Journal of Civil Engineering (IEB), 45 (2) (2017) 117-132

Journal of
Civil Engineering
IEB

Influence of different operational and water quality parameters on the ultraviolet (UV) disinfection efficiencies in household or community based water storage units used in small water supply systems

Md. Kabir Uddin Sikder, Mahbuboor Rahman Choudhury and Muhammad Ashraf Ali

Department of Civil Engineering
Bangladesh University of Engineering & Technology, Dhaka 1000, Bangladesh

Received 03 December 2017

Abstract

Increasing acceptance of ultraviolet (UV) disinfection in household or community based water storage units in small water supply systems demands in-depth performance analysis of the disinfection process. The present study aims to assess UV disinfection efficiency, measured on the basis of fecal coliform removal efficiency, through a series of experiments under different operational and water quality conditions. It was observed that lamp intensity, exposure time, distance of water collection location from lamp, and height of the lamp relative to the height of the storage unit have significant influence on disinfection efficiency. 100% fecal coliform removal was observed after 20 minutes exposure time in collection ports located at right angles to the axis of the lamp and located within the length of the lamp. Least disinfection efficiency was observed in locations exactly below the tip of the lamp, where some residual fecal coliform concentration was observed even after 45 minutes exposure time. High initial turbidity and color concentrations were found to influence the disinfection efficiency. Prolonged inactivation of UV lamp demonstrated recovery of fecal coliform through dark repair. The results from the present study will enable design of effective UV disinfection units in small water supply systems throughout the country.

Keywords: Ultraviolet, disinfection, water supply, water storage, efficiency.

---

1. Introduction

Bangladesh has made significant advancement in improving drinking water supply coverage in the past three decades(UNICEF and WHO 2015).Ground water sources, consisting of primarily shallow tubewells, deep tubewells, as well as ring wells, shallow and very shallow shrouded tube wells, are the major sources of water supply throughout the country, which cover approximately 97.6% of the total public water supply points in rural areas of Bangladesh (WHO 2015). Besides, surface water sources and rain water harvesting systems (RWHS), accounting for of about 1.5% and 0.9%, respectively of public water points in rural areas are suitable sources for water supply in many parts of the country (WHO 2015). The presence of elevated levels of arsenic in groundwater in many parts of the country (BGS and DPHE 2001; Hug *et al.* 2011; BBS and UNICEF 2015) forced people to choose surface water sources or RWHS for drinking purposes, especially in areas were suitable arsenic-free deep aquifers are not available. On a national scale, 25.5% of water sources have Arsenic concentration exceeding the WHO guideline value of 10 ppb, and 12.5% have Arsenic exceeding national standard of 15 ppb (BBS and UNICEF 2015). Water from surface water sources (e.g. ponds, lakes, rivers etc.) is used for drinking purpose through use of pond sand filtration (PSF) or some other forms of treatment (Ali 2006; ITN-BUET 2015). Scarcity of non-saline and potable ground water aquifers and elevated salinity in surface water in the coastal regions of Bangladesh promoted higher use of surface (pond) water and RWHS in these regions(Islam *et al.* 2011 2013). For example, PSF and RWHS together account for 6.7%, 5.9%, and 9.1% of water supply points, respectively in Khulna, Satkhira and Bagerhat districts, which are the major coastal districts suffering from both high salinity and arsenic contamination (DPHE 2012). The rainwater-harvesting systems essentially store the rainwater during the rainy season in household or community level water storage tanks/reservoirs (Islam *et al.* 2011 2013). However, the surface water (PSF) and rainwater harvesting sources in Bangladesh, typically used without any disinfection, face very high microbial contamination (Kamruzzaman and Ahmed 2006; Karim 2010; Islam *et al.* 2011).

Although the abundance of suitable sources resulted in improved water supply coverage, the quality of water at the consumer end is still a big concern (Mahmud *et al.* 2007; Ali *et al.* 2014). This can be primarily attributed to the water supply systems adopted throughout the country (Mahmud *et al.* 2007; Ali *et al.* 2014). Apart from a few developed urban regions of Bangladesh most of the localities receive drinking water through household or community based small water supply systems (Mahmud *et al.* 2007; Ali *et al.* 2014). Most of these small water supply systems do not have any piped distribution network and the users have to go to the designated point sources to collect potable water (Howard and Bartram 2005; Mahmud *et al.* 2007). Where small scale piped network exists, terminal disinfection of supplied water is practiced infrequently (Mahmud *et al.* 2007).The consumers of non-piped small water supply systems usually have water storage facilities at the household or community level, which basically ensure water supply to the household or community between water collection periods from a point source(Wright *et al.* 2004). In addition to the reliability of source, the quality of drinking water provided through the small water supply systems depends on other post-source issues like the cleanliness of the transfer pathways (e.g. transfer containers), hygiene practice, quality and cleanliness of the storage facilities (both near the source and at individual households/community level) etc. (Wright *et al.* 2004; Fisher *et al.* 2011; Ali *et al.* 2014). Thus in small water supply systems, pathogen contamination of potable water can take place in any step starting from source to end point of consumption (Wright *et al.* 2004; Fisher *et al.* 2011; Ali *et al.* 2014). The existing situation in small water supply systems in Bangladesh led to the practice of disinfection at household or community level to ensure safe drinking water and prevent various waterborne diseases (Ali *et al.* 2014; ITN-BUET 2015). Although the drinking water standards in the country requires the water to be free from fecal coliform (FC) bacteria (DoE 1997), Recent research work suggested that many commercially available household or community level water purification units (mostly comprising of different filtering technologies) in Bangladesh are not very effective in removing FC (Redwan *et al.* 2014). Disinfection is carried out for inactivation or destruction of pathogenic organisms to prevent spread of waterborne diseases (EPA 2011). Various methods for disinfection of drinking water include: (a) chemical methods (like chlorination, ozonation, chlorine dioxide disinfection, chloramine disinfection etc.); and (b) physical methods (like boiling, ultraviolet (UV) radiation etc.) (EPA 2011). The chemical disinfection processes have different concerns related to operation and maintenance, as the dosing of chemicals for disinfection needs to be adjusted with varying water quality (Gadgil 1998; EPA 2013). So skilled operator is required for conducting chemical disinfection (Gadgil 1998; EPA 2013). Also there is a chance of producing harmful byproducts like trihalomethanes (in case of using chlorine), chlorite or chlorate (in case of using chlorine dioxide), and carcinogenic bromate byproducts (in case of using ozone) in different chemical disinfection processes (Kerwick *et al.* 2005; EPA 2013).

On the other hand, the physical methods of disinfection do not produce objectionable byproducts in the treatment process (Gadgil 1998). One major concern with physical systems is its reliance on constant energy supply during disinfection operation (Gadgil 1998). These methods require less skilled operators and intermittent maintenance of the system (Gadgil 1998). In small water supply systems, disinfection becomes a challenge since a single family or small communities do not have necessary facilities or skills to disinfect water properly (Gadgil 1998). Some recent research works suggest that UV disinfection could be effective for disinfection of water in household and community level rainwater harvesting systems and PSFs (White *et al.* 2007; ITN-BUET 2015). Interest in UV disinfection is growing due to its ability to inactivate pathogenic microorganisms without forming regulated disinfection byproducts (DBPs) (Gadgil 1998; Kerwick *et al.* 2005). UV light has proven effective against Cryptosporidium, which is resistant to commonly used disinfectants like chlorine (Kerwick *et al.* 2005; EPA 2011; Redwan *et al.* 2014). Simple operation, easier maintenance, low cost installation-operation and desired performance are key factors (Gadgil 1998; Kerwick *et al.* 2005) of increasing interest in UV disinfection at household levels for many small-scale water supply systems of the country. However, there is no systematic set of data for assessing effectiveness of UV disinfection for household or community based water storage setup in small water supply systems. The performance of UV disinfection is likely to depend on a number of factors, e.g. intensity of UV lamp, exposure time, characteristics of water (level of bacterial contamination, turbidity and color), and shape/size of container/chamber used for disinfection (Gadgil 1998; EPA 2011). It is therefore very important to systematically assess the performance of UV disinfection under various operational and water quality conditions in household based disinfection units. The present research aims to assess the effectiveness of UV disinfection at consumer-end of small water supply systems. The specific objectives of the present study are: (a) to assess the effect of UV lamp intensity and exposure time on disinfection, (b) to evaluate the efficiency of UV disinfection at different distances (from UV lamp) and locations within the disinfection container/chamber, (c) To evaluate the influence of initial contamination level on disinfection by UV lamp, and (d) to assess the impact of water quality (presence of turbidity, color, pH) on disinfection efficiency by UV lamp.

2. Materials and methods

2.1 Collection and preparation of water samples

For each set of experiments it was necessary to keep the water sample as identical as possible to assess the effectiveness of UV disinfection. At the same time it was also not possible to do all experiments with water collected in a single water-sampling event. Hence efforts were made to keep the water quality similar in different batch experiments so that the results of a given batch experiment could be compared to assess effectiveness of different operational and water quality parameters on UV disinfection. Also to assess the effect of water quality parameters (e.g. turbidity, color, pH, initial FC concentration) on UV disinfection, a number of water samples were prepared by varying these water quality parameters. Primary sources of water for the present research were: surface water (pond water) and ground water. Water from these sources was brought to the laboratory and prepared for the batch experiments as follows:

- *Water with variable turbidity and color:* Batch experiments were carried out with water samples having turbidity less than 5 NTU and more than 20 NTU. The water collected from the surface water (pond water) sources gave turbidity values less than 5 NTU, and color concentrations of 23 and 58 Pt-Co unit. In order to increase the turbidity and produce a water sample of turbidity more than 5 NTU, turbid material (mud) was added to the water. Reduction of turbidity was achieved either by filtration or by mixing pond water with ground water having low (~0.3 NTU) initial turbidity. Similar approach was adopted to produce water having different color concentrations. For the present study the initial color concentrations used in the disinfection batch experiments were 23, 58, and 154 Pt-Co units. Amended water with turbid material (having a turbidity of 25 NTU) gave a color concentration of 154 Pt-Co units.
- *Water with variable pH:* The pH of water samples in some batch experiments were maintained at constant value during the entire length of the experiment by addition of small aliquots of hydrochloric acid and/or sodium hydroxide in the water containers. The pH values were kept at 6.5, 7, and 8 during the batch experiments carried out to evaluate the influence of pH on UV disinfection.
- *Water with varying initial FC concentration:* The initial FC concentration of the pond water was very high and the colony forming units were too numerous to count (TNTC). On the other hand the groundwater had no fecal coliform in it and had negligible turbidity (~0.3 NTU). For batch experiments, groundwater was mixed with pond water at a volumetric ratio of 1:1 to produce amended water with a countable initial FC concentration.

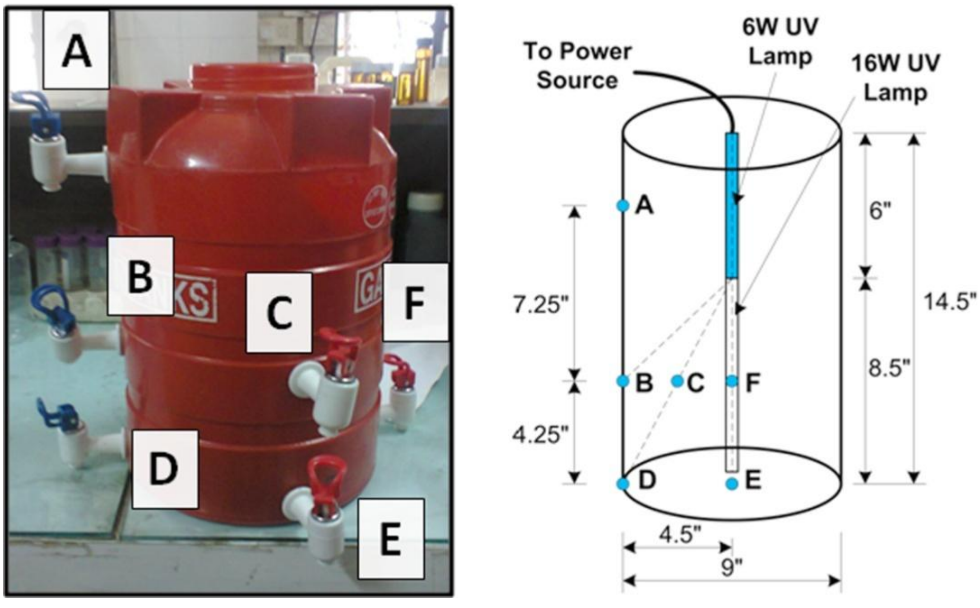

Fig. 1. The 15-litre water tank used in UV disinfection experiments with location of different water collection taps. Tubes of suitable lengths were attached to taps located at the periphery of the tank to collect the water from the designated locations (A, B, C, D, E, and F) as shown in the schematic diagram of the 15-litre tank.

2.2 *Design of water storage containers for assessment of UV disinfection efficiency*

In order to assess the effectiveness of UV disinfection process in household based disinfection units, two different sizes of containers have been designed to carry out the batch experiments.

The two containers were cylindrical in shape with a volume of 15 liters and 60 liters, respectively. The sizes of the tanks were selected to reflect usual household and small community based water storage units used at the consumer end in small water supply systems in Bangladesh. The height and diameter of the 15-litre tank were 14.5 inch (36.8 cm) and 9 inch (22.9 cm), respectively. The 15-litre tank was fitted with six sampling ports (Port A to F) for collection of water samples from different locations relative to the UV lamp within the tank as shown in Figure 1. Samples were collected from all ports at 0, 10, 20, 30, and 45 minutes intervals in different batch experiments after exposure to UV irradiation. Port A was used to collect water to be disinfected from 11.5 inch (29.2 cm) above the bottom and on the periphery of the tank. Port B, C and F were used to collect water from 4.25 inch (10.8 cm) above the bottom and 0 inch (0 cm), 2.25 inch (5.7 cm), and 4.5 inch (11.4 cm) inside the tank from the periphery, respectively. Similarly, Port D and E were used to collect water from the bottom-edge, and bottom-center of the tank, respectively. Tubes of suitable lengths were attached to taps located at the periphery of the tank to collect water samples from the designated locations shown in Figure 1. UV lamps of either 6W or 16W intensities were used to assess and evaluate the effectiveness of UV disinfection.

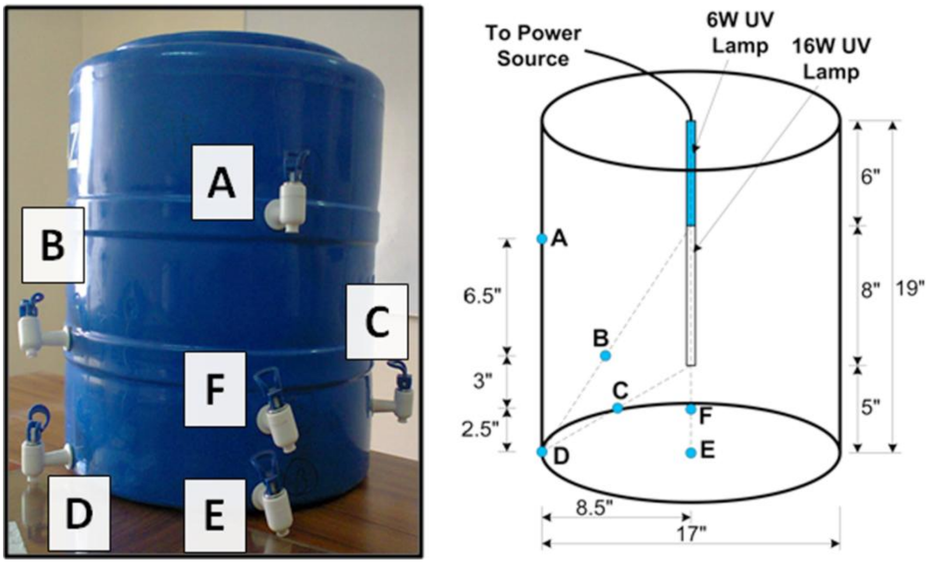

Fig. 2. The 60-litre water tank used in UV disinfection experiments with location of different water collection taps. Tubes of suitable lengths were attached to taps located at the periphery of the tank to collect the water from the designated locations (A, B, C, D, E, and F) as shown in the schematic diagram of the 60-litre tank.

On the other hand, the height and diameter of the 60-litre tank were 19 inch (48.3 cm) and 17 inch (43.2 cm), respectively. The 60-litre tank was also fitted with six sampling ports (Port A to F) for collection of water samples from different locations relative to the UV lamp within the tank as shown in Figure 2. Samples were collected from all ports at 0, 10, 20, 30, and 45 minutes intervals after exposure to UV irradiation. Port A was used to collect water to be disinfected from 12 inch (30.48 cm) above the bottom and on the periphery of the tank. Port B was used to collect water from 5.5 inch (14 cm) above the bottom and 4.25 inch (10.8 cm) inside the tank from the periphery. Port C and F were used to collect water from 2.5 inch (6.35 cm) above the bottom, and 4.25 inch (10.8 cm) and 8.5 inches (21.6 cm) inside the tank from periphery, respectively. Similarly, Port D and E were used to collect water from the bottom-edge, and bottom-center of the tank respectively. UV lamps of either 6W or 16W intensities were used to assess and evaluate the effectiveness of UV disinfection. Arrangements were made for fitting UV lamps at the top-center of both the containers as shown in Figure 3. A UV lamp set is composed of a lamp envelope (quartz glass), an adapter to connect to power supply, and UV lamp itself. At first UV lamp was connected with the adapter, then the lamp was placed inside the lamp envelope. Open end of the lamp envelope was made watertight so that water cannot come in contact with UV lamp. An opening was made on the top-center of the container to fix the UV lamp as shown in Figure 3. Finally, this opening was also made air tight so that UV light did not come in contact with eyes.

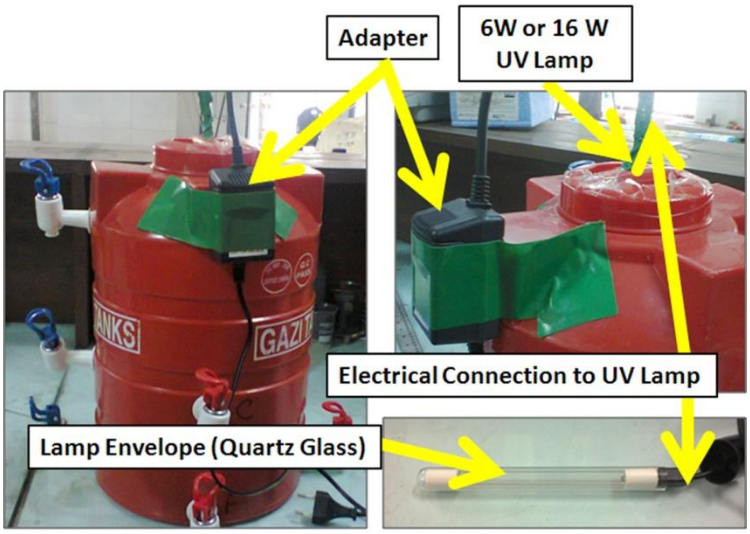

Fig. 3. Arrangements showing connection of the UV lamp in a water tank for carrying out the disinfection experiments.

2.3 *Batch experiments under varying operational and water quality parameters for assessment of UV disinfection efficiency*

A series of batch experiments were carried out to investigate the efficiency of UV disinfection under different operational condition (like intensity of UV lamp, UV exposure time, location of water collection point etc.) and varying water quality (like varying turbidity, color, pH and initial FC concentration). For a particular water sample, the water tank (volume of 15 or 60 liter) was filled with the sample and then the UV lamp (intensity of 6W or 16W) was positioned vertically inside the water tank. Before connecting the UV lamp with power supply, a water sample was collected from one of the ports to measure the initial level (raw/ 0 minute) of fecal contamination (FC). During each set of experiment, the raw water was subjected to exposure of the UV lamp for a certain period of time (10, 20, 30 and 45 minutes).At the end of each specific exposure time period, water samples were collected from the sampling ports and were tested for fecal coliform (FC). As previously described, configuration of the sampling ports enabled sampling of water samples at different locations relative to the UV lamp and at different distances away from the UV lamp. Results of the disinfection experiments were analyzed and compared for assessing the effect of varying physical configuration, properties of UV lamp and water quality on UV disinfection efficiency. Both natural (e.g. from pond, river, rainwater) and amended water (e.g. groundwater amended with polluted water containing microorganisms) was used as raw water in the disinfection experiments. The batch experiments, investigating the effect of different operational parameters (intensity of UV lamp, UV exposure time, location of water collection point etc.) on UV disinfection efficiency, were carried out using water samples having a turbidity of less than 5 NTU. For other batch experiments, investigating the effect of different water quality parameters on UV disinfection efficiency, the water qualities (like initial FC concentration, turbidity, color, pH) were varied following the steps described in section 2.1. To assess the possible recovery of microorganism from UV damage through “photo reactivation” or “dark repair”, a number of tests were carried out by using amended water with 15-litre water tank and 16W UV lamp. Water samples were collected from port D after 0 minute (raw water) and 45 minutes of exposure to UV lamp and then the UV lamp was switched off. Water samples were again collected after 1.5 hours and 24 hours from port D. Collected samples were tested for FC. Results of the experiments were analyzed for assessing the possible recovery of microorganisms from UV damage.

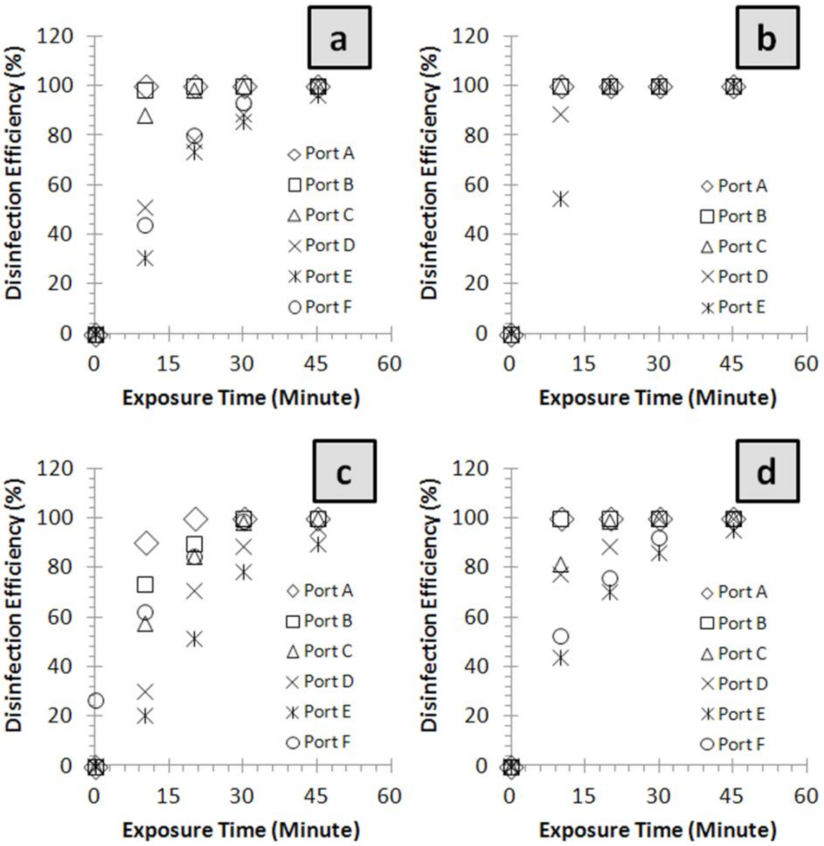

Fig. 4. UV disinfection efficiencies achieved after different exposure time for water samples collected from different ports in (a) 15-litre water tank with 6W UV lamp; (b) 15-litre water tank with 16W UV lamp; (c) 60-litre water tank with 6W UV lamp; and (d) 60-litre water tank with 16W UV lamp. Water quality data given in Table 1.

2.4 *Analytical methods*

Fecal coliform were determined using membrane filtration technique.100 ml of water samples were filtered through 0.45 μm pore size membrane filter (Millipore Corp., Bedford, MA, USA), and the filters were placed on m-FC agar plates. The m-FC agar plates were incubated at 44 ± 0.5°C for 24 hours for enumeration of bacterial colonies. After incubation period, bacterial colonies were counted, and the results were expressed as colony forming unit per 100 milliliters (cfu/100ml) of sample (APHA-AWWA-WEF, 1998). Turbidity of the water samples was measured using a portable turbid meter (Model 2100P, HACH, USA). pH meter (Model WTW pH 3400i, Germany) and spectrophotometer (Model DR2010, HACH, USA) were used to measure the Color and pH of the water samples.

3. Results and discussions

3.1 *Effects of different operational parameters on disinfection efficiency*

As mentioned previously, the UV disinfection efficiency was assessed in a series of batch experiments by varying different operational parameters. These operational parameters were

(1) UV lamp intensity, (2) UV lamp exposure time, (3) distance from UV lamp, and (4) location of collection point relative to the lamp. The following sections describe the effect of these operational parameters on the UV disinfection efficiency based on results of laboratory batch experiments:

3.1.1 Effect of UV lamp intensity on disinfection efficiency

In order to evaluate the effects of UV lamp intensity on disinfection efficiency, a number of experiments were carried out in 15-litre and 60-litre water tanks fitted with 6W or 16W UV lamps, as described previously. Table 1 and Figure 4 show the residual FC concentrations and the disinfection efficiencies, respectively, for water samples collected from different ports of the 15-litreand 60-litrewater tank (see Figure 1 and 2 for port location) fitted with 6W and 16W UV lamps at different exposure times. It should be noted that among the sampling ports identified in Figures 1 and 2, "port E" (located vertically below the UV lamp) receives the least amount of UV light, while "port A" (located perpendicular to vertical axis of the lamp) receives the highest amount of UV light. Figure 4 clearly show that for a particular sampling point, the effectiveness of disinfection depends significantly on the intensity of UV lamp and higher UV lamp intensity will result in greater disinfection efficiency for a specific exposure time interval.

However, water samples collected after different exposure times from "port A" during the same batch experiment indicated that the lamp intensity does not have any impact on disinfection efficiency; for both the 6W and 16W UV lamp experiments the FC concentrations dropped to zero after 10 minutes.

For a particular container, the effect of UV lamp intensity on disinfection efficiency varied significantly among sampling ports. Residual FC concentrations of water samples collected from other sampling ports (B, C, D and F) of both water tanks confirm this observation (Table 1). The effect of lamp intensity on disinfection efficiency is relatively lower for sampling points that receive higher level of UV light (e.g. A, B and C), while it is higher for sampling points that receive relatively lower level of UV light (e.g. D, E and F).

3.1.2 Effect of exposure time on disinfection efficiency

The results shown in Table 1 and Figure 4 indicate that exposure time has a clear effect on disinfection efficiency. With increasing exposure time, higher disinfection efficiency will be achieved in water collected from a given collection point. However, as discussed above, the effect of exposure time is also influenced by the position of the sampling port with respect to the lamp. For experiments conducted in the 15-litre container (with 6W UV lamp), complete removal of FC was achieved with 10 minutes and 20 minutes of exposure time in sampling "port A" and "port B", respectively. While for "port C" and "port D", complete removal of FC required 30 minutes and 45 minutes of exposure time, respectively. For "port E", residual FC decreased with increasing exposure time, but complete removal of FC could not be achieved even after 45 minutes of exposure time.

3.1.3 Effect of distance from UV lamp on disinfection efficiency

To evaluate the effects of distance from UV lamp on disinfection, disinfection efficiencies were evaluated along two lines: (a) from the tip of the lamp to the bottom (along the axis of the lamp, i.e. port F and E); and (b) from the tip of the lamp to the bottom edge of the tank(along port C and D) (see Figures 1 and 2 for locations of ports in 15-litre and 60-litre tanks, respectively). From Table 1it can be observed that increasing distance from the lamp (along the axis of the lamp), results in decreasing disinfection efficiencies. Table 1 also shows the residual FC concentrations and disinfection efficiencies of the ports C and D (located along the line from the tip of the lamp to the bottom edge of the tank). The results indicate that for shorter exposure time, distance has a pronounced effect on disinfection efficiency; the effect gradually diminishes as exposure time increases. So for a particular exposure time, the shorter the distance from UV lamp, the higher the disinfection efficiency.

Table 1

Residual fecal coliform (FC) concentration (cfu/100ml) in water samples collected from different collection ports of the 15-litre and 60-litre water tanks after different exposure time periods (in minutes) to UV lamps of 6W and 16W intensities

Test Water Quality	Tank Size	UV lamp intensity	Port[a]	Residual Concentration of Fecal Coliform (cfu/100ml)				
				Exposure Time				
				Raw/0 Min	10 Min	20 Min	30 Min	45 Min
Amended Water Pond water (initial turbidity 3.11 NTU and Color 40 Pt-Co) and Groundwater (initial turbidity 0.3 NTU and Color 7 Pt-Co) mixed at 50:50 ratio	15 Liter	6W	A	122	0	0	0	0
			B	122	2	0	0	0
			C	122	14	2	0	0
			D	122	60	27	14	0
			E	122	84	32	17	4
			F	122	68	24	8	0
Pond Water (Initial turbidity 3.99 NTU, Color 58 Pt-Co)	15 Liter	16W	A	53	0	0	0	0
			B	53	0	0	0	0
			C	53	0	0	0	0
			D	53	6	0	0	0
			E	53	24	0	0	0
			F	--[b]	--[b]	--[b]	--[b]	--[b]
Pond Water (Initial turbidity 4.25 NTU, Color 27 Pt-Co)	60 Liter	6W	A	118	11	0	0	0
			B	118	31	12	0	0
			C	118	50	18	2	0
			D	118	82	34	13	4
			E	118	94	57	25	12
			F	118	86	44	18	1
Pond water (Initial turbidity 4.10 NTU, Color 30 Pt-Co)	60 Liter	16W	A	116	0	0	0	0
			B	116	0	0	0	0
			C	116	21	1	0	0
			D	116	26	13	0	0
			E	116	65	34	16	5
			F	116	55	28	9	0

Note: [a] See Figure 1 and 2 for location and details of ports. [b] Batch experiments carried out in 15 liter water tank using 16 watt UV lamp do not have any data for "port F", because the UV lamp covered almost the entire length of the 15-litre tank and hence the collection point of "port F" was occupied by the lamp.

3.1.4 Effect of location of collection point relative to the UV lamp on disinfection efficiency

The residual FC concentrations and disinfection efficiencies in different ports of the 15-litre and 60-litre tanks (given in Table 1 and Figure 4, respectively) indicate that position of sampling point within the disinfection container has a significant effect on disinfection efficiency. The UV lamps are linear in dimension; the 6W lamp is about 6 inch in length, while the 16W lamp is about 14 inch in length. When a 15-litre tank is fitted with a 6W lamp, there remains an 8.5-inch gap between the tip of the lamp and the bottom of the tank. On the other hand, when a 16W lamp is fitted to the 15-litre tank only a gap of 0.5 inch remains between the tip of the lamp and the bottom of the tank.

Similarly, when a 60-litre tank is fitted with a 6W lamp, a 13-inch gap remains between the tip of the lamp and the bottom of the tank; the gap reduces to about 5 inch when a 16W lamp is fitted to the 60-litre tank. The areas below the lamp receive the least intensity of UV light, whereas the areas surrounding the lamp receive higher intensity UV light.

Thus, in all cases sampling ports E and F (located directly below the UV lamp) received the least intensity of UV light, while sampling port A received the highest-intensity UV light, being located perpendicular to the lamp axis. The other sampling ports (i.e. B, C and D) are in "intermediate" position with respect of getting UV light. A different situation arises when a 16W lamp is used in a 15-litretank. In this case, the lamp almost covers the entire length of the tank; thus sampling port E is just 0.5 inch below the tip of the lamp (and there is no place for sampling port F). For 16W UV lamp in a 15-litre tank, excellent disinfection efficiencies were achieved for all sampling points (Figure 4), including sampling port E (which in this case is located just about 0.5 inches below the tip of the UV lamp). However, it took about 20 minutes of exposure time for FC to reach zero level for points D and E, compared to 10 minutes for points A, B and C.

For experiments carried out in the 60-litre tank using 16W UV lamp complete removal of FC could not be achieved at port E, located about 5 inch vertically below the tip of the UV lamp, after 45 minutes exposure time(Table 1). Hence for a particular water tank fitted with UV lamp, selection of collection point of treated water is very important. For better treated water quality, collection point should be located perpendicular to the axis of the UV lamp; this has also been recommended by EPA (2011). Higher the gap between the tip of the lamp and the bottom of the tank, higher will be the risk of poor disinfection in the zone of the container below the tip of the lamp.

3.2 Effects of varying water quality on UV disinfection efficiency

Constituents in the water to be disinfected affect the performance of UV disinfection. The water quality parameters that commonly affect the performance of UV disinfection system include initial FC concentration, turbidity, color, temperature, pH, suspended solids, etc. The effect of initial FC concentration, turbidity, color, and pH of water on UV disinfection efficiency is discussed in the following sections.

3.2.1 Effect of initial FC concentration

Lower initial FC concentration yielded greater disinfection efficiencies using UV lamps. Table 2 summarizes the results showing effects of initial FC concentration on disinfection efficiencies at ports A, B, C, D, and E of a 15-litre water tank fitted with a 6W UV lamp and for a 60-litre water tank fitted with a 16W UV lamp for two different initial FC concentrations (TNTC and countable). A closer examination of results presented in Table 2 reveals that from the point of view of drinking purpose (for which zero FC is required), the effect of initial FC concentration is not as pronounced as "exposure time".

For example, Table 2 shows that irrespective of initial FC concentration (i.e. TNTC or 122 cfu/100 ml), 45 minutes of exposure time is needed for achieving zero FC concentration at port D of the 15-litre water tank fitted with a 6W UV lamp. Whereas for the same 15-litre water tank fitted with 6W UV lamp, irrespective of initial FC concentration (i.e. TNTC or 122 cfu/100 ml), zero FC is not achieved at port E even after 45 minutes of exposure time.

3.2.2 Effect of turbidity

Several experiments were carried out with initial turbidity less than 5 NTU (3.11 NTU) and more than 5 NTU (25 NTU) to assess the effect of turbidity on disinfection efficiency. Table 3 shows the results obtained from these experiments for collection port D and port A of the 15-litre water tank fitted with a 6W UV lamp and 60-litre water tank fitted with a 16W UV lamp, respectively. After 10 minutes exposure to UV lamp, disinfection efficiency of 50.8% and 12.3% could be achieved at port D for water with initial turbidity of 3.11 NTU and 25 NTU, respectively.

Again after 45 minutes exposure, complete disinfection (i.e. zero residual FC) could be achieved at port D for water with initial turbidity of 3.11 NTU; however, that was not the case for water with initial turbidity of 25 NTU. Similarly, after 10 minutes exposure to UV lamp, disinfection efficiency of 100% and 92.6% could be achieved at port A for water with initial turbidity of 3.11 NTU and 25 NTU, respectively.

Again after 45 minutes exposure, complete disinfection (i.e. zero residual FC) could be achieved at port A for water with initial turbidities of 3.11 NTU and 25 NTU. Similar experiments were carried out in the 60-litre tank fitted with a 16W UV lamp with water having initial turbidity of 4.1 NTU and 23.4 NTU. Table 3 shows the results of these experiments (for port A and port E). These data also show that initial turbidity has a significant influence on disinfection efficiency, especially for shorter exposure times.

3.2.3 Effect of color

Table 4 indicates the residual FC concentration in the water having different initial color concentrations (23 Pt-Co to 154 Pt-Co) and collected from port D of the 15-litre tank fitted with 6W UV lamp after different exposure time interval. The data indicate that after 10 min exposure to UV lamp, disinfection efficiency of water with initial color of 23, 58, and 154 Pt Co were 89.5%, 79.3% and 42% respectively. Again after 30 min exposure, disinfection efficiency reached 100% with water samples with initial color of 23 Pt Co and 58 Pt Co; whereas disinfection efficiency of 86.6% was achieved for water sample with initial color 154 Pt Co. From the results provided in Table 4 it can be resolved that lower intensity of initial color in the water results in higher UV disinfection efficiency.

3.2.4 Effect of pH

Raw water samples having pH values of 6.5, 7, and 8 were used to evaluate the effects of pH on UV disinfection. Test results of residual FC concentration in water collected from port D and port B after different exposure time periods from the 15-litre and 60-litre water tanks, respectively, are provided in Table 5. From the table it appears that disinfection efficiency is independent to pH value within the range of 6.5 to 8.

3.3 Effect of photo-reactivation or dark repair

No microorganisms were present in the treated water after 45-minute exposure to 16W UV lamp in the 15-litre water tank. After 45-minute exposure time, the UV lamp was switched off and the water was kept in the tank for 24 hours. No symptom of reactivation of microorganism (i.e. zero FC concentration) was observed after 1.5 hours in water sample collected from port D from the time of switching off the UV lamp.

However, the water collected from the same port after 24 hour of lamp switch-off showed a FC concentration of 5-cfu/100 ml. This result showed evidence of photo reactivation after prolonged inactivation of UV lamp.

Table 2
Residual fecal coliform (FC) concentration (cfu/100ml) in water sample (with different initial fecal coliform concentrations) collected from different collection ports of the 15-litre and 60-litre water tanks after different exposure periods to UV lamps of 6W and 16W respectively.

Test Water Quality	Tank Size	UV lamp intensity	Port[a]	Residual Concentration of Fecal Coliform, cfu/100ml				
				Exposure Time				
				Raw/0 Min	10 Min	20 Min	30 Min	45 Min
Amended Water Pond water (initial turbidity 3.11 NTU and Color 40 Pt-Co) and Groundwater (initial turbidity 0.3 NTU and Color 7 Pt-Co) mixed at 50:50 ratio	15 Liter	6W	A	122	0	0	0	0
			B	122	2	0	0	0
			C	122	14	2	0	0
			D	122	60	27	14	0
			E	122	84	32	17	4
Pond Water (Initial turbidity 3.78 NTU, Color 46 Pt-Co)	15 Liter	6W	A	TNTC	2	0	0	0
			B	TNTC	4	0	0	0
			C	TNTC	TNTC	2	0	0
			D	TNTC	TNTC	52	30	0
			E	TNTC	TNTC	TNTC	61	21
Pond Water (Initial turbidity 4.25 NTU, Color 27 Pt-Co)	60 Liter	16W	A	116	0	0	0	0
			B	116	0	0	0	0
			C	116	21	1	0	0
			D	116	26	13	0	0
			E	116	65	34	16	5
Pond water (Initial turbidity 3.78 NTU, Color 63 Pt-Co)	60 Liter	16W	A	TNTC	0	0	0	0
			B	TNTC	5	0	0	0
			C	TNTC	56	15	1	0
			D	TNTC	TNTC	24	2	0
			E	TNTC	TNTC	TNTC	TNTC	TNTC

Note: [a] *See Figure 1 and 2 for location and details of ports.*

Table 3
Comparison between the residual FC concentrations of water with different initial turbidity at port D, port A of 15-litre water tank fitted with 6W UV lamp and port E, port A of 60-litre water tank fitted with 16W UV lamp. Pond water sample collected for this experiment was used directly for initial turbidity condition of less than 5 NTU. For initial turbidity of more than 5 NTU, amended water with turbid material (mud) was used.

Tank Size	UV Lamp Intensity	Port	Time of Exposure	Residual FC (cfu/100ml)	
				Turbidity < 5 NTU (3.11 NTU)	Turbidity > 5 NTU (25 NTU)
15 Liter	6W	Port D	Raw/0 Min	122	122
			10 Min	60	97
			20 Min	27	62
			30 Min	14	46
			45 Min	0	18
		Port A	Raw/0 Min	122	122
			10 Min	0	9
			20 Min	0	0
			30 Min	0	0
			45 Min	0	0
				Turbidity < 5 NTU (4.10 NTU)	Turbidity > 5 NTU (23.4 NTU)
60 Liter	16W	Port E	Raw/0 Min	116	116
			10 Min	65	94
			20 Min	34	58
			30 Min	16	37
			45 Min	5	14
		Port A	Raw/0 Min	116	116
			10 Min	0	11
			20 Min	0	0
			30 Min	0	0
			45 Min	0	0

Note: ^{a} *See Figure 1 and 2 for location and details of ports.*

3.4 Selection of water tank and position of UV lamp

Based on the results of the present study, some guidelines can be developed for the selection of water tank for water storage in small water supply systems. The key findings from the experimental results are as follows:

- The height of water tank should approximately be the same as effective length of the UV lamp and the UV lamp should be located at the center of the tank for optimum disinfection of water.
- Selection of lamp intensity is likely to be governed by the height/length requirement. So UV lamp should be selected in such a manner that its length commensurate with the height of the water tank.
- Water collection port should be located at a position perpendicular to the axis of the UV lamp to ensure collection of disinfected water after shortest possible exposure time.
- Turbidity of water to be disinfected should be below 5 NTU, and color intensity should be below 50 Pt-Co. While lower initial FC concentrations are preferable, if other

conditions/criteria (discussed above) could be fulfilled, initial FC concentration is probably not a major concern.

- If the above criteria could be fulfilled, an exposure time of about 30 minutes should be enough for effective disinfection (i.e. reducing FC to zero level in the treated water) of surface water or rainwater.
- Disinfected water should not be collected and consumed after prolonged inactivation of UV lamp to avoid the photo reactivation or dark repair of microorganisms.

Table 4

Residual FC concentration and corresponding disinfection efficiency at port D for water with different initial color in 15-litre water tank fitted with 16W UV lamp. The collected pond water samples with color concentrations of 23 and 58 Pt-Co units were directly used in the experiments. Amended water with turbid material (mud) gave a color concentration of 154 Pt-Co units and a turbidity of 25 NTU.

Port	Exposure Time	Residual FC (cfu/100ml)		
		Initial Color 23 Pt Co	Initial Color 58 Pt Co	Initial Color 154 Pt Co
Port D	Raw/0 Min	19	53	112
	10 Min	2	11	65
	20 Min	0	0	31
	30 Min	0	0	15
	45 Min	0	0	0

Table 5

Residual FC concentration in water having different pH at port D of the 15-litre water tank and port B of the 60-litre water tank fitted with 16W UV lamp. For these experiments, the pH of the collected pond water samples was controlled by addition of small aliquots of HCl and/or NaOH

Tank Size	UV Lamp Intensity	Port	Exposure Time	Residual FC concentration (cfu/100ml)		
				pH 6.5	pH 7	pH 8
15 Litre	16W	Port D	Raw/0 Min	19	45	87
			10 Min	3	7	13
			20 Min	0	0	1
			30 Min	0	0	0
			45 Min	0	0	0
60 Litre	16W	Port B	Raw/0 Min	116	102	112
			10 Min	0	0	0
			20 Min	0	0	0
			30 Min	0	0	0
			45 Min	0	0	0

Note: ^{a} See Figure 1 and 2 for location and details of ports.

4. Conclusion

In small water supply systems (e.g., tube well, pond sand filter, rainwater harvesting), disinfection becomes a challenge since a single family or small communities do not have necessary facilities and skills to disinfect water, particularly by chemical means. . Even many existing piped water supply systems in urban areas cannot ensure pure drinking water, primarily due to contamination taking place within the distribution network. For UV lamps available in the market, manufacturers provide only the time of exposure needed for a particular UV lamp to disinfect specific quantity of water. But nothing is mentioned about the shape/size of the tank in relation to the UV lamp, location of UV lamp, distance/location of water collection point from UV lamp, and effects of different water quality parameters on UV disinfection. The results from the present study will help in designing effective UV disinfection systems to be used in small water supply system i.e. at family/community level. In this study, a range of laboratory experiments were carried out to assess effectiveness of UV disinfection in cylindrical tanks, which are commonly used for storage of water at household/small community level. Particular focus has been provided on the effects of important operational (e.g., intensity of lamp, exposure time, distance/location) and water quality parameters (e.g., initial FC concentration, turbidity, color, pH). It was found that intensity of lamp, exposure time and water collection location in the tank has significant influence on disinfection efficiency. Among different water quality parameters considered, initial turbidity and initial color concentrations were found to affect the disinfection efficiency the most. The findings from the study increased the level of understanding of UV disinfection system in small cylindrical shaped disinfection units used for water storage in small water supply systems.

Acknowledgements

This work was supported by a research grant from the Directorate of Advisory, Extension & Research Services (DAERS), Bangladesh University of Engineering and Technology (BUET). The views and opinions of authors expressed herein do not necessarily state or reflect those of DAERS, BUET or any agency thereof. The authors thankfully acknowledge the Environmental Engineering Laboratory staffs and authorities at BUET for supporting with necessary lab setup activities regarding this research work.

References

Ali M.A. 2006 Arsenic Contamination of Groundwater in Bangladesh. *International Reviews for Environmental Strategies*, 6(2), 329–360.

Ali M.A., Rahman M.M., Choudhury M.R., Mahmud S.G., Sutherland D. & Ahmed A., 2014 *Water Safety Plan (WSP) A Risk Based Approach for Water Safety*, 1st ed. World Health Organization (WHO) Country Office, Bangladesh.

APHA-AWWA-WEF 1998*Standard Methods for the Examination of Water and Wastewater* 20th edn., American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

BBS& UNICEF 2015*Multiple Indication Cluster Survey, 2012-2013, Progotic Pathey*, Final Report, Bangladesh Bureau of Statistics (BBS), Dhaka, Bangladesh and United Nations Children's Fund (UNICEF), Dhaka, Bangladesh. http://www.unicef.org/bangladesh/MICS_Final_21062015_Low.pdf (accessed 20 October 2015)

BGS& DPHE 2001*Arsenic Contamination of Groundwater in Bangladesh*, Report WC/00/19. British Geological Survey (BGS), Keyworth and Department of Public Health Engineering (DPHE), Bangladesh.http://www.bgs.ac.uk/research/groundwater/health/arsenic/Bangladesh/reports.html (accessed 15 October 2015)

DoE 1997*The Environment Conservation Rules, 1997*, Bangladesh Department of Environment, Ministry of Environment and Forest, Government of the People's Republic of Bangladesh.

DPHE 2012 *National MIS for WSS in Bangladesh*, Department of Public Health Engineering, Policy Support Unit (PSU), Local Government Division, Ministry of Local Government, Rural Development and Cooperatives, Government of the People's Republic of Bangladesh.

EPA 2011*Water Treatment Manual: Disinfection*, 2nd ed. Environmental Ptotection Agency, Wexford, Ireland. http://www.epa.ie/pubs/advice/drinkingwater/watertreatmentmanualdisinfection.html#.VnkLdmC-WyM (accessed 20 October 2015)

Fisher S., Kabir B., Lahiff E.& MacLachlan M. 2011 Knowledge, attitudes, practices and implications of safe water management and good hygiene in rural Bangladesh: assessing the impact and scope of the BRAC WASH programme. *Journal of Water and Health*, 9(1), 80–93.

Gadgil A. 1998Drinking Water in Developing Countries. *Annual Review of Energy and the Environment*, 23(1), 253–286.

Howard G. & Bartram J. 2005 Effective water supply surveillance in urban areas of developing countries. *Journal of Water and Health*, 3(1), 31–43.

Hug S.J., Gaertner D., Roberts L.C., Schirmer M., Ruettimann T., Rosenberg T.M., Badruzzaman A.B.M. & Ali M.A. 2011 Avoiding high concentrations of arsenic, manganese and salinity in deep tubewells in Munshiganj District, Bangladesh. *Applied Geochemistry*, 26(7), 1077–1085.

Islam M.A., Sakakibara H., Karim M.R.& Sekine M. 2013 Potable water scarcity: options and issues in the coastal areas of Bangladesh. *Journal of Water and Health*, 11(3), 532–542.

Islam M.A., Sakakibara H., Karim M.R., Sekine M.& Mahmud Z.H. 2011 Bacteriological assessment of drinking water supply options in coastal areas of Bangladesh. *Journal of Water and Health*, 9(2), 415–428.

ITN-BUET 2015 *Alternative Options for Access to Safe Water in Coastal Areas*, Project Completion Report, International Training Network Centre, Bangladesh University of Engineering and Technology (ITN-BUET).

Kamruzzaman A.K.M. & Ahmed F. 2006 Study of Performence of Existing Pond Sand Filters in Different Parts of Bangladesh, in: *Sustainable Development of Water Resources, Water Supply and Environmental Sanitation*: Proceedings of the 32nd WEDC International Conference. pp. 377–380.

Karim M.R. 2010 Microbial contamination and associated health burden of rainwater harvesting in Bangladesh. *Water Science and Technology*, 61(8), 2129–2135.

Kerwick M., Holt D., Kerwick M., Reddy S. & Chamberlain A. 2005 A methodology for the evaluation of disinfection technologies. *Journal of Water and Health*, 3(4), 393–404.

Mahmud S.G., Shamsuddin S.A.J., Ahmed M.F., Davison A., Deere D.& Howard G. 2007 Development and implementation of water safety plans for small water supplies in Bangladesh: benefits and lessons learned. *Journal of Water and Health*, 5(4), 585–597.

Redwan A.M., Ghosh S. & Rahman M.M. 2014 Effectiveness of UV-Technique for Water Disinfection in Dhaka City. *International Journal of Scientific & Engineering Research*, 5(1), 1393–1399.

UNICEF& WHO 2015*Progress on Sanitation and Drinking Water - 2015 Update and MDG Assessment*. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, WHO, Geneva, Switzerland, UNICEF, New York, USA.http://www.wssinfo.org (accessed 1 December 2015)

White K.H., Soward L.R.& Shankle G. 2007 *Harvesting, Storing, and Treating Rainwater for Domestic Indoor Use*, Texas Commission on Environmental Quality, Arlington, Texas, USA. http://rainwaterharvesting.tamu.edu/files/2011/05/gi-366_2021994.pdf(accessed 1 December2015)

WHO 2015 *Evidence of the Effectiveness of Household and Community WASH Interventions in Increasing Climate Resilience*, Environmental Health Unit, World Health Organization (WHO), Dhaka,Bangladesh.http://www.searo.who.int/bangladesh/publications/effectiveness_of_household/en/ (accessed 1 November 2015)

Wright J., Gundry S.& Conroy R. 2004 Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine & International Health*, 9(1), 106–117.