination									
Initial turbidity (NTU)	10		30		70		100		300	
	Control	Clarified	Control	Clarified	Control	Clarified	Control	Clarified	Control	Clarified
Cloth filtration	1.31	1.39	0.92	0.95	–	–	0.52	0.47	0.07	0.24
Settling/decanting	1.18	1.41	0.81	1.37	0.73	1.32	0.75	1.37	0.29	1.14
Sand filtration	0.95	1.36	0.30	1.17	0.16	1.24	0.17	1.06	0.02	1.13

Sand filtration and settling/decanting before chlorination were both effective at reducing chlorine demand and maintaining free chlorine residual in stored water across all initial turbidity levels from 10 to 300 NTU, with only slight free chlorine decay seen over time even at high initial turbidity levels. Cloth filtration was not an effective means of reducing chlorine demand and maintaining free chlorine residual in stored waters.

Analysis of the free chlorine residual results over 24 hours in the chlorination-alone controls provides valuable insight into variation of chlorine demand in waters with similar turbidity. As seen in Table 3, the free chlorine residual level at 24 hours in the unclarified control water varied from 0.95 to 1.31 $mg\,l^{-1}$ in waters of 10 NTU. At 300 NTU, this variation was 0.02–0.29 $mg\,l^{-1}$. This variation highlights that similar turbidities do not necessarily indicate similar chlorine demand. This result is consistent with the chlorine demand variation seen at turbidities of 10–100 NTU in other studies (Lantagne 2008). The use of settling/decanting or sand filtration not only decreases turbidity, but also removes some of the compounds exerting chlorine demand and leads to maintenance of more consistent free chlorine residual levels over time.

A chlorine dosage of 1.875 $mg\,l^{-1}$ provides a maximum concentration-time (CT) factor of 56.25 $mg\text{-}min\,l^{-1}$ 30 minutes after chlorination. A CT factor of 56.25 is sufficient to inactivate most bacteria, viruses and some protozoa that cause waterborne diseases, although inactivation effectiveness is also dependent on pH and temperature (CDC 2008). Maintaining free chlorine residual levels over time increases the effectiveness of the sodium hypochlorite at inactivating any biological contaminants that may be introduced to the water during storage.

Recommendations for implementing organizations

Organizations considering point-of-use chlorination programmes in areas with turbid water are faced with the difficult decision of how to address turbidity in their water treatment programme. Options to address turbidity, include: 1) no pre-treatment (i.e. direct chlorination of turbid water with a double dose (3.75 $mg\,l^{-1}$) of hypochlorite solution); 2) pre-treatment of turbid water with a physical clarification mechanism, such as cloth filtration, settling/decanting, sand filtration, or a combination of the above before chlorination; 3) pre-treatment of turbid water with a chemical coagulation step, such as alum or moringa seeds before chlorination; and 4) treatment of turbid water with an alternative household water treatment product, such as a ceramic or biosand filter, or the Procter & Gamble product PuR™.

The first option is to recommend direct chlorination of turbid waters. Previous results have shown that free chlorine residual can be maintained with direct chlorination of turbid water from 10 to 100 NTU at a sodium hypochlorite dosage of 3.75 $mg\,l^{-1}$ (Lantagne 2008); however, at higher turbidities direct chlorination may be less effective, and users may object to the lack of visual improvement during treatment, and the taste and odour of the treated water.

The second option is to recommend the use of physical clarification methods. The research presented herein details the effectiveness of settling/decanting and sand filtration before chlorination in reducing turbidity and maintaining free chlorine residual over time. A single 1.875 $mg\,l^{-1}$ dosage of sodium hypochlorite can be added after the clarification step to ensure adequate disinfection and maintenance of free chlorine residual in storage. Although cloth filtration reduced turbidity somewhat, it did not effectively help to maintain the free chlorine residual over time. Thus, although cloth filtration can be recommended to

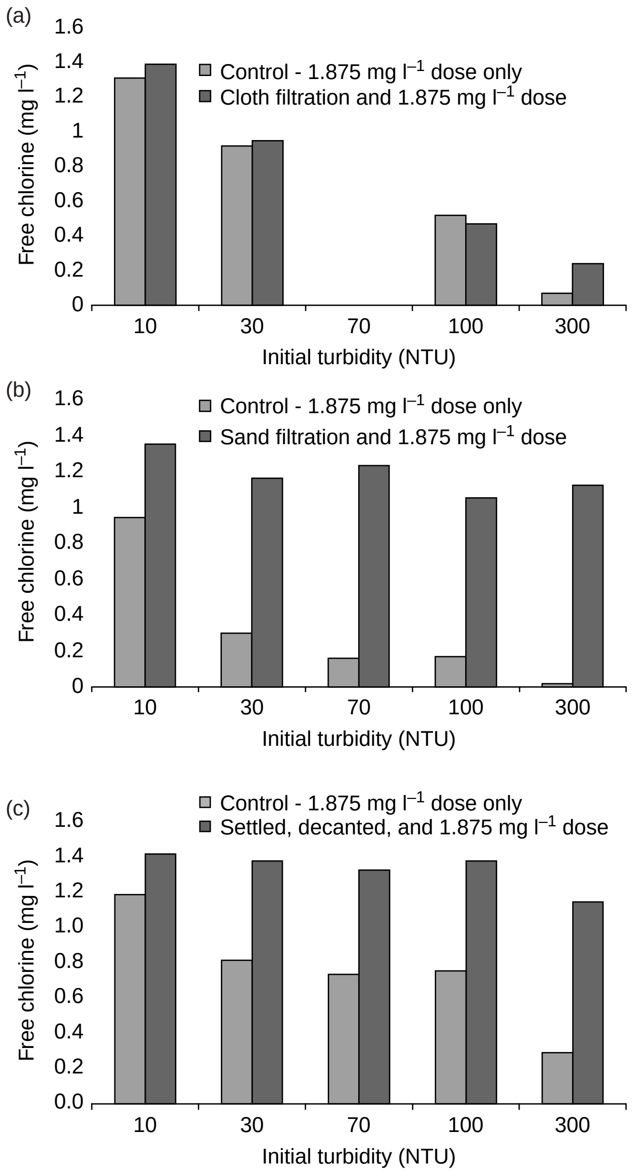

Figure 4 | Efficacy of pre-treatment mechanisms in maintaining chlorine residual 24 hours after chlorination: (a) in control and cloth filtered waters of 10–300 NTU turbidity; (b) in control and sand filtered waters of 10–300 NTU turbidity; (c) in control and settle/decanted waters of 10–300 NTU turbidity.

improve the water's appearance and increase user acceptability, a double dosage of 3.75 mg l^{-1} of sodium hypochlorite is still needed to ensure adequate disinfection and maintenance of free chlorine residual in storage without further treatment such as settling/decanting or sand filtration. Note that pre-treatment by settling/decanting or cloth filtration does not reduce THM formation potential compared with chlorination-only controls (Lantagne *et al.* 2008). The effect of pre-treatment with sand filtration on THM formation has not been evaluated.

The third option is to recommend the use of locally available chemical coagulants, such as moringa seeds (*Moringa oleifera*) or alum (aluminium sulphate), for pre-treatment of turbid water before chlorination. The use of moringa seeds before chlorination has been shown to reduce turbidity and increase THM formation potential in treated water (Lantagne *et al.* 2008); alum use before chlorination has not been evaluated for THM formation potential reduction. Neither has been evaluated for efficacy in maintaining free chlorine residual in treated water or for the necessary dose needed for adequate treatment.

The fourth option is to recommend the use of an alternative household water treatment product. Both ceramic filtration and biosand filtration are proven to reduce turbidity, improve microbiological quality, and reduce diarrhoeal disease when used at the household level (Stauber *et al.* 2006; Brown *et al.* 2007). It is not standard with either filter to recommend post-filtration chlorination to prevent recontamination during storage, but can be encouraged for complete treatment. The flocculant/disinfectant powder PuR™, manufactured and marketed by the Procter & Gamble Company, is proven to reduce turbidity, THM formation potential (Lantagne *et al.* 2008) and diarrhoeal disease incidence in users (Crump *et al.* 2005).

The factors that influence which of these four options for addressing turbid water is recommended by a sponsoring organization include the cost of treatment, local availability and acceptability to the users. For example, in Kenya, all four of these household water treatment options are available. Enough sodium hypochlorite to treat 500 litres of turbid water directly (or 1,000 litres of clear water, turbid water pre-treated with sand filtration or settling/decanting) costs KSH20 (US$0.25); enough PuR™ to treat 10 litres of turbid water costs KSH7 (US$0.088); and biosand filters and ceramic filters, which can last many years if maintained correctly, are available for a one-time installation cost of US$10–100. The household water treatment product decision depends on both the sponsoring organization's assessment and preferences, as well as on user preference and financial decision-making.

Further research to determine the effectiveness of, and necessary dosage for, locally available pre-chlorination chemical coagulants, such as moringa and alum, at reducing turbidity and maintaining free chlorine residual is recommended. In addition, research on the effects of sand filtration and alum use before chlorination on THM formation potential reduction is indicated. Lastly, because the sources of turbidity are variable, our results warrant replication in other turbid source waters.

CONCLUSIONS

Diarrhoeal diseases kill an estimated 1.9 million people each year, and point-of-use chlorination with sodium hypochlorite is a proven intervention that can reduce diarrhoeal disease incidence and protect health in developing countries. Implementation of SWS programmes in areas with turbid water has been complicated by unanswered questions regarding correct sodium hypochlorite dosage, potential THM risk and user acceptability. Two locally available water clarification mechanisms, sand filtration and settling/decanting, were found to be effective at reducing turbidity and chlorine demand when used before chlorination of turbid waters. Cloth filtration was shown to reduce turbidity, but not chlorine demand. The recommended sodium hypochlorite dose after sand filtration or settling/decanting is $1.875\,\mathrm{mg\,l^{-1}}$, and after cloth filtration is $3.75\,\mathrm{mg\,l^{-1}}$. These pre-chlorination clarification mechanisms can be recommended by implementing organizations to improve the effectiveness, increase the acceptability and reduce the cost of chlorinating turbid water at the household level.

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