LOW COST WATER QUALITY INTERVENTIONS FOR THE PREVENTION OF DIARRHEAL DISEASE

by

Katherine Dwyer Philp

BS, Cornell University, 2003

MAT, University of Pittsburgh, 2004

Submitted to the Graduate Faculty of

The Graduate School of Public Health in partial fulfillment

of the requirements for the degree of

Master of Public Health

University of Pittsburgh

2008

UNIVERSITY OF PITTSBURGH

Graduate School of Public Health

This thesis was presented

by

Katherine Dwyer Philp

It was defended on

April 8, 2008

and approved by

Todd Reinhart, Associate Professor, Infectious Diseases and Microbiology, Graduate School of Public Health, University of Pittsburgh

Jeanette Trauth, Associate Professor, Behavioral and Community Health Sciences, Graduate School of Public Health, University of Pittsburgh

Conrad Dan Volz, Assistant Professor, Environmental and Occupational Health, Graduate School of Public Health, University of Pittsburgh

Thesis Director: Martha Ann Terry, Senior Research Associate, Behavioral and Community Health Sciences, Graduate School of Public Health, University of Pittsburgh

LOW COST WATER QUALITY INTERVENTIONS FOR THE PREVENTION OF DIARRHEAL DISEASE

Katherine Dwyer Philp, MPH

University of Pittsburgh, 2008

More than 2.2 million deaths occur worldwide each year due to diarrheal disease, mostly in children under five years of age, making it a problem of great public health significance. In developing countries, improving water at the household or point-of-use level has decreased the spread of diarrhea-related illnesses more than treatment of water at the source. Additionally, improving the quality of water has been shown to be as important in interrupting disease transmission pathways as increasing the quantity of water and improving general sanitation. Therefore, new technologies are being promoted for use in developing countries as low-cost methods of disease prevention. The current paper reviews interventions designed for water improvement at the household level, paying particular attention to related reductions in diarrhea as a primary disease outcome. Once shown to be effective at reducing disease in field or laboratory trials, the technology must then be promoted among and accepted by its intended users. Drawing upon the principles of community based participatory research, a framework is given for health professionals wishing to implement any novel technology or water quality intervention in a community setting.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

Thank you to Dr. Terry, for always believing I could, even when I didn’t.

1.0 INTRODUCTION

The numbers and statistics on global access to water and sanitation are staggering: more than 1.1 billion people lack access to safe drinking water worldwide (WHO/UNICEF, 2004). Sub-Saharan Africa is among the hardest hit regions, with 42% of the population living without access to clean water. Lack of sanitation is an even greater problem, with an estimated 2.6 billion living worldwide without adequate sanitation, and 64% of sub-Saharan Africa living without sanitation (WHO/UNICEF, 2004).

From a public health standpoint, the impact of the lack of clean water is significant. Nearly 60% of infant mortality can be linked to a water-related infectious disease; globally, diarrhea is the third largest cause of morbidity and the sixth largest cause of mortality, causing up to 2.2 million deaths per year (Montgomery & Elimelech, 2007). Morbidity and mortality are greatest amongst children under five years of age (WHO/UNICEF, 2004; Fewtrell et al, 2005; Montgomery & Elimelech, 2007; Tumwine et al., 2002). According to one report, "the magnitudes of the mortality and morbidity from waterborne diarrheal diseases unquestionably make them the planet's biggest environmental health threat to populations" (Gadgil, 1998, pg. 256).

Loss of fluid (dehydration) is the major cause of mortality associated with generalized diarrheal diseases, especially in young children (Clasen, Roberts, Rabie, Schmidt, & Cairncross, 2001). However, diarrhea also causes poor absorption of nutrients and, over long periods of time, can inhibit growth, reduce resistance to infection, promote disorders of the gut and bowels (Clasen et al., 2001), and cause impaired cognitive development (Clasen & Carincross, 2004). Disability-adjusted life years (DALYs) is a measure that combines death and disability in a single index; the global burden for water-related diseases is approximately 61,966,000 DALYs (WHO, 2008). In comparison, the global burden of malaria is estimated at only 46,486,000 DALYs (WHO, 2008). Thus, morbidity and mortality associated with diarrheal disease are indeed significant causes of concern for public health professionals.

Not only can the adverse effects of lack of water services be measured in DALYs and the burden of disease, but they are also reflected in the economic and social lives of developing countries. For example, many women in developing countries spend a significant portion of their day hauling water from a source to their home, up to six hours a day by some estimates (WHO/UNICEF, 2005). This often prevents young girls from attending school and women from engaging in income-generating activities such as selling produce or handmade products (Montgomery & Elimelech, 2007). One study found that, in rural Kenya in 1990, the value of time spent hauling water was equal to US$0.31 per hour (Whittington, Mu, & Roche, 1990). Multiplied by six hours, this equals $1.86, almost double the average income of US$1 per day or less in rural areas of Kenya (United Nations, 2008). In addition, it is estimated that over 10 million person-years of time and effort are lost annually (mostly by women and girls), and that global health care costs could be greatly diminished if diarrheal disease burden could be reduced (Pryer, 1993).

This paper focuses on water quality interventions and technologies, as a thorough review of both water quality and sanitation improvements would be beyond the scope of this project. A critical review of the current literature as related to water quality innovations is included, followed by recommendations for the use of the technologies reviewed to help guide the work of other professionals attempting to apply the interventions to community-based settings.

1.1 WATER AND TRANSMISSION OF DISEASE

A wide variety of pathogens known to cause diarrhea and other diseases are excreted in the feces of humans and animals. Viruses, bacteria, protozoa, and parasitic worms can employ a number of transmission routes (Curtis, Cairncross, & Yonli, 2000): the first option is to pass from human feces into the environment into a new human host; the second option is for the pathogen to multiply in the environment after being excreted by the first human host to increase the chance of meeting and colonizing a new human host; third, the pathogen can leave the human host via

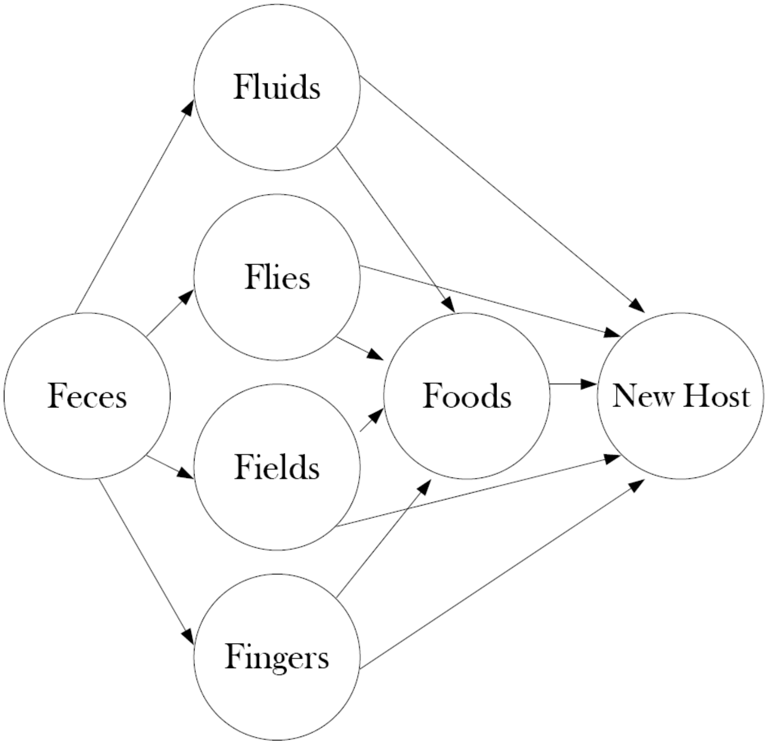

Figure 1. The F-Diagram

feces to the environment, be ingested by an animal host, where it is then released back into the environment before ingested into a new human host; the fourth option is that pathogens for which animals are the principal reservoir "cross over" and colonize humans via the environment. The "environment" can be represented through the F-diagram, as seen in Figure 1 (Curtis et al., 2000). Once excreted, pathogens may be passed from fingers, foods, or fluids into the new host. Flies landing on the excreta may carry pathogens to foods, while feet treading in fecally contaminated dirt or other material can bring pathogens into the home, where children playing on the floor may encounter them. Contaminated water may be used for food preparation, or may be used directly for hydration. It is important to note that "all of the transmission routes shown in the F-diagram can be blocked by changes in domestic hygiene" (Curtis et al., 2000, pg. 25).

Although multiple studies cite the fecal-oral route as the mode of transmission for most pathogens (Burch & Thomas, 1998; Clasen et al., 2001; Clasen & Carincross, 2004; Leclerc, Schwartzbrod, & Dei-Cas, 2002), they point out that most of these pathogens are waterborne, and are therefore transmitted via drinking water. Viruses that cause gastroenteritis can persist for weeks to months in the aquatic environment (Schwab, 2007). Some protozoa may remain viable for many months in this environment, and when nutrients and warmth are available, bacteria will multiply rapidly (Curtis et al., 2000). In fact, a hospital-based prevalence study of children from a rural town in Kenya suggests that contaminated drinking water was the primary mode of transmission of disease, followed by fecal-oral transmission through multiple other exposure routes, such as unwashed hands or food (Saidi et al., 1997).

Water supplies are often contaminated with fecal matter (coliforms) and polluted with a variety of microorganisms, including viruses such as Encephalomyocarditis virus, rotavirus, bacteriophage F2, and pathogenic bacteria such as *E. coli, Vibrio Cholerae, Str. Faecalis, S.*

Paratyphii, and. *S. typhii* (Tumwine et al., 2002). In addition, yeasts, moulds, protozoa, helminthes, and spore- and cyst-forming organisms may also be found in water supplies (Burgess & Onyonge, 2004). Several examples of the diseases caused by some of these organisms are shown in Table One.

Table 1. Water-Borne Pathogens and their Possible Etiologies

Bacteria	Diarrhea, cholera, enteric and typhoid fever, dysentery
Viruses	Hepatitis, polio, diarrhea, meningitis, lung diseases
Protozoa	Giardiasis, amoebic dysentery, diarrhea
Helminthes (worms)	Round worm, guinea worm, schistosomiasis

* Adapted from Burch & Thomas, 1998

While several sources cite rotavirus as the leading cause of diarrhea hospitalization among children worldwide (Prashar, Bresee, Gentsch, & Glass, 1998; Prashar, Gibson, Bresee, & Glass, 2006; Schwab, 2007; Wilhelmi, Roman, & Sanchez-Fauquier, 2003), and human noroviruses as the overall leading cause of gastroenteritis worldwide (Schwab, 2007), the relative contribution of any one etiologic agent to the presence of diarrhea within a given region has been shown to be influenced heavily by season of the year (Mutanda, Gemert, Kangethe, & Juma, 1986) and place. The most frequently identified pathogen varies across the world, from pathogenic *E. coli* in Uruguay (Torres et al., 2001), to rotavirus in Vietnam (Nguyen, Van, Huy, Gia, & Wientraub, 2006) to *Giardia lamblia* in Jordan (Nimri & Meqdam, 2004). Pathogenicity varies even within countries, as is the case in Kenya, where *G. lamblia* is the most common isolate in the Maasailand and Kiambu regions and *A. lumbricoides* is the most common isolate for the Kakamega region (Joyce, McGuigan, Elmore-Meegan, & Conroy, 1996). This is not surprising given the geography of the three regions, with the former two being hot, dry climates, and the latter being near an equatorial rainforest. *A. lumbricoides* is heavily influenced by soil type and rainfall, and would not be expected to thrive in the Maasailand and Kiambu regions (Joyce et al., 1996).

Clinically, it is nearly impossible to distinguish diarrhea caused by a virus from diarrhea causes by bacteria or other pathogens (Wilhelmi et al., 2003). Given the above information regarding variation of pathogens by time and place, effective treatments for diarrheal disease and subsequent intervention selection will depend on knowing the infectious agent causing disease. Several techniques are available to detect pathogens in host feces and the hosts themselves, including detection of antigens in feces and PCR techniques (Wilhelmi et al., 2003). Unfortunately, these tests are time- and cost-intensive and may not be readily available in developing countries. In addition, a study that tested the serologic response to antigen testing in human subjects found that the technique was useful for *Giardia intestinalis*, but not for *Norovirus, C. Parvum*, or Enterotoxigenic *E. coli* (Crump et al., 2007). Therefore, in resource-limited settings, prevention of disease rather than treatment should be a main focus, and interventions that are effective against a wide range of pathogens are preferable.

1.2 WATER TREATMENT

According to one reference, “The most important way to obtain safe drinking water for a community is to protect its source from fecal contamination and to sufficiently isolate it from dumping of household garbage, industrial waste, mining and quarrying activities, and agricultural runoffs of fertilizers, herbicides, and pesticides" (Gadgil 1998, pg. 268). Pollution and contamination occur in many places where the water source cannot be protected, and therefore, such water requires treatment before consumption. Treating contaminated water at the source is a difficult and expensive endeavor, but “leading institutions and national governments have traditionally focused on implementation of large, centralized treatment systems" (Montgomery & Elimelech, 2007, pg. 20). These types of systems generally serve only urban areas, due to their population density, and tend to have high capital costs, lack proper operation in developing countries, and have an over-reliance on technology that is not affordable or well-maintained (Montgomery & Elimelech, 2007). Moreover, a review of 30 studies on source treatment of water versus point of use (POU) treatment concluded that household POU treatment of water is more effective in preventing diarrhea (Clasen et al., 2001).

POU treatment is effective where centralized systems, such as piped water systems, might be otherwise difficult to install. The crucial advantage of POU treatment is that it provides decontamination of pathogen-infected water immediately before consumption, breaking the exposure chain (Montgomery & Elimelech, 2007). The importance of this can be seen in rural Africa, where even a “safe” source, a deep well that is otherwise pathogen free, becomes contaminated from poor hygiene practices during collection, storage, and handling of the water (World Bank, 2004). Additionally, a meta-analysis of water, sanitation, and hygiene interventions in developing countries found that reduction of diarrheal cases is doubled when water is treated immediately before use (Fewtrell et al., 2005).

POU treatment technologies can be grouped into four main categories:

1. Physical removal of pathogens (filtration, absorption, or sedimentation)
2. Chemical treatment (usually sodium hypochlorite disinfection, but can include chemical flocculation, or treatment with other chemical agents)

3. Heat treatment (boiling or pasteurization) and ultraviolet (UV) radiation using the sun (solar disinfection) or a UV lamp
4. Combination Approaches (filtration combined with disinfection)

Educational or behavioral approaches and safe storage are not classified as treatment technologies in this review, but are considered in a class by themselves, to be used as stand-alone interventions for disease reduction, or in combination with any of the above technologies. “Safe storage” refers to containers that are designed to keep purified water safe from recontamination. For example, some containers have openings too narrow to allow a contaminated hand to enter into the water.

There are, of course, obvious advantages and disadvantages to each method. Table 2 compares some of the most widely used methods to disinfect contaminated water. Boiling with firewood or other such fuel sources is one of these (and one of the most microbially efficient). However, it is environmentally unsustainable, using up to 1kg of wood per liter of boiled water (Tumwine, 2005), provides no residual protection against recontamination after cooling, is associated with a risk of scalding (Mintz, Bartram, Lochery, & Wegelin, 2001), and is costly in terms of time and effort (Burgess & Onyonge, 2004).

Chlorine is one of the most effective, and least expensive chemical disinfectants used for POU treatment (Mintz et al., 2001) having been shown to reduce diarrheal illness by up to 85% in some cases (Quick, Venczel, & Mintz, 1999). However, it is often rejected by many people because of taste (Altherr, Mosler, Tobias, & Butera, 2006), and can become too expensive in some rural areas. Filtration is often too expensive for poor, rural peoples (Clasen, Brown, Collin, Suntura, & Cairncross, 2004), as is UV irradiation (Sobsey, 2002). Solar disinfection, as noted in

Table 2, is simple, inexpensive, and has moderate microbial efficacy, though it does not function in all temperatures and weather conditions.

Table 2. Comparison of Methods of Point-of-Use Water Treatment

Method	Availability	Difficulty	Cost	Microbial
Boiling with fuels	Varies	Low-Moderate	Varies	High
Exposure to Sunlight (Solar)	High	Low-Moderate	Low	Moderate-High
UV Irradiation (lamps)	Varies	Low-moderate	Moderate-high	High
Plain Sedimentation	High	Low	Low	Low
Filtration	Varies	Low-Moderate	Varies	Varies
Chlorination	High-Moderate	Low- Moderate	Moderate	High
Coagulation-Flocculation	Moderate	Moderate	Varies	Varies

* Adapted from Sobsey (2002)

1.3 WATER TREATMENT INTERVENTIONS

It is generally accepted by health authorities that safe water plays an important role in the prevention of outbreaks of diarrheal and other waterborne diseases (Hunter, 1997). Therefore, the World Health Organization (WHO) accepted standard for water quality allows no detectable level of harmful pathogens at the point of distribution (WHO, 2006). However, due to multiple pathways of waterborne pathogen infection, such as ingestion of contaminated food or beverage, person-to-person contact, and direct or indirect contact with infected feces, improvements in water quality alone may not necessarily interrupt disease transmission (see F-diagram, Section 1.1) (Clasen & Carincross, 2004). Therefore, it is suggested that interventions for the prevention of diarrheal and other waterborne diseases not only include improved water quality, but also include steps to improve sanitation (disposal of human feces), increase quantity of and access to water, and promote hand washing and hygiene practices (Whittington et al., 1990). Some authors have gone as far as suggesting that improved hygiene and sanitation are more important than safe water in the reduction of diarrheal and other waterborne diseases (Sobsey, 2002; Esrey & Habicht, 1986).

Due to the recommendation of a multifaceted approach, several authors have promoted interventions that rely on household water treatment combined with sanitation techniques as a viable option to prevent outbreaks of diarrheal disease (Elimelech, 2006; Mintz et al., 2001; Souter et al., 2003; Wilderer, 2005). However, the only study reviewed that implemented a combined approach of water treatment with hand washing education showed no additive effects of these practices and concluded that it may not be cost effective to deliver both a technology and educational campaign (Luby et al., 2006). Other multiple environmental intervention studies appear to lack an additive effect as well (Clasen et al., 2001). Additionally, a study implementing a ceramic water filter without any educational or communications component found a mean reduction in diarrhea prevalence among users of 64% (Clasen et al., 2004), similar to a 53% reduction among children (under age 15) who received only a hand washing intervention (Luby, et al., 2005), indicating that a simple and easy-to-use technology may actually yield better results than education alone. These results contrast sharply with previous reviews that indicate the ineffectiveness of water quality improvements as stand-alone interventions (Esrey & Habicht, 1986; Cairncross, 1989). According to one author, "It is now well documented that the provision of safe water alone will reduce diarrheal and other enteric diseases by 6 to 50%, even in the absence of improved sanitation or other hygiene measures" (Sobsey, 2002, pg. 4).

The remainder of this section will review low-cost interventions with particular reference to diarrheal disease as a primary outcome.

1.3.1 Chemical Treatment

The focus of the following section will be on treatment technologies that aim to inactivate pathogens or other water-borne microbes through chemical processes. Specific attention will be given to interventions appropriate for developing nations that can be applied at the household level.

1.3.1.1 Free Chlorine

Free chlorine is the most widely used water disinfectant available today, and one of the most affordable (Sobsey, 2002). It is highly effective against nearly all waterborne pathogens, with the exception of *Cryptosporidium parvum* oocysts and *Mycobacteria* species (Sobsey, 1989). The most practical form of free chlorine for point-of-use water disinfection is liquid sodium hypochlorite (Sobsey, 2002); occasionally, calcium hypochlorite is also used (Arnold & Colford, 2007). It is recommended that the chlorine solution be produced by a local manufacturer or in the community itself using water, salt and an electrolytic cell (Centers for Disease Control and Prevention, 2001). Both types of hypochlorite solution are inexpensive, and have the additional advantage of providing residual protection against recontamination for hours to days (Sobsey, 1989).

Most of the studies conducted since the early 1990s have been part of the Centers for Disease Control and Prevention's (CDC) efforts to promote the Safe Water System (SWS). This is a three-component intervention that consists of chlorination, safe storage, and educational approaches (See Section 1.3.6.1). This section reviews only those studies that have not combined free chlorination treatment with safe storage or education.

In an early study on the use of chlorination, it was found that cholera infection was decreased by 57.8% in the chlorinated group as compared to a control group (Deb et al., 1986). The families were provided with chlorine tablets and instructed on how to use them, but were not otherwise provided with instruction on any hygiene measures. Note that there was also no instruction on safe storage in this study, as participants were able to chlorinate in any vessel they chose.

A meta-analysis that reviewed both chlorine-only interventions and those that used the SWS, however, found an enhanced effect of safe storage and education in urban and peri-urban settings (Arnold & Colford, 2007). There were not enough high quality trials to examine the effects in rural settings, and every trial that included safe storage also included education, so the two effects could not be examined separately from one another.

Only a few published studies have reported no positive health benefits following water treatment with free chlorine. Interestingly, in one of these studies, a double-blind methodology was utilized, and no difference was found in community rates of diarrhea following chlorination (Kirchoff et al., 1985). A meta-analysis of interventions to prevent diarrheal disease reported that none of the double-blinded studies reviewed showed a statistically significant protective effect from the intervention (Clasen et al., 2001), suggesting that the Hawthorne effect (the effect of being under investigation) or courtesy bias (the tendency of subjects who know they are in the intervention group to overstate the effect to please the researcher) (Clasen et al., 2001) may play a role in the effectiveness of interventions. However, another review (Sobsey, 2002) review cites other methodological problems with the above study, such as possible incorrect chlorine dosing, potential intake of other water sources, and lack of hygiene education.

In a second study that chlorinated a public water-supply system in Pakistan, children who drank from the treated supply actually had a significantly increased risk of diarrhea compared to children using groundwater sources in a control village, despite the fact that the water from the source was microbially improved following chlorine treatment (Jensen et al., 2003). The authors suggest that the incidence of diarrhea in the villages was independent of the drinking water and was due instead to other routes of transmission (see F-diagram, Section 1.0). However, their choice of microbial indicator was *E.coli*, which may show poor correlation with other causes of enteric disease in water sources, such as viruses and protozoa, especially *Cryptosporidium parvum* (Jensen et al., 2003). *C. parvum*, as noted previously, is highly resistant to chlorination, and may cause gastroenteritis in children (Yousafzai & Bhutta, 2000) and adults (Fayer, 2004).

There are several drawbacks to the use of chlorine, in addition to its ineffectiveness against chlorine-resistant pathogens. If large quantities of organic material are present, there is reduced effectiveness against parasites and viruses as chlorine binds to the organic material, and more chlorine is necessary to disinfect water (Crump et al., 2007). The addition of larger quantities of chemical may also produce an unpleasant taste and odor, decreasing willingness of people to drink the water (Reller, Mendoza, & Lopez, 2003). Perhaps most significant, chlorine disinfection by-products (DBPs) may pose a substantial risk to human health, including an increased risk of bladder cancer and the lower intestinal tracts (Leavens, Blount, DeMarini, Madden, Valentine, & Case, 2007). Epidemiologic studies have found an association between fetal deaths in women and DBP concentrations in the 1-49 μg/L range (Wigle, Arbuckle, Walker, Wade, Liu, & Krewski, 2007). A survey of water plants across the U.S. reported DBPs in drinking water ranging from 1-50 μg/L (Leavens et al., 2007), which is within the maximum DBP limit of 80 μg/L (EPA, 1998). WHO Guidelines for certain DBPs are as high as 200 μg/L (CDC, 2008), but some references claim that drinking water used in the SWS and other chlorination projects do not exceed these levels (Lantagne, Quick, & Mintz, 2006). The CDC admit, “There is a slight risk, measured in one additional cancer per 100,000 people after 70 years, to the ingestion of THMs [types of DBPs] at the WHO guideline value level” (CDC, 2008). However, they offer no information on the risk of spontaneous abortions, stillbirths, or neural tube defects in pregnant women (Leavens et al., 2007). While the risk due to death from diarrhea outweighs the risk due to death from cancer in developing nations, more research into the possible hazards of consuming DBPs is being conducted to ensure the safety of those who consume treated water.

1.3.1.2 Chemical Coagulation, Flocculation, and Sedimentation

In much of the literature, the terms coagulation and flocculation have been used interchangeably to refer to the process whereby particulates in solution come together to form a clump or a “floc.” It is important to distinguish between the two processes. According to one definition, coagulation is the destabilization of a solution, whereas flocculation is the agglomeration of particles within that solution that have been destabilized (Bratby, 1980). In other words, coagulation refers to aggregation on a molecular level, while flocculation refers to aggregation on a macro-particulate level.

Alum (aluminum sulphate) and iron are commonly used coagulant/flocculants, though treatment with such chemicals is generally beyond the skills and capabilities of most household users, and is considered by many to be best left to trained personnel at water treatment facilities (Sobsey, 2002). Despite these limitations, however, alum has been used at the household level to treat water for centuries in many parts of the world (Sobsey, 2002). In western Kenya, for example, alum is commonly used to clarify turbid drinking water (Crump et al., 2004).

Due to the difficulties of using alum for home-based treatment, however, new methods have been developed to make coagulation/flocculation accessible to potential users. The PUR water sachets, developed by Procter & Gamble Co. (Mason, OH), are one example. These packets include the same chemicals used in municipal water treatment plants, scaled down and placed into one-time use packets intended for the treatment of small volumes of water. These sachets combine precipitation, coagulation, and flocculation with disinfection, as they contain not only ferric sulphate as a flocculant, but also calcium hypochlorite as a disinfectant (Crump et al., 2004). PUR is currently marketed in the United States for camping and wilderness purposes, and for use in disaster-related emergencies (P&G, 2008).

Several studies have examined the use of PUR sachets in developing nations. In a study comparing PUR packets, chlorine, and alum as water treatments for home use, the PUR sachets performed best in waters that were both highly contaminated and highly turbid (Crump et al., 2004). Alum combined with chlorine disinfectant was useful in reducing contamination levels of *E. coli*, but was less effective at mitigating turbidity than the PUR packets. Alum alone was able to mitigate turbidity, but was not effective at reducing *E. coli* concentrations. Chlorine was not able to mitigate turbidity, and while it achieved high E. coli reductions in low turbidity waters, it was not useful for highly turbid waters (Crump et al., 2004). For western Kenya, where source waters are often highly turbid and highly contaminated, PUR packets were most effective.

The authors of the above study then implemented the PUR packets in a community-based trial in western Kenya to examine their ability to reduce diarrheal disease. Compared to controls, the flocculant/disinfectant reduced diarrhea prevalence by 19% (Crump et al., 2005). However, chlorination alone reduced diarrhea prevalence by 26%, a non-significant difference between the two interventions. In a similar study in Guatemala, the PUR packets combined with a safe storage vessel were most effective at reducing diarrhea incidence (29% reduction compared to controls), but again, the intervention was not significantly different from treating with chlorine alone (25% reduction compared to controls) (Reller, Mendoza, & Lopez, 2003).

Evaluations of PUR have also been conducted in emergency settings following flooding due to tropical storms (Colindres, Jain, Bowen, Domond, & Mintz, 2007), and in refugee camps (Doocy & Burnham, 2006). Following flooding from Tropical Storm Jeanne in Haiti, 410,000 sachets of PUR were donated to the relief efforts. Despite intense educational and marketing interventions, use of the sachets following the disaster was low (fewer than 25% of households reported using PUR more than five times over two to four weeks). In addition, once the free supply ran out, less than 25% of the surveyed population said they would be willing to pay for PUR (Colindres et al., 2007).

In refugee camps in Liberia, PUR sachets reduced diarrhea prevalence by 83% when compared with baseline data, and by 91% when compared with controls who had received only improved storage (Doocy & Burnham, 2006). The authors attribute the extremely large reductions in diarrheal disease to two factors: high compliacne to the intervention (95.4%

compliant), and the possiblity of epidemic diarrhea in camp settings (20% prevalence at baseline). They suggest that higher reductions in diarrhea may be seen in epidemic situations as opposed to those settings in which diarrhea is endemic (Doocy & Burnham, 2006).

As noted above, PUR sachets are useful in situations where water is highly turbid and highly contaminated, and the results of the above studies suggest that compliance to an intervention may be based heavily on factors not explored in either of the emergency situations described, such as the educational programs that accompany the intervention, taste issues, and issues of time involved with disinfecting water with PUR sachets. Several drawbacks to PUR sachets include the potential for dry product to cause injury to humans and animals (P&G, 2008), changes to taste and odor of the water at higher doses (Crump et al., 2004), and problems with disposal of the floc residue. While the instructions for United States residents indicate that the floc should be placed in a latrine or away from children and animals (P&G, 2008), this may be difficult in developing nations where many areas do not have latrines or adequate refuse disposal areas. In addition, the packets themselves may constitute a waste issue following use.

1.3.1.3 Other Chemical Treatment

Other chemical treatments are currently being investigated as potential methods of water purification. Several low-cost interventions are reviewed below which all show promise in the developing world for their ease of use and affordability.

Silver

Silver is known to be a powerful antibacterial and antiviral agent, having been used since ancient times (Feng, Wu, Chen, Cui, Kim, & Kim, 2000). It inactivates microorganisms by interfering in biochemical pathways, primarily by binding to the sulfhydryl groups (-SH) of proteins (Silvestry-Rodriguez, Bright, Uhlmann, Slack, & Gerba, 2007). The only known side effect in humans is a condition known as argyria (permanent discoloration of the skin), which results from long-term exposure to large doses of silver compounds (Potters for Peace, 2006). WHO has set a maximum level of 100 μg/L of silver for water disinfection without potential health risks (Silvestry-Rodriguez et al., 2007).

Silver is often used with ceramic filters to promote the bactericidal effects of the systems; usually colloidal silver is painted on the ceramic in a thin layer before or after firing (Potters for Peace, 2006). However, it may be possible to remove pathogens using free silver in drinking water. One published study examined the effect of silver nitrate, in a concentration of 100 μg of silver per liter of water, on *Pseudomonas aeruginosa* and *Aeromonas hydrophila,* two organisms known to cause gastroenteritis (Silvestry-Rodriguez et al., 2007). In trials conducted in both the presence and absence of humic acid (organic matter), there was a greater than 6 log reduction in bacterial counts of *P. aeruginosa* after eight hours in water treated with silver solution, with no significant differences between the two trials. After nine hours, in varying pH conditions, *A. hydrophila* also reached a greater than 6 log reduction, again without significant differences between the two trials. These results indicate that silver is not as sensitive as chlorine to the presence of organic matter, and that its antibacterial properties are not affected by pH. In addition, silver does not form harmful by-products like chlorine, perhaps making it an preferred choice as a disinfectant.

However, microbial resistance to silver has been reported, despite silver having been used to control *Legionella* in U.S. hospitals for at least five years without evidence of tolerance or resistance (Silvestry-Rodriguez et al., 2007). It has been suggested that anternating between silver and chlorine could help prevent the development of resistance (Silvestry-Rodriguez et al., 2007), but further research is needed before conclusively promoting silver as a water disinfectant.

Lime Juice Disinfection of V. cholera

Although seemingly simplistic, the addition of lime juice to food (Rodrigues et al., 2000; Mata, Vargas, Saborio, & Vives, 1994) and water (Dalsgaard, Reichert, & Mortensen, 1997) is an effective strategy to prevent cholera, caused by the pathogen *Vibrio cholerae*. Factors decreasing the survival of *V. cholerae* include high temperatures, acidic pH, and low moisture (Kolvin & Roberts, 1982). Therefore, it is assumed that lime juice prevents the survival of *V. cholerae* by making the food or liquid more acidic. In the only published study on water, concentrations of 1-5% lime lowered water acidity below pH 4.5, and reduced *V. cholerae* by greater than 99.999% in two hours (Dalsgaard et al., 1997). Other studies have shown that the addition of lime juice to cabbage and lettuce reduces *V. cholerae* by greater than 99.99% (Mata et al., 1994), while peanut sauce with two to five limes has no *V. cholerae* growth after three hours of adding the pathogen (Rodrigues et al., 2000). Although lime juice shows promise as a potential household water treatment, further studies should be conducted on water before conclusively reporting on its efficacy in preventing cholera transmission.

Other Chemicals

Removing viruses from water has proven to be one of the biggest challenges investigators face in water quality research. Increasingly, researchers are turning to nanotechnology, or microscopic particles, in an attempt to remove viral particles from water. One example of a nanoparticle that has been recently investigated for its anti-viral properties is colloidal zirconia (ZrO_2). The particles are 5-10 nm in size, and possess a positive surface charge (Wegmann, Michen, Luxbacher, Fritsch, & Graule, 2007). This is important, as many viruses possess a net negative surface charge and will therefore be attracted to an opposing charge.

Using MS2 coliphages (non-pathogenic virus-like particles that are accepted models for real viruses), one team studied the application of colloidal zirconia on a ceramic filter (Wegmann et al., 2007). Unfortunately, certain characteristics of the zirconia were discovered that made it unsuitable as a nanoparticle coating for ceramic filters. For example, once applied to the ceramic and dried, the particles were easily redispersable in water and required a heat treatment called sintering to ensure particle adherence to the ceramic. Sintering caused the particles to grow in size, resulting in a loss of specific surface area, thereby decreasing the anti-viral capacity of the filter, which is directly related to this measure (Wegmann et al., 2007). If the sintering problem could be removed, the coating should increase the specific surface area available for viruses to adsorb to. However, if this occurs, the flowrate of the filter (the output of water per hour) decreases greatly due to the fact that the particles block pores that water once flowed through. For these reasons, research is now being conducted on nanoparticles that do not easily wash out of filters during operation, do not change during sintering, and do not impair flowrate of the filter (Wegmann et al., 2007).

1.3.2 Solar Disinfection

Solar disinfection of contaminated water shows promise as a low-cost, user-friendly technology that may be implemented in many areas of the developing world. The basic method of solar disinfection, SODIS, is reviewed here first, followed by several examples of SODIS variations and attempts at improving upon the original method.

1.3.2.1 SODIS

Electromagnetic radiation emitted from the sun can be harnessed for POU water disinfection (Mintz, Bartram, Lochery, & Wegelin, 2001), and in fact, has been used in India since about 2000 BC, where water was filtered through charcoal and exposed to the sun (Conroy, Elmore-Meegan, Joyce, McGuigan, & Barnes, 1996). A renewed interest in solar disinfection has led to the development of the SODIS system, a solar water project that has been researched since the early 1980s, (Acra, 1984; Sommer, 1997; Weglin, 2001) and is still being thoroughly investigated.

Inactivation of pathogens is achieved through the destructive effects of UV radiation ("optical disinfection"), through increased temperature ("solar pasteurization" or "solar distillation"), or through the synergistic effects of temperature and optical mechanisms (Mintz et al., 2001; McGuigan, Joyce, Conroy, Gillespie, & Elmore-Meegan, 1998) (see Figure 2). The exact mechanism by which SODIS inactivates pathogens is not yet fully understood.

Ultraviolet light is divided into three main components: UV-A, UV-B, and UV-C wavelengths. UV-C is not of concern because it does not pass through the atmosphere, instead

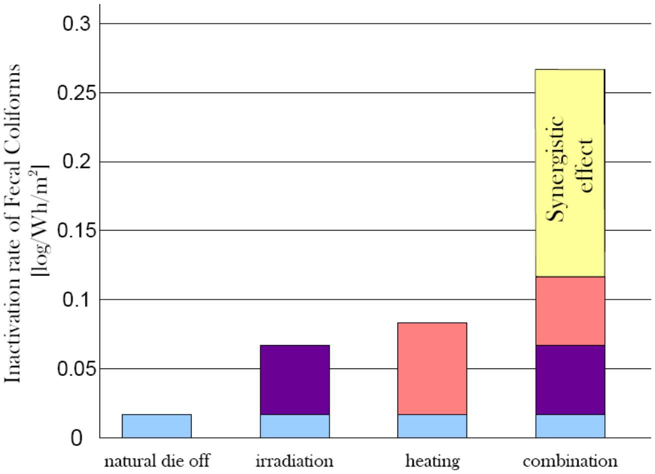

Figure 2. Synergistic Effect of UV-Radiation and Temperature on Fecal Coliforms in Raw Water

becoming absorbed by the ozone layer (SANDEC, 2008). UV-B may also be unimportant when using polyethylene terephthalate containers (see below) for SODIS, as this material absorbs wavelengths within the UV-B range (SANDEC, 2008). It is believed that it is UV-A light that produces reactive oxygen species (free radicals, OH·) that can damage microorganisms by oxidizing nucleic acids, proteins, or other cellular components (Berney, Simonetti, & Egli, 2006; Oates, Shanahan, & Polz, 2003). High temperatures can cause denaturation of proteins, which may also kill the organism (Oates et al., 2003).

A variety of materials, exposure times, water conditions, and temperatures have been tested, with optimal containers identified as clear plastic soda bottles (up to 2 liters in volume) made of polyethylene terephthalate (PET) plastic, due to their high transmission of ultraviolet A rays, general availability (Mintz et al., 2001), and chemical stability (Weglin M. , 2001). Glass bottles may also be used, and in fact, have been shown to achieve complete inactivation of pathogens in approximately 80% of the time required for PET bottles holding identical fluid amounts (Duffy et al., 2004). However, plastic is preferred over glass because it is less prone to breakage and more easily transported when empty. PET bottles can be used for several months for the SODIS system; after heavy use, bottles lose UV-A transmittance ability (Figures 3 and 4) due to mechanical scratching or optical property changes in the PET material (not chemical, as noted above; therefore, the molecules do not migrate into the water). The byproducts formed as a result of the UV radiation are known as photoproducts.

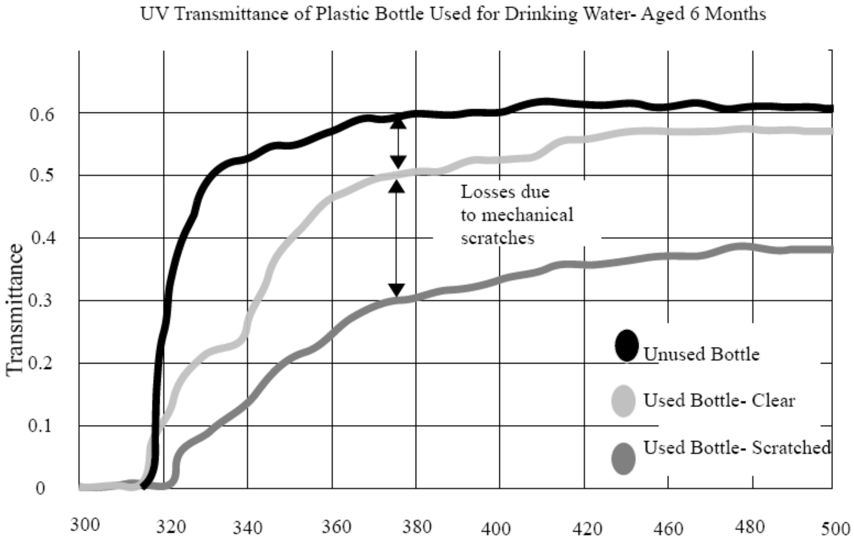

Figure 3. UV-Transmittance Losses Due to Mechanical Scratches

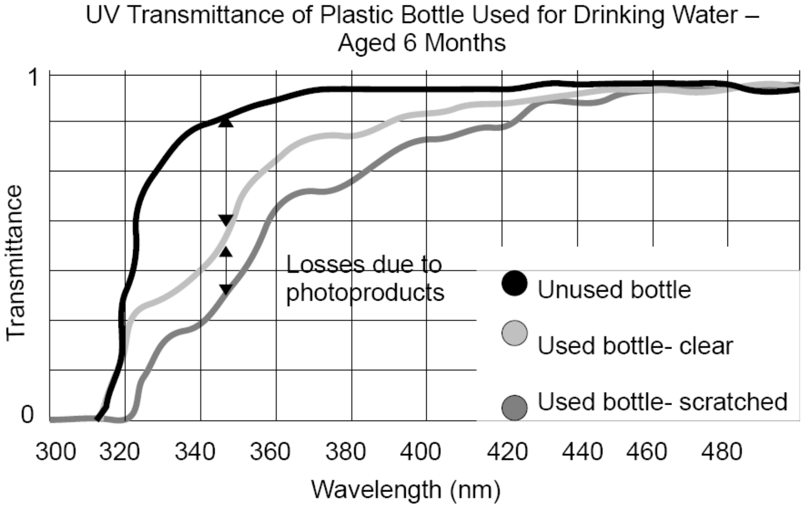

Figure 4. UV-Transmittance Losses Due to Photoproducts

Temperatures for SODIS must reach at least 45 degrees C for at least seven hours of strong to medium solar irradiances (40-70mWcm^{-2}) (McGuigan et al., 1998). Several studies indicate that this is feasible even for highly turbid water (i.e. the water is not clear, therefore, UV radiation cannot penetrate very far into the bottle) that is highly infected with *E. coli* (McGuigan et al., 1998; Joyce, McGuigan, Elmore-Meegan, & Conroy, 1996). Because increased heat increases the bactericidal effects of UV radiation, the process may be enhanced by painting the rear half of the bottle black (or coating it with dark mud) and keeping the bottle sheltered from the convective cooling effects of the wind (McGuigan, Joyce, Conroy, Gillespie, & Elmore-Meegan, 1998). However, under overcast skies, such containers may take up to two days to completely inactivate contaminants (Oates et al., 2003). As such, reflective rear surfaces are preferable if available, either in the form of heavy-duty aluminum foil or as a custom built stainless-steel backing for the bottles (Mani, Kanjur, Singh, & Reed, 2006). Bacterial inactivation also increases as dissolved oxygen increases; therefore, periodic shaking and aeration of the bottle during exposure should speed up the disinfection process (Reed, 1997) (see Figure 5). Solar concentrators can also be created using locally available materials (cardboard and aluminum foil), which reduce disinfection time to under two hours in full sunlight (Martin-Dominquez, Alarcon- Hererra, Martin-Dominquez, & Gonzalez- Hererra, 2005).

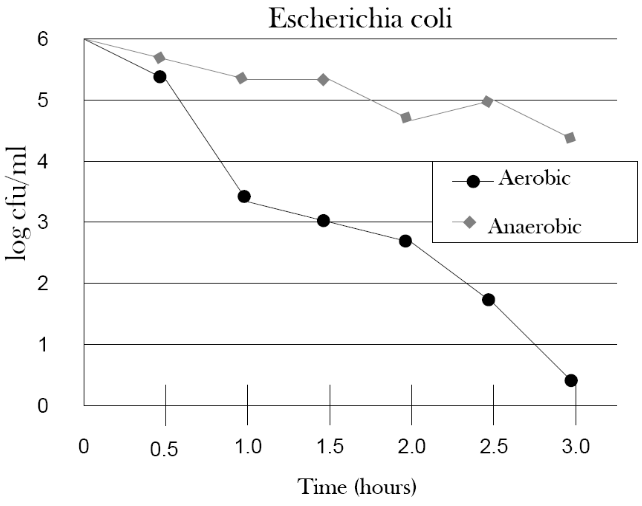

Figure 5. Inactivation of *E. coli* under aerobic and anaerobic conditions

Several studies have examined the efficacy of SODIS (under simulated or laboratory conditions) for inactivating particular strains of pathogens. Results show that SODIS is highly effective against *Escherichia coli* (McGuigan et al., 1998), *Giardia lamblia* (McGuigan, et al., 2006), *Salmonella typhimurium* (Smith, Kehoe, McGuigan, et al., 2000), poliovirus (Heaselgrave, Kilvington, Kehoe, & McGuigan, 2006), *Cryptosporidum parvum* (Méndez-Hermida, McGuigan, Boyle, Sichel, & Fernández-Ibáñez, 2007), *Shigella flexneri* (Berney et al., 2006; Kehoe, Barer, Devlin, & McGuigan, 2004), *Vibrio cholerae* (Berney et al., 2006), *Pseudomonas aeruginosa*, *Candidia albicans*, *Fusarium solani*, and both the trophozoite stage of *Acanthamoeba polyphaga* (Lonnen, Kilvington, Kehoe, Al Touati, & McGuigan, 2005) and its cyst form (Heaselgrave et al., 2006).

A serious concern with the SODIS system is the possibility of a phenomenon known as photorepair. This occurs when the enzyme photolyase is activated by exposure to wavelengths of 350-450nm and begins to repair damage that has been done to the cell (Bohrerova & Linden, 2007). In a photorepair study of *E.coli*, comparing laboratory lamps to full sunlight exposure, the microorganisms were first DNA damaged to a level of 4-5 log inactivation before re-exposure to lamps or solar light (Bohrerova & Linden, 2007). The researchers found that after 15 minutes of solar exposure, photorepair rates were identical to those achieved in laboratory conditions in up to 240 minutes under the lamps. However, after 15 minutes, the survival of the *E. coli* cells began to decrease, indicating that the intensity of sunlight (which was 10 times greater than that of the lamps) caused irreversible damage to the cells that could not be repaired by the photolyase enzyme. Other studies have concluded that photorepair is unlikely following SODIS disinfection, given the lack of viable *E. coli* in cultures taken more than 12 hours after the experimental treatment (Joyce et al., 1996), and scanning electron micrographs that show serious damage to oocysts of *C. parvum* following 10 hours of exposure (McGuigan et al., 2006).

Another related concern with the use of SODIS is the possibility of dark-repair mechanisms, such as those induced by the *rec*A gene and subsequent RecA protein produced by the gene. The RecA protein coordinates DNA repair, cell division, and a number of other cellular processes (Stohl et al., 2003) following UV radiation. The dark repair mechanism is important if water is irradiated and then stored in a dark place. Following UV fluences (doses) higher than 400 J/m^2, the German standard for drinking water disinfection, researchers found indication of *rec*A gene activity (*rec*A mRNA) in opportunistic bacteria using Northern blot analysis (Jungfer, Schwartz, & Obst, 2007).

Although there have been many studies of SODIS under simulated or laboratory conditions (see Table 3), there have been only three articles documenting field trials of SODIS in "real" or community-based settings (Conroy et al., 1996; Conroy, Elmore-Meegan, Joyce, McGuigan, & Barnes, 1999; Rose, 2006). Whereas laboratory studies have had exceptional success using the SODIS system, with little to no pathogenic contamination remaining after several hours of sunlight exposure, the three field trials found only partial reduction in the incidence of diarrheal cases, ranging from 16% (Conroy et al., 1999) to 40% (Rose, 2006) in children under five years of age, and 9% in children aged 5-16 years of age (Conroy et al., 1996). However, SODIS reduced severe diarrhea (i.e., that which prevents performance of duties) by 26% in the 5-16 year old age group over a three month period compared to a control group. (Of note, one unpublished summary of a Ph.D. Thesis by Hobbins, 2003 also claims to have reduced individual risk of diarrhea by 40% in children under the age of 5 years).

There may be several reasons for the low reduction in diarrheal morbidity, when there should be no pathogens consumed from SODIS water. First, the study that reported a 40% reduction in diarrhea found this despite discovering that 85% of children consumed sources of drinking water other than the disinfected water (Rose, 2006). Second, there is a possibility of recontaminating disinfected water during storage, transfer, and improper handling, such as dipping contaminated containers or hands into a storage vessel (Burgess & Onyonge, 2004). Perhaps most importantly, it should be noted that a meta-analytic review found that the methodology employed by two of the three field trials (Conroy et al., 1996; Conroy et al., 1999) was "inadequate," lacked blinding, as well as the inclusion of randomized participants (Clasen et al., 2001). This indicates that, while SODIS shows great promise as an affordable, efficient water disinfection technique, there remains a great deal of work to be done before any conclusions can be drawn regarding its impact on the health of a population.

1.3.2.2 Semi-Continuous SODIS

Developed by Xanat Flores for her Master of Engineering project at Massachusetts Institute of Technology, Semi-Continuous SODIS (SC-SODIS) is a novel approach to a well-known technology, aimed at reducing the barriers to use of traditional SODIS systems. The results of a study in Nepal were consistent with a previous study by SODIS project initiators which found that barriers to the adoption of SODIS include "unpleasant taste of water," "no bottles available," and that people "don't trust the method" (EAWAG, 2008). However, the main barrier in the Nepal study (83% of respondents) was the workload of women (Rainey & Harding, 2005).

The SC-SODIS system consists of the same PET bottles used in traditional SODIS, glued together in parallel, along with PVC piping, in such a way that water will flow through the system at an exposure time of two days (see Figure 6). The flux of the system has been set at two days because, according to some authors, this is the recommended solar exposure time for optimal disinfection capacity of nearly all pathogenic organisms (Oates et al., 2003). Once the bottles have been glued together in the specified arrangement, they are placed on a rooftop or other surface exposed to full sunlight for the majority of the day (see Figure 7). The system requires the use of a holding tank that can be placed on the roof or other elevation, and can be filled manually or with a mechanical or electric pump. The angle of inclination is dependent on the latitude of the location where the system will be placed, so that the bottles will obtain radiation perpendicular to the rays of the sun (Oates et al., 2003; Flores, 2003).

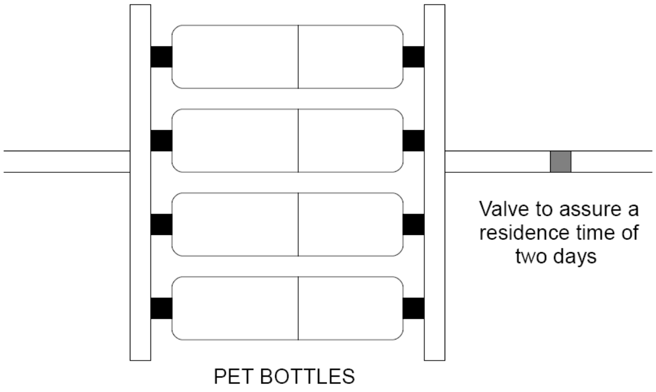

Figure 6. SC-SODIS Detail

During field testing of the SC-SODIS system in Nepal, in January of 2003, one of the coldest months in the region, solar radiation only reached SODIS threshold levels of 2500Whr/m^2 over one day of exposure on two occasions, and only after two days of combined radiation on several other occasions. Despite these low radiation levels, "SC-SODIS did not seem to create a medium for microbial organisms to proliferate" (Flores, 2003, pg. 85). Microbial tests for total coliforms showed decreases in all but two cases, and microbial reductions were inversely proportional to days of exposure and flow rate.

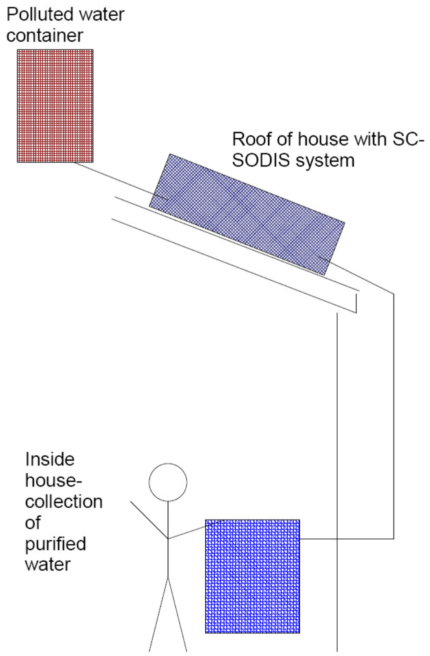

Figure 7. Schematic of SC-SODIS system as seen from outside a home

The longer exposure times due to reduced flow rate equates to longer exposure to the damaging effects of solar radiation, and therefore decreases survival of pathogens in the water.

In order for a system to be utilized, it must not only be microbially efficient, it must also be culturally and economically acceptable to the community in which it is placed. As mentioned above, the traditional SODIS system, while economically feasible for many, may place a heavy burden on already overworked women of the family, resulting in resistance to using the system. In a social feasibility study undertaken as part of the larger body of work referenced above, it was found that the laboriousness of taking out several PET bottles every day for SODIS, lack of inadequate training, and a lack of understanding of how solar disinfection works all contributed to the discontinuation of a SODIS project in the SC-SODIS study area (Flores, 2003). In addition, only those houses with easily accessible roofs could be utilized for the SODIS system, due to the presence of livestock (e.g. cattle and goats) that would step on, break, chew, or otherwise damage the bottles if left on the ground. Therefore, a system that disinfected larger quantities of water at one time with less work required, that could be utilized on all houses, and that would reduce the workload of women would appear to be socially acceptable by this population. It was suggested by the author, however, that there is a great need for educational support for such projects, as the knowledge regarding the relationship between disease states and contaminated water is poor (Flores, 2003). See section 1.3.4 for more information on educational interventions.

1.3.2.3 SPC-DIS

Solar photocatalyic disinfection, or SPC-DIS, is the name given to the process in which the photocatalyst titanium dioxide (TiO_2) is used within SODIS reactors to "enhance and accelerate the inactivation rate of bacterial pathogens" (Lonnen et al., 2005, pg. 877). In a study comparing free TiO_2 powder to immobilized TiO_2 that had been adhered to a glass slide, the suspended powder was 1.21 times more effective at increasing the efficiency of solar disinfection of *E.coli* than the immobilized form (Salih, 2002).

The photocatalyst is believed to work by producing free radical species (•OH) that are generated in water in both the presence of light and TiO_2 (Salih, 2002). As noted in Section 1.3.2.2, these highly reactive oxygen species are responsible for damaging cellular components. Therefore, in theory, the effects of TiO_2 should be counteracted by the presence of •OH scavengers. To test this hypothesis, investigators studied the effect of TiO_2 in the presence and absence of two •OH scavengers, DMSO and Cys (Salih, 2002). In the absence of TiO_2 during sunlight exposure, no change in disinfection was observed. However, in the presence of the scavengers, a complete reduction in TiO_2 enhancement was observed, suggesting that •OH is, in fact, involved in SPC-DIS reactions. The authors suggested that bacterial cells may form aggregates with TiO_2 due to opposing cellular charges, and therefore give •OH a greater chance to reach the bacterial cell wall or membrane and cause damage. This is consistent with the observation that only cells close to immobilized TiO_2 in the previously mentioned experiment were affected by the photocatalyst. Another study backs these findings, stating "the mean distance between bacteria and immobilized TiO2 increase and cause a diminution of the probability of attack by •OH as compared to suspended TiO_2" (Rincon & Pulgarin, 2003). One study hypothesizes that the destruction of the cell membrane and wall leads to rapid leakage of potassium ions, with slower release of proteins and RNA (Saito, Iwase, Horie, & Morioka, 1992). This is in contrast to accepted theory on lethal cellular damage, which purports that 90% of radiation-induced death is due to loss of nuclear material (Salih, 2002).

Unfortunately, the use of TiO_2 for point-of-use water treatment is not currently practiced, nor is it likely to be feasible. The photocatalyst would have to be removed following solar exposure and prior to human consumption (Pozzo, Baltanas, & Cassano, 1997), making it unlikely that communities and households would adopt such a complex system. By immobilizing the photocatalyst on an insert that could be placed within the SODIS reactor, however, one could make less work for the users of the system and increase the likelihood of adoption. As we have already seen, however, the immobilization of TiO_2 on glass makes the photocatalyst less effective than when placed freely in solution.

More recent studies found that immobilizing the TiO_2 on acetate sheets, such as those used with overhead projectors, cut bacterial inactivation to approximately 25%-66% of the time required by traditional SODIS (Duffy et al., 2004; Lonnen et al., 2005), and reduced *C. parvum* oocyst viability by 50% (Méndez-Hermida et al., 2007). While no studies could be found comparing the efficacy of the acetate sheets to suspended TiO_2, it can be assumed that the sheets have reduced effectiveness compared to suspended particulate due to the reasons described above, yet are still an improvement over traditional SODIS systems. Investigations are now underway to determine if these TiO_2 impregnated acetate sheets can be produced locally in rural areas of the developing world for point-of-use household treatment (Duffy, et al., 2004; Lonnen et al., 2005; Méndez-Hermida et al., 2007).

1.3.2.4 UV Lamps

Ultraviolet (UV) light systems are currently used in large-scale waste water and drinking water treatment plants in Europe and the U.S. (Cohn, 2002). There are two types of systems currently available for household or point-of-use treatment; a submerged lamp or an in-air version that is mounted above a thin layer of water (Sobsey, 2002). A comparison of these two systems is shown in Figure 8.

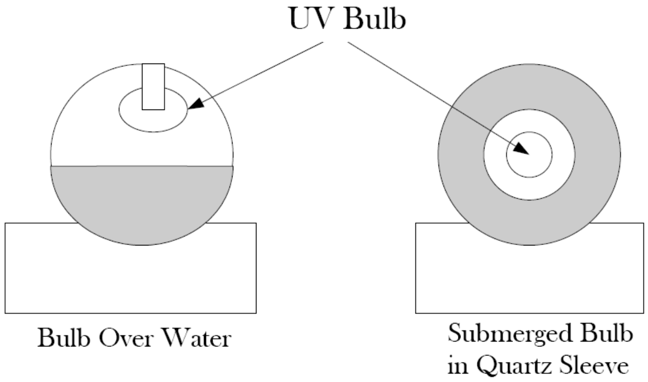

Figure 8. Comparison of Bulb Over Water and Submerged Bulb UV Systems

The in-air system was designed due to concerns with lamp fouling, a process that involves the buildup of inorganic and organic matter on the outside of the bulb (Cohn, 2002), decreasing the UV light's passage into the water. However, the in-air systems lose some UV transmittance due to atmospheric and surface adsorption, making them somewhat less effective at disinfection (Sobsey, 2002). In the submerged design, the bulb is placed in a quartz sleeve, to protect the electronics of the lamp, and to protect the bulb from breakage due to temperature fluctuations (Cohn, 2002; Sobsey, 2002). The quartz sleeve is also susceptible to fouling, however, and may require cleaning every two to three months to every day, depending on water source content (Sehnoui REF).

UV irradiation, similar to sunlight exposure (see Section 1.3.2.3) has been shown to be very effective for the inactivation of bacterial and protozoan pathogens, and almost all known viruses, with the exception of adenoviruses (Linden, Thurston, Shcaefer, & Malley, 2007). Adenovirus may be inactivated using polychromatic lamps (emit UV radiation that is made up of more than one wavelength), but there is a concern with using polychromatic lamps due to the production of nitrite (Sharpless & Linden, 2001).

Relative advantages of UV lamps include high pathogenicity, simple application at the household level, and they do not require chemicals, cause unpleasant taste or odor in the water, or toxic chemical by-products (Sobsey, 2002). Disadvantages include the need for cleaning (dependent on type of lamp), replacement of lamps every year to two years, and the need for a source of electricity (Sobsey, 2002; Cohn, 2002). The need for electricity may be a limiting factor in many rural areas.

No epidemiological could be found that implemented the UV lamps in communities in developing countries that also assessed any disease outcomes. Despite the lack of evidence to suggest that UV lamps could be a useful technology in communities, they are still recommended for use in the home in several reviews (Sobsey, 2002; Gadgil, 1998).

1.3.3 Filtration

The following section reviews methods of physically removing pathogens from water, either by mechanically blocking the pathogen's movement through a filter medium, or through electrostatic interactions between charged particles. Many of these methods are being explored for their extreme low cost and ease of use at the household level.

1.3.3.1 Cloth or Paper Filtration

Filtration, in its most basic form, consists of little more than pouring dirty water through a cloth. Filtration of water or other beverages (e.g., wine) has been practiced for centuries using cotton, linen, or other cloth, or compressed fibers, such as cellulose paper (Sobsey, 2002). Sari cloth, such as that found in India and other regions of the world, is recommended for the filtration of various pathogens when outbreaks are linked with copepods or other eukaryotic organisms in water, as is often the case with the bacterium *Vibrio cholerae* (Huq et al., 1996). Cloth is also useful in areas where waterborne pathogens tend to be larger in size, as in areas where guinea worm larvae (dracunculiasis) and schistomes are present. In fact, cloth or paper filtration is recommended by the World Health Organization as an essential intervention for dracunculiasis (Sobsey, 2002), based on findings that it has achieved unmatched success in disease prevention in Ghana (Olsen, Magnussen, & Anemana, 1997) and Nigeria (Aikhomu, Brieger, & Kale, 2000).

While cloth and paper filtration is an affordable and simple water treatment method, they are ineffective against concentrations of free bacteria, viruses, or other pathogens smaller than the pore size of the cloth. Viruses are the smallest of the waterborne pathogens (ranging from 20-100 nanometers); bacteria are medium sized (ranging from .5 to 3 micrometers); and protozoan parasites are the largest (most are 3 to 30 micrometers) (Sobsey, 2002). A typical cloth pore size is about 20 micrometers (Brown, 2007), meaning that all but the largest of the waterborne pathogens are able to filter through the cloth. Therefore, more efficient means of filtration have been developed for community and household use.

1.3.3.2 Slow Sand Filtration

Slow sand filtration is an effective method for improving the physical, chemical, and bacteriological quality of contaminated water (Huisman & Wood, 1974). Slow sand filtration differs from rapid sand filtration in that the latter does not include biological filtration, and is therefore not included in this review. There are several elements common to all slow sand filters:

1) A water reservoir, the principal function of which is to maintain pressure needed to force the water through the filtration medium;
2) A filter medium (usually sand);
3) An under-drainage system, which supports the filter medium and provides an unobstructed route for the filtered water to leave the underside of the filter; and
4) A control system to regulate the flow velocity of water through the system (Huisman & Wood, 1974).

As pathogens travel through the filtration medium, they are removed via interception with sand particles, straining effects, and most importantly, the adsorptive physical properties of the sand on the pathogens (Huisman & Wood, 1974). The organisms, as well as algae and any other organic material, collect in the top layer of the sand, eventually forming what is known as a 'schmutzdecke'; this layer becomes an active part of the filtration process, as various microorganisms (protozoa, especially) trap and digest other pathogens entering the schmutzdecke (Huisman & Wood, 1974). After passing through this organic layer, the water filters through the sand layer, a process which may take several hours, hence the name given to the system.

There are several models of slow sand filters available today; the model that will be used for illustrative purposes in this review is the Manz Slow Sand Filter, as seen in Figure 9, developed by Dr. David Manz of the University of Calgary during the early 1990s (Manz, Buzunis, & Morales, 1993). The Manz Filter is adapted for intermittent use at the household level, thus its relevance to this review. Most slow sand filters were thought to require a continuous flow of water through the shmutzdecke, providing oxygen and nutrients to the organisms within the layer; with stagnation, the shmutzdecke would quickly begin to die, thereby reducing the effectiveness of the filter.

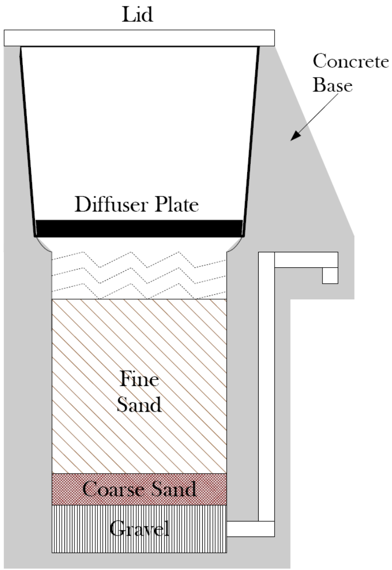

Figure 9. Schematic of a Manz Slow Sand Filter

However, the Manz filter raises the drain pipe back up to a level one to eight cm above the sand layer (traditional filters drained at the bottom of the apparatus). This adaptation ensures that the water level will be maintained just above the level of the sand. Manz showed that this layer of water is small enough to allow oxygen to permeate to the organic layer by simple diffusion (Manz et al., 1993). Therefore, water can be added intermittently, as needed, by families in their homes for personal disinfection purposes.

The Manz filter is constructed of locally available materials, readily found in most areas of the world. It can be made using plastic, though concrete is preferred for several reasons: it is more readily available in many places, it does not need to be replaced frequently, is less prone to damage (especially the delicate filter spout, which is located on the inside of the concrete version), is lower in cost, and can be manufactured by local people (CAWST, 2007). However, it is heavier and less portable than plastic.

Once constructed, the Manz filter is not immediately ready for use, due to the lack of a shmuztdecke. In a study examining the process of “ripening,” the accrual of the biological layer, the filter reached maximum *E. coli* reductions of 99% after 17 days of intermittent use of 40 L of water per day (Stauber et al., 2006). Unripened filter removal efficiency was as low as 63%. Eventually, however, continued use of the filter causes debris to clog the pore openings between the pores of the sand, and therefore the system must be cleaned when filtration output begins to decrease. To clean the filter, the sand must be swirled or agitated so that the debris is loosened and suspended in the standing layer of water (CAWST, 2007). If water used in the filter is of relatively low turbidity (less than 30 NTU) the need to clean the system is infrequent, taking place once every several months, depending on flow rate. After cleaning, it is recommended that the system be allowed to ripen for at least two days before drinking to allow the shmuztdecke to reform (Elliott, Stauber, Koksal, DiGiano, & Sobsey, 2008).

No published studies could be found that examined the impact of the Manz filter on diarrheal disease or other infectious diseases. Most published works have been laboratory based, or, if field based, have focused on the microbially quality of water produced by the filter. For example, one study examined the impact of the filter on *Giardia lamblia* oocysts and *Cryptosporidium parvum* oocysts (Palmateer et al., 1999). The shmutzdecke and sand layers were able to contain 100% of the *Giardia* cysts over 29 days, whereas *Cryptosporidium* showed some ability to pass through the filter until day 22, perhaps due to its smaller size. Despite allowing some organisms through, the filter still retained over 99.98% of the *Cryptosporidium,* reaching potentially infective levels on only two of 29 days. Another study found that the grain size of the sand and the hydraulic loading rate impact the efficacy of the filters on removal of *Cryptosporidium* (Logan, Stevik, Siegrist, & Ronn, 2005). 'Hydraulic loading' refers to the pressure head of water that sits on top of the sand to force itself through the filter. The increased surface area that accompanies smaller grain sizes affords greater opportunity for adsorption of pathogens, while an increase in hydraulic residence time (a slower flow rate) ensures that heavier oocysts do not get pushed to the bottom of the filter and break through to the outflow pipe (Logan et al., 2005).

Viruses were somewhat more difficult to remove from the filter, and did not always correlate well with *E. coli* removal patterns, indicating that *E. coli* may not be the preferred indicator organism for enteric viruses (Elliott et al., 2008). The pH of the feed water changes the efficiency of the filtration media, increasing or decreasing attractive charges between oppositely charged particles. Further research is necessary to fully understand the mechanisms of virus removal, however.

Concrete Manz filters, costing approximately US $10-20, are an affordable and long-lasting means of reducing the microbial load of contaminated water. An additional benefit is that they may also reduce the levels of harmful chemical impurities. Research should be conducted to determine if the success that the Manz filter has found in the laboratory can be translated into success in reducing diarrheal and other diseases in the field.

1.3.3.3 Ceramic Filtration

Among conventional water filters, the most promising innovations are ceramic water filters, which are manufactured in a basic pot shape (see Figure 10) or in a tube shape, often called a candle-filter (see Figure 11). Pathogens are removed from the contaminated water as it passes through the filter from the top compartment to the lower storage compartment.

Many filters are impregnated with colloidal silver or silver nitrate as a bacteriostatic agent (see Section 1.3.1.3 for more information), which may aid in the overall reduction of pathogens. In low-cost, locally made ceramic filters, such as those made by Potters for Peace, a global NGO working to produce filters for resource poor nations, the design, method of production, quality assurance and quality control (QA/QC) measures, firing temperature, and other characteristics may vary widely (Brown, 2007). Various types of clays, glass, or other fine particles are blended with sawdust or other materials, shaped, dried, and then fired, during which time the sawdust burns out, leaving pores ranging in size from .6-3.0 microns (Latagne, Quick, &

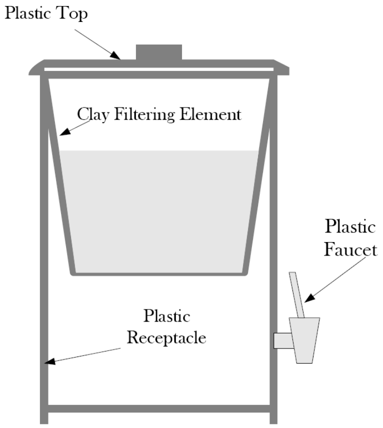

Figure 10. Schematic of a ceramic filter in a pot shape

Mintz, 2008). Studies have shown that the majority of bacteria are removed mechanically through the pores, but a silver coating is necessary to achieve 100% reduction in bacteria (Latagne, 2001). Against protozoa, the filters are 99.99% effective, but their effectiveness against viruses is currently unknown (Latagne, Quick, & Mintz, 2008).

Most current manufacturers make their filters out of locally available clay and sawdust, but new materials are being tested, such as hydroxyapatite (HA) ceramic (Yang, Ning, Xiao, Chen, & Zhou, 2007), due to its ability to provide both positively and negatively charged sites, thereby making it a more effective absorbent. In laboratory tests, porous HA ceramic showed a 100% separating effect on *E. coli* cells, while scanning electron micrographs showed that the cells adhered to the larger pores of the ceramic or were blocked by pores that were too small in diameter to allow the bacteria to pass (Yang et al., 2007). HA has not yet been tested thoroughly in combination with silver coatings, or examined as a viable alternative to other ceramics, in terms of cost effectiveness and social acceptability.

While the relative success of laboratory testing shows promise for “candle” ceramic filters (Sobsey, 2002), it is important to determine an intervention's success in the field. In a randomized controlled trial of household based “candle” ceramic filters in Columbia, only 47% of samples from households that received the filters had water samples that met WHO guidelines for zero total thermotolerant coliforms (TTCs) (Clasen, Parra, Boisson, & Collin, 2005). This was a great improvement from control groups that had only 0.9% of samples meeting WHO guidelines. The manufacturer of the model used in this study, however (Katadyn Ceredyn^{TM} filters), claims a greater than 99.99% reduction in coliforms.

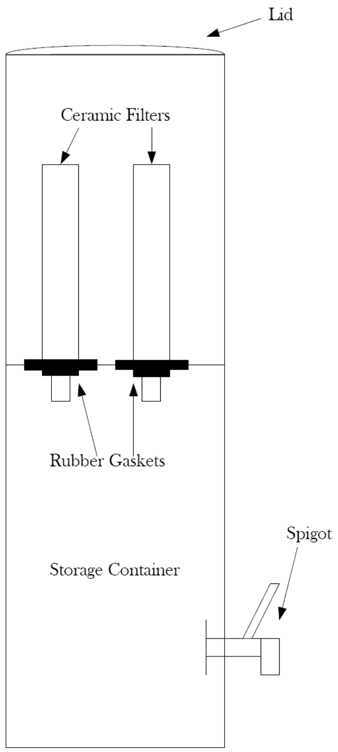

Figure 11. Schematic of a ceramic filter unit in a candle shape

In a second, nearly identical, study by the same authors in Bolivia, using the same product, the introduction of the filters resulted in 0 TTCs for the experimental households for the entire 25 weeks of the study duration (Clasen et al., 2004). To explain these differences in total coliforms, the authors suggest that cultural acceptance of the filters may be the answer. For example, in the Bolivia trial, all intervention households reported liking the filter, 92% reported that it was not inconvenient, and the same percentage reported feeling better since using the filter (Clasen et al., 2004). The Columbia study did not directly address likes or dislikes of the system, but suggested that among the three study sites used for this research, one was very rural and one was very urban, implying that these populations had the lowest levels of prior hygiene instruction. This could possibly have led to a lack of understanding of reasons for use of the filter, and subsequent improper use of the filter, due to a lack of knowledge about transmission pathways.

Despite the somewhat disappointing microbial results in the Columbia study, there was nevertheless an association between the presence of a household filter and diarrhea reduction. Persons within experimental households had a 60% lower prevalence of diarrhea than control households (Clasen et al., 2005). In the Bolivia trial, the intervention group's prevalence of diarrhea decreased by 77.2% from baseline while the control group increased by 2.7%. For children less than five years old, the risk of diarrhea was reduced by 83%. These reductions were seen despite the fact that 40% of intervention householders noted that they at least occasionally drank unfiltered water while away, while at work (27%), or when the filter was empty or too slow (27%). (Clasen et al., 2004) These results indicate that even a microbially imperfect system can be effective at reducing diarrhea in populations, that greater effects may be seen if proper education is included, and that systems should be culturally appropriate.

1.3.4 Educational Interventions

According to one author, "Diarrheal diseases, along with many other illnesses burgeoning in the developing world, have strong behavioral components. It follows, then, that behavioral interventions would hold promise in reducing their incidence and improving public health" (Thevos, Kaona, Siajunza, & Quick, 2000, pg. 367). The interventions discussed here are those that promote hand washing only, and those that promote a full array of hygiene behavior changes, termed Hygiene Education Programs.

1.3.4.1 Hand Washing Interventions

Hygiene promotion interventions "constitute a range of activities aimed at encouraging individuals and communities to adopt safer practices within domestic and community settings to prevent hygiene-related diseases that lead to diarrhea" (Ejemot, Ehiri, Meremikwu, & Critchley, 2008, pg. 2). One such activity is hand washing promotion. Though at first glance, hand washing may appear to have little to do with water, it is directly related to the quality of water used to wash hands, as will be seen below.

Two meta-analyses have been conducted to assess the effectiveness of hand washing promotion in reducing diarrheal disease (Curtis & Cairncross, 2003; Ejemot et al., 2008). The first meta-analysis examined the effectiveness of hand washing with soap in community based studies and estimated the reduction in diarrheal risk at up to 47% (Curtis & Cairncross, 2003). The second study assessed only randomized controlled intervention trials, including studies in countries of any income level, and found only a 30% overall reduction in diarrheal episodes (Ejemot et al., 2008). The lower observed effect in the latter analysis may be due to the more stringent inclusion criteria as compared with the previous analysis. It is important to note that the results of these meta-analyses cannot be generalized to all age groups, as in both of the reviews, most trials were conducted with children under age fifteen years, and the majority under age seven years (Curtis & Cairncross, 2003; Ejemot et al., 2008).

The specificity of the above results, however, mirrors the current epidemiology of diarrheal disease. Children younger than one year are at highest risk of death due to diarrhea (Luby et al., 2004a). Infants, who are incapable of washing their own hands, are the most vulnerable to diarrheal diseases as they are unable to break the transfer chain between their hands and mouth. Therefore, some authors argue that this age group would benefit greatly from hand washing interventions that would decrease pathogen transmission from parents or siblings to the infant (Luby et al., 2004a).

In a cluster randomized controlled trial in urban squatter settlements in Karachi, Pakistan, experimental households were given soap and hand washing education, whereas control households were visited at the same frequency as experimental households with educational supplies not related to hygiene promotion, such as children's books, pencils, and notepads. Infants unable to wash their own hands had 39% fewer days of diarrhea if they lived in households supplied with soap and hand washing education compared with control households (Luby et al., 2004a). This was less than the 57% reduction seen in children ages 5 to 15 years in experimental households who were capable of washing their own hands.

In a similar study conducted by the same authors, also in squatter settlements in Karachi, the effectiveness of the provision of soap without education was compared to chlorination provided with encouragement to regularly treat water (Luby et al., 2004b). Compared to control households, the provision of soap alone resulted in a 56% lower incidence of diarrhea in children under 15 years of age after one year of experimental treatment. The provision of chlorine and encouragement, however, resulted in a 73% lower incidence of diarrhea in children under 15 years of age. One possible limitation to this study is the fact that the intervention groups represented three geographically separated neighborhoods, each of which showed differences at baseline testing in soap buying habits and the presence of flush toilets. As the authors themselves note, "It is possible that either these or some other unmeasured difference in the communities contributed importantly to the difference in diarrhea incidence noted in the different groups" (Luby et al., 2004b, pg 426).

Cultural practices and religious patterns must be taken into consideration when promoting hand washing. For example, in Bangladesh, where many people have concepts about the separation of the right and left hand for specific purposes (such as using the left hand only for cleaning post-defecation), 56% of women observed during a hand washing trial washed only their left hands (Hoque, Juncker, Sack, Ali, & Aziz, 1996). In addition, several projects emphasized the use of ash for hand washing because soap is not easily affordable by the majority of the population. However, ash is not readily available in city slums where gas or kerosene are used in place of wood fires (Hoque et al., 1996), making the intervention useless for many of the country's residents.

The effect of soap distribution alone on diarrheal episodes has been examined as a motivator for hand washing in refugee camps in Malawi (Peterson, Roberts, Toole, & Peterson, 1998). While the study found reported use of soap for hand washing to be low (only 28% of mothers reported washing their children's hands with soap), the authors nevertheless reported an association between the presence of soap in households with a decreased incidence of diarrhea (all household members). The authors suggest that, because women are the primary water carriers, food preparers, and child care providers (activities associated with the transmission of diarrhea (Roberts, Chartier, Chartier, Malenga, Toole, & Rodka, 2001), that hands cleaned with soap during tasks other than hand washing, such as laundry or other cleaning, may be the mechanism for the observed protective effect of the soap.

Hand washing interventions may take substantial resources, such as trained personnel, community organization, the provision of a water supply and ample soap (Ejemot et al., 2008), and may take more time to develop than interventions that do not utilize such resources. As the authors of a hand washing intervention noted, the approach was "prohibitively expensive for widespread implementation" (Luby et al., 2004a). For this reason, low-cost interventions with behavioral components must be developed in order to achieve the greatest impact in disease reduction.

1.3.4.2 Hygiene Education Programs

Again, though not a direct water related intervention per se, hygiene intervention programs can target behaviors that directly relate to water treatment, water use, and other healthy and safe water behaviors. However, according to a review of over 500 articles that had been published by 1987, only three met the criteria for satisfactory evidence of behavior change due to health education (Loevinsohn, 1990). In a follow-up to that review, a second study, published in 2001, found only three additional articles with evidence that behavior change or health improvements had occurred in developing countries (Curtis et al., 2001). One may question, then, given the evidence of the efficacy of the above interventions, if it is worthwhile to put scare resources into health promotion in developing countries. Although hygiene promotion accompanies many programs for the control of diarrheal disease, evidence supporting its ability to prevent disease is still minimal (Pinfold & Horan, 1996).

Several programs claim to have achieved behavior change, some over the long term, using hygiene education programs. One large-scale program in Burkina Faso targeted mothers, older sisters, and “maids” (young girls who help with housework), who are the principal caregivers of young children (Curtis et al., 2001). They were targeted with the key message that hands should be washed after contact with stools, and messages about safe stool disposal. The motivating factor for the mothers was not found to be disease avoidance, but that hygiene is socially and aesthetically desirable. Channels of communication included house-to-house visits by hygiene specialists, discussion groups in the community, street theater, and local radio programs.

This program resulted in changes in mothers' behavior, increasing the proportion of mothers who washed their hands with soap after using the latrine from 1% to 17%, and the proportion that washed with water but no soap doubled from 35% to 74%. Hand washing after cleaning a child's bottom rose from 13% to 31%. However, safe stool disposal practices did not change from baseline to final evaluation. The authors suggest that this lack of change was due to the relatively high baseline practice of safe stool disposal, whereas hand washing had a much lower baseline. They state, "In general it is easier to demonstrate convincing changes when starting from a low base" (Curtis et al., 2001, pg. 524).

1.3.5 Safe Storage

Only a few studies have examined the impact of using only safe storage on keeping water free from microbial contaminants. One study, also reviewed in Section 1.3.3.1, compared the efficacy of chlorine treatment versus safe storage in the prevention of cholera (Deb et al., 1986). The storage containers were locally produced earthenware vessels (called 'sorais') with a narrow neck for filling and a separate narrow spout for pouring. Both openings were small enough to prevent hands or cups to be dipped into the vessel. As expected, the study found that both treatments improved disease outcomes significantly over control groups. Somewhat surprisingly, use of the sorais saw improved outcomes over chlorination, reducing *V. cholerae* infection by 74.6% and 57.8% respectively. The authors do not conclude if use of the sorai is statistically significantly better than chlorination, but the results are encouraging in that the vessel is culturally acceptable, does not change the taste or odor of the water, requires little instruction, and is affordable.

It is important to note that safe storage is only effective when the primary water source is relatively clean. Studies have reported that water is often contaminated from source to point-of-use (Vanderslice & Briscoe, 1993; Wright, Gundry, & Conroy, 2004), and that improved storage is an appropriate intervention to prevent such contamination (Wright et al., 2004). A meta-analysis of source and point-of-use practices also found that covered storage containers were lower in microbes than non-covered containers, implicating hands and cups dipped into the water as a possible source of contamination (Wright et al., 2004). This is consistent with the growing evidence that suggests a new paradigm for interventions in diarrheal disease is necessary to account for the "high-risk zone between collection and consumption of drinking water" (Garrett, et al., 2008, pg. 7).

The strategy to prevent human contamination of otherwise clean water sources has been to develop specialized containers, much like the sorai, that prevent hands and cups from entry, and to provision the container with taps that allow for easy water dispensing, again without allowing the water to come into contact with hands. While many of these containers have been used in tandem with the Safe Water System (see Section 1.3.6.1), one study evaluated the use of what was termed an "improved bucket" for the prevention of diarrhea (Roberts et al., 2001). This was a 20-liter bucket with a hole in the top small enough to prevent hand entry but large enough to allow for filling at hand pumps. The lid had a painted symbol of a hand with a line through it to discourage hand entry. The buckets also had a pour spout, a top handle, and a handle on the bottom side opposite the spout to aid in pouring.

Eighty-five households (310 participants) initially received the improved buckets for use in collecting and storing water. According to study authors, the buckets were popular with refugees, and following the intervention, only seven families wanted to trade the improved buckets for their old buckets, which were more convenient for chores such as washing clothes, children, dishes, or other household tasks (Roberts et al., 2001). In addition to cultural acceptability of the improved buckets, mean fecal coliform samples were an average of 53% lower than in regular ration buckets (controls). Although there were no statistically significant differences in the diarrhea rates in all household members in intervention versus control groups, the improved bucket decreased the diarrhea rates of children under five years of age by approximately 30% versus that of the control group. This may be an important finding because infants and children younger than five years are at much higher risk of death from diarrhea than older children and adults (WHO/UNICEF, 2004). As noted in Section 1.3.4.1, infants are incapable of washing their own hands and therefore cannot prevent the transfer of pathogens from their hands to their mouth, and may also become contaminated from the dirty hands of caregivers (Luby et al., 2004a). They also come into contact more frequently with the environment (e.g. the ground in and around their homes) and may play in (or ingest) fecally contaminated dirt (Curtis et al., 2000). While the improved bucket may not have intervened in the environmental pathway for infants and small children, they may have benefited indirectly by caregivers who had washed their hands with cleaner water. (See Section 1.3.4.1, and Luby et al., 2004a for more information), thereby interrupting the transfer of pathogens from adults to infants.

In the refugee camp trial, the authors note that much of the population rejected efforts by camp officials to chlorinate the water. In such circumstances, when a population is highly resistant to change, or in an emergency situation when resources are scarce, safe storage by itself may be a viable option to prevent the transmission of pathogens that cause diarrhea. Perhaps more importantly, safe storage should be considered an important component of any water quality intervention program that seeks to prevent diarrheal disease and reduce the potential for human recontamination of disinfected water.

1.3.6 Combined Approaches

As noted in Section 1.3, evidence exists that combined approaches are no more effective at disease prevention than stand-alone interventions (Clasen et al., 2001). However, several studies reviewed below suggest that further investigation into the synergistic effects of multiple or combined interventions is warranted.

1.3.6.1 The Safe Water System

Developed by the Centers for Disease Control and Prevention (CDC) and the Pan American Health Organization/WHO, the Safe Water System (SWS) consists of three components: point-of-use water treatment with locally produced sodium hypochlorite (NaCL) solution (see Section 1.3.1.1); safe water storage (see Section 1.3.5); and behavior change techniques (see Section 1.3.4) (CDC, 2008). Field trials of the SWS have been conducted in resource-poor countries around the world and are summarized in Table 4.

In a pilot trial in Bolivia, both study and control groups received health education from community health volunteers, but only the intervention group received the modified storage vessel (a 20-L plastic vessel with a tap and narrow mouth for filling) and chlorine solution (Quick et al., 1999). Over a five month period, investigators witnessed a significant 44%

Table 3. Summary of SWS trials.

Reference	Location	Storage Vessel	Education	Control Group	Randomization	Outcome Measure	Results
Garrett et al., 2008	Kenya	Local Clay	Social Marketing	Yes	No	Reported D+ in children <5 yrs[a]	65% D+ reduction
O'Reilly et al., 2007	Kenya	Clay and Improved Plastic	School based	Yes	No	School Absenteeism	35% decrease
Quick et al. 1999	Bolivia	Special Vessel[b]	Labels and community health workers	Yes	Yes	Reported D+ in all householders	44% D+ reduction
Lule et al., 2005	Uganda	Special Vessel	Home visits	Yes	Yes	Reported D+ in HIV+ persons	25% D+ reduction
Migele et al., 2007	Kenya	Local Clay	School based	No	No	Clinic visits for D+	82% reduction in clinic visits
Sobsey et al. 2003	Bangladesh	Improved Plastic	None	Yes	Yes	Reported D+ in children <5 yrs	20.8% D+ reduction
Sobsey et al. 2003	Bolivia	Improved Plastic	Education provided, no methods described	Yes	Yes	Reported D+ in all householders	43% D+ reduction
Semenza et al., 1998	Uzbekistan	Special Vessel	Hygiene Education, no methods described	Yes	Yes	Reported D+ in all householders	85% D+ reduction
Daniels et al., 1999	Guinea-Bissau	Special Vessel	None	No	No	*V. cholerae* in ORS[d] samples	100% *V. cholerae* reduction
Sobel et al., 1998	Guatemala	Special Vessel	Education, no methods described	Yes	Yes	Total and fecal coliforms in street-vended beverages	Approx. 40% reduction in total coliforms 89% reduction in fecal coliforms
Mhafouz et al. 1995	Saudi Arabia	Household Tanks					48% D+ reduction
Handzel, 1998	Bangladesh	Improved Plastic[c]	Home Visits on chlorination only	Yes	Yes	Reported D+ in children <6 years	29% D+ reduction

a. D+ = diarrhea

b. Special vessels: CDC vessel- high density polyethylene, about 20-L, valve to dispense water, 6-9cm opening to fill and clean, and a comfortable handle.

c. 12-L plastic jerry can

d. ORS = Oral rehydration solution

reduction in diarrhea incidence in the intervention group, dropping from 0.38 episodes per person to 0.21 episodes per person. The protective effect was strongest for infants less than one year old, reducing diarrheal incidence by 53%, and children aged 5-14, reducing incidence by 59%. For children ages 1-4 and those greater than 15 years, the reduction in the mean number of diarrhea episodes did not reach statistical significance. The authors speculate that the lack of protective effect in children ages 1-4 may be due to their "ability to walk and explore their surroundings, and their inability to avoid potential pathogens in a feaces-laden environment" (Quick et al., 1999, pg. 88). As noted previously, reducing diarrheal incidence in this age group may require environmental interventions in addition to water quality improvements due to the interaction of the child with the environment and multiple exposure pathways (see F-diagram, Section 1.1). The lack of reduction in the older age group (greater than fifteen years) may be due to the protective effect of age; rates of diarrhea are already lower in this age group, and therefore may not change significantly with an intervention.

The authors suggest that the three program components combined (safe storage, chlorine and chlorine residuals, and hygiene education) led to the reductions in diarrhea seen in this study (Quick et al., 1999). Hygiene education, however, is obviously ineffective for children less than one year old, and so this cannot directly be responsible for the effect. In fact, in a study comparing the SWS in Bolivia and Bangladesh, only the Bangladesh trial found a significant lower diarrhea incidence in children under five years of age in intervention households as compared to control households (Sobsey, Handzel, & Venczel, 2003); the Bangladesh trial received no education beyond basic instruction of the container, while in Bolivia, basic health and hygiene education was provided. These results lead one to consider if the nearly 85% reduction in diarrhea attack rates in children under 5 in a study of the SWS in Uzbekistan

(Semenza, Robert, Henderson, Bogan, & Rubin, 1998) is the result of chlorination and safe storage, or the combined effects of the complete program, including hygiene education.

In answer to this question, one study appears to have evidence supporting the latter. In a study assessing the SWS in rural Kenya, the educational component was present as evidenced by community mobilization efforts as well as a social marketing campaign. Multivariate analysis revealed that each intervention component was independently associated with a decreased risk of diarrheal disease in children less than five years of age (Garrett et al., 2008). However, living in an intervention village showed a lower risk of diarrhea than any single intervention, suggesting that combined interventions "might improve the general village environment and have greater impact than single interventions" (Garrett et al., 2008, pg. 7). As suggested by a simulation exercise on diarrheal disease, there are interdependencies of transmission pathways, and blocking several of these routes through combined interventions should be preferable over those that block a single route (Eisenberg, Scott, & Porco, 2007).

Taking the above into consideration, one can see that interventions such as the SWS that promote chlorination to eliminate harmful pathogens in water, safe storage to prevent recontamination of water, and hygiene education that emphasizes hand washing, proper food handling, and appropriate sanitation, may be effective at blocking multiple transmission routes. For example, chlorination intervenes if the source water is polluted with pathogens and provides residual protection against recontamination. Safe storage prevents contamination of clean water from fingers, and hygiene education has the potential to intervene at the level of contaminated fluids, foods, and fingers (see F-diagram, Section 1.1). In this manner, the SWS has the potential to have a large impact on children under the age of five years, who are not the direct recipients of the intervention education or instruction. (See Section 1.3.4.1 for more information on the benefits of adult hand washing on infant and child health).

The potential for intervention at multiple pathways may also help explain the variance in outcomes seen in Table 3. For example, what might account for the 41% difference in diarrhea reduction between Quick et al.'s 1999 study in Bolivia and Semenza et al.'s 1998 study in Uzbekistan? Both used the same vessel and reported diarrhea rates among all household users, yet the Uzbekistan trial found a much high reduction in diarrhea. One possible difference is that participants in the Uzbekistan trial were asked to wash their fruits and vegetables only with chlorinated water (Semenza et al., 1998) while in the Bolivia trial, labels were applied to the vessels indicating possible uses of clean water, such as hand washing, cleaning utensils, and washing produce (Quick et al., 1999), but were not specifically directed to do any of the above behaviors. In Uzbekistan, in addition to the chlorinated water intervening in the fluid pathway, it would also have blocked the transmission route from contaminated foods (from flies landing on the food or from being washed with contaminated water), and may have indirectly cleansed hands as they were washing the food, imparting yet another benefit to participants. In Bolivia, the labels may not have been as effective in spreading hygiene messages as simple direct instruction, meaning fewer people used the chlorinated water for purposes other than drinking, and therefore, only one transmission route (fluid) was blocked through the intervention. Therefore, the importance of proper instruction and hygiene education cannot be overlooked when implementing the SWS.

The SWS has not only been effective in young children, but has also proven useful in other populations. In a randomized controlled trial of HIV positive patients in Uganda, use of the SWS resulted in a 20% reduction in diarrhea episodes and 26% fewer days with diarrhea in HIV positive patients versus HIV negative controls (Lule et al., 2005). Another study, conducted in Guatemala, examined the use of the SWS at improving the quality of street-vended beverages (Sobel et al., 1998). By providing street vendors with a special plastic vessel with a small opening and a tap for water dispensing, along with chlorine solution and soap for hand washing, investigators found they could significantly improve the bacterial contamination of street-vended beverages (Sobel et al., 1998). Intervention vendors' beverage samples had significantly lower fecal coliform bacteria and *E. coli* counts than controls, and the level of chlorine in their vessels was consistently high enough to eliminate enteric pathogens. In addition, the system was widely accepted, being sought after by non-intervention vendors, as they felt customers perceived system users' beverages to be safer. Both intervention and control groups (now possessing the vessels) were still using the system correctly at follow-up five months later (Sobel et al., 1998). Once again, however, the investigators stress the importance of education in the use of the system: "repeated instruction, enforcement, or modification of the system will be necessary to induce the vendors to continue using the system to store and dispense beverages" (Sobel et al., 1998, pg. 386).

In terms of cost-effectiveness, the SWS appears to be one of the cheapest systems to improve the quality of life currently available to developing countries. Chlorination was the most cost-effective intervention per DALY averted in an analysis of water quality interventions for preventing diarrhea in both Sub-Saharan Africa and South-east Asia (Clasen, Haller, Walker, Bartram, & Cairncross, 2007). While cost estimates increase when including the price of the vessel in addition to chlorination, plastic vessels, which can cost around US $3.50 (Sobel et al., 1998), last a minimum of three years with proper use. These costs can be somewhat reduced by producing local clay pots, which cost about a dollar less (US) than the plastic version (Makutsa et al., 2001). In a school in rural Kenya, the SWS cost the school approximately US $1820 annually (Migele, Ombeki, Ayalo, Biggerstaff, & Quick, 2007). However, due to reductions in medical costs, personnel costs, tutoring for absent children, and firewood purchases for boiling water, the school actually saved $2085 a year, or $5.50 per pupil.

The SWS continues to be implemented in regions around the world and further investigations continue to determine its suitability for use in remote populations without access to mass media and other health campaigns, often the primary proponents of the system (Ram et al., 2007), its appropriateness in emergency situations (Mong, Kaiser, Ibrahim, Rasoatiana, & Quick, 2001), and application in the clinic setting (Parker et al., 2006). Overall, the SWS shows great promise for extended use in multiple situations, and continued research is needed to examine the effects of its various components.

2.0 FRAMEWORK FOR COMMUNITY HEALTH PRACTITIONERS

This section is intended to assist public health practitioners in implementing community-based projects using any of the above mentioned water quality interventions (or interventions yet to be developed). It is divided into parts by "components" which logically flow from one phase to the next, although it is not presumed that one will necessarily follow the components in order. In real-world settings it may be useful to rearrange the order of the components; so long as all elements of the framework are completed, the practitioner should have a solid foundation from which to implement his or her program.

2.1.1 Component One: Community Health Assessment of the Target Population

Community health assessment (CHA), a process that gathers information necessary for community change and empowerment (Hancock & Minkler, 1997) may serve different purposes for different practitioners. For some, it is the starting point for community-based program planning; for others, it is a way to detect the changing needs of a community over time and to adjust services based on those needs (Gilmore & Campbell, 2005). Whatever the desired outcome, it is important to note that community participation is a key feature of most assessments, where researchers work "in partnership with the community, rather than viewing it as a setting in which professionals conduct investigations known only to them" (Gilmore &

Campbell, 2005, pg. 5). This is consistent with current definitions of Community Based Participatory Research (CBPR): “a partnership approach to research that equitably involves community members, organizational representatives, and researchers in all aspects of the research process” (Israel et al., 2001, pg. 2).

There are many approaches to conducting CHA, but broadly speaking, researchers can frame their thinking in terms of needs and capacity. Undertaking a health assessment that seeks to uncover problems within the community, determine the community’s desires for change, and examine ways in which outside expertise can help improve these target problem areas is in line with a “needs assessment” strategy, which “is used to determine the problems and goals of the residents of a given community to assure that an intervention will respond to the needs of the population that is being sampled” (Marti-Costa & Serrano-Garcia, 2001, pg. 269).

An alternate paradigm is the “capacity assessment” approach. Capacity is defined as “individual and collective resources that can be brought to bear for health enhancement” (Gilmore & Campbell, 2005, pg.7). Capacity assessment, therefore, is defined as the “measure of actual and potential individual, group, and community resources that can be inherent and/or brought to bear for health maintenance and enhancement” (Gilmore & Campbell, 2005, pg. 8). Instead of examining ways in which external aid may be relied upon to improve the community’s current problems, the capacity approach measures the internal resources of the community that may be mobilized for health change and improvement.

The two approaches may, at first, seem to be dichotomous ways of viewing CHA, but upon closer examination, one finds that the processes are actually complementary (Gilmore & Campbell, 2005). For example, one can use a traditional needs assessment process to determine the problems that are most relevant to the target population, and to determine its interest in changing the current state. If one finds that water quality is of no relevance to the target population because most of the population is starving, then the community interest in improving water quality may be low, and likelihood of an intervention succeeding would also be low. Conversely, if water quality is of high relevance to the population, capacity assessment techniques can be used to determine the skills, abilities, and strengths already present in the community to help build and develop the intervention. Examples of these community strengths might be a highly-organized women's group, a group of unemployed but skilled laborers who could be employed constructing materials for the intervention, or trained educators who are well-respected in the community and might serve as advocates of the intervention.

It is important to reiterate the importance of *people* in the process of needs and capacity assessment, as "involvement in [the] planning and implementation [of health assessments] can contribute to the development of meaningful working relationships" (Gilmore & Campbell, 2005, pg. 11). Not only that, but early work with the community provides the foundation for work yet to come: the implementation of the intervention. For a theoretical background of this type of community-based work, see Rothman, 2001, and his review of modes of community development, particularly Locality Development Mode, which "presupposes that community change should be pursued through broad participation by a wide spectrum of people" (pg. 28).

Certain quantitative methods should be used to conduct the CHA, including primary and secondary data collection, such as surveys, health records, and locally relevant geographic data to describe the demographics and health characteristics of the target population. In addition, qualitative data methods, such as focus groups, semi-structured interviews with key informants, and observation may prove extremely useful in developing a complete health profile of the population. For example, a "neighborhood assets mapping" method developed for rural communities in the United States may show promise if adapted for developing countries (McKnight & Kretzmann, 1990). A neighborhood assets map lays out the locations of community resources such as schools, churches, libraries, law enforcement agencies, and health centers, characterizing each as a primary, secondary or potential building block. Primary building blocks are those assets that are largely within community control; secondary building blocks are still located within the community, but are controlled by outsiders; and potential building blocks are resources originating outside the community that are controlled by outsiders. There appears to be no reason why this approach could not be adapted to identify resources in the developing world, such as a community water pump or talents of the local people, such as artisans or skilled laborers.

2.1.2 Component Two: Selection of Appropriate Water Quality Technology

Following the results of a CHA, one should have enough knowledge of the community to determine if issues of water quality are a priority in the population. It may be the case that only a subset of the population lists water as a priority, perhaps women with young children. This does not necessarily translate into a concern with water quality by the community, though it is understood by the research team that poor water quality may be a contributing factor to the high prevalence of diarrheal disease among children in the community (and perhaps among adults, as well). In addition, results of the CHA should reveal data relevant to the causes of the high diarrhea rates in the community. If transmission appears to be primarily promoted through a lack of sanitation and hygiene, intervening at the water route may not be as effective as installing new pit latrines and instituting hygiene education practices.

Once it is determined that an intervention surrounding water quality has the potential to a) be accepted by the community and b) make an impact on disease transmission, selection of an appropriate water quality intervention must take place. There are multiple factors to consider when selecting an appropriate water quality technology (WQT). One reference suggests using the following seven items to score water quality technologies, listed in order of importance (Kerwick, Reddy, Holt, & Chamberlain, 2005):

1) Inactivation efficiency: Does it inactivate bacteria, viruses, and *Cryptosporidium parvum*?
2) DBP formation: Are disinfection by-products formed?
3) Toxicity: Does the technology comply with current toxicity standards?
4) Aesthetics: Is taste, odor, or color impaired?
5) Costs: Is the operation of the technology feasible?
6) Scalability: Can the technology be developed from bench and pilot scale to an operational scale?
7) Residual: Is a residual produced that provides protection from recontamination?

In addition, the authors stress that sustainable development and environmental implications must be given due considerations throughout the technology development process, such as the transportation requirements for non-locally available materials, or high energy costs for some technologies (Kerwick et al., 2005).

All of the above requirements will be considered important in the selection of a WQT, with the exception of toxicity, for several reasons. First, these recommendations are concerned with preventing diarrheal disease in populations; any technology that also eliminates toxins or chemicals in water is considered an additional health benefit. Second, “most chemicals arising in drinking-water are of health concern only after extended exposure of years, rather than months" (WHO, 2004, pg. 145). In terms of mortality, most populations in developing countries are at greater risk of dying from diarrheal disease than from a chemically induced toxic effect.

Most technologies fail to meet all of the above guidelines. For example, chlorine, the most widely used disinfectant, fails the first criteria by being ineffective against *Cryptosporidium parvum*. Currently, in developed areas where *Cryptosporidium* is a threat to human health, treatment processes in addition to chlorination are required to remove the pathogen (Kerwick et al., 2005). It also fails criteria two, three, and four, by creating disinfection by-products, failing to combat toxic products, and altering the taste and odor of water. However, it is cost-effective, easily implemented at large and small-scale applications, and is one of the few treatment procedures that leaves residual protection against recontamination.

The above recommendations fall short in a few areas, failing to consider the populations in which many of these technologies will be used. Revised recommendations are proposed below, with new strategies highlighted in bold type:

1) Inactivation efficiency: Does it inactivate bacteria, viruses, and *Cryptosporidium parvum*?
2) DBP formation: Are disinfection by-products formed?
3) Aesthetics: Is taste, odor, or color impaired?
4) **Safe Storage: Is consideration given to safe storage following disinfection?**
5) **Ease of Use: How many steps are involved in the process?**
6) Costs: Is the operation of the technology feasible?
7) Scalability: Can the technology be developed from bench and pilot scale to an operational scale?

8) Residual: Is a residual produced that provides protection from recontamination?

In the revised recommendations, toxicity is removed as a criterion, and safe storage and ease of use are included. Safe storage is an important part of any intervention, given higher priority than residual protection, as proper storage can safely protect water from recontamination. Ease of use is another critical component of water quality technologies, especially in countries where the burden of labor falls heavily on women. The more complex the system, the less likely the user will be to adopt the intervention, due to demands on time and energy.

It is recommended that, consistent with a CBPR approach, the community be invited to participate in the selection of the WQT. This may be accomplished through community forums, planning groups, or the creation of advisory committees. These types of groups may already be established following the completion of the CHA, and a logical next task for them would be the selection of the WQT.

2.1.3 Component Three: Use of Theory

Once the WQT has been selected, ideally in a collaborative decision-making process with community members, one must begin to think about the ways in which the technology will be introduced to and integrated into the community. It is in this phase when theories of behavior change are relevant. Studies have shown that theory-based interventions are more effective than those that are not based on theory (Stanton, Black, Engle, & Pelto, 1992). A theory, according to one author, is “an explanation of why a phenomenon occurs the way it does” (Freudenberg, Eng, Flay, Parcel, Rogers, & Wallerstein, 1994). Multiple theories and models are used by health professionals, including the Health Belief Model, Social Cognitive Theory, Trans-theoretical Model, Theory of Planned Behavior, Social Ecological Model, and Diffusion of Innovations

Theory, to name a few. A review of these theories is beyond the scope of this document (for qualified discourse on the subject, see Glanz, Lewis, & Rimer, 1992). The current discussion will focus on integrating practice and theory, highlighting some principles of program design that should be guided by theory.

A potential problem with the application of many theories is that they have been tried and tested in multiple settings in Westernized countries, but there are little to no data regarding their applicability in developing countries. Several searches in popular research databases for most of the theories listed above yields few results outside of the United States (and almost none related to diarrheal disease). While some theories, like the Health Belief Model (HBM) have been examined for multi-cultural sensitivity within minority populations in the U.S. (Glanz, Lewis, & Rimer, 2002), evidence of cultural applicability is mediocre at best. One author has noted that the HBM and similar models are best suited to middle-class Americans (Good, 1994). Given this information, "we should not expect these models to be productive in explaining behavior in social contexts where commonsense knowledge of the world takes a quite different form" (Yoder, 1997). One model that does appear to have been researched thoroughly in multiple global markets is the Diffusion of Innovations Theory (Rodgers, 2003). Social Cognitive Theory also claims global relevance, though the evidence is not prolific (Bandura, 2002).

Further research is needed to conclusively determine the applicability of health behavior theories to developing countries, but evidence does show that *not* using a theory is more detrimental than using one that may not be culturally relevant (Stanton et al., 1992). However, it is often difficult to integrate theory with real-world practice.

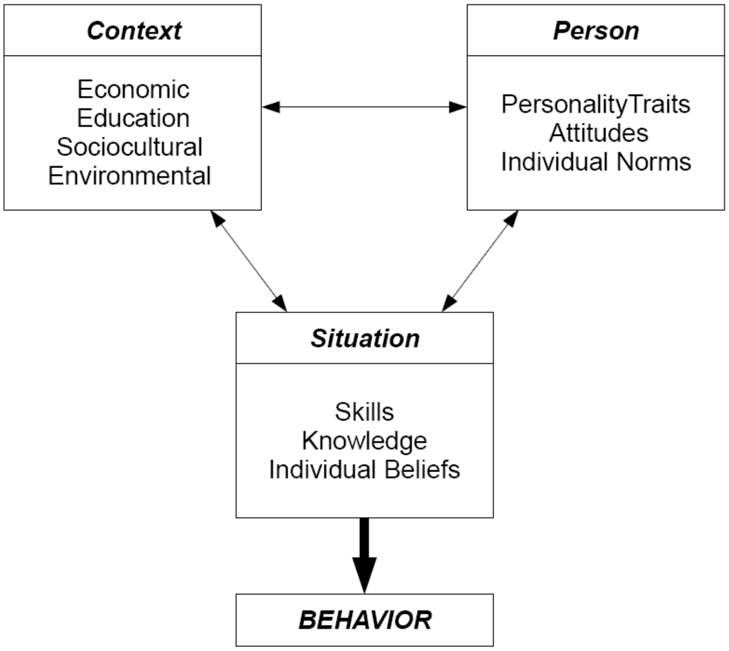

Figure 12. Heuristic framework for behavior outcomes.
Adapted from Pick et al., 2003

Figure 12 shows a heuristic framework for how behavior is influenced in real-life situations. The first box is *context*, which refers to the circumstances of an individual's life. This may include economic factors, education level, sociocultural factors shared within a society (norms, values, and beliefs), and external environment. The second box, *person*, refers to characteristics that reside within the individual, such as basic personality traits, attitudes, and individual norms. The third box depicts the *situation*, referring to the demands placed on an individual to which he or she must respond. How one responds depends on the skills available for use, present level of knowledge, and individual beliefs. These three boxes create the fourth and final box, *behavior*. Theory explains where to intervene to feed back to the first three boxes, which, by a continuous modification process, changes the output of the behavior.

Examining issues of adherence to prescription medications, one may find that context plays a important role in low adherence; patients cannot afford copays and therefore take pills every other day to "stretch" their budget; the pharmacy with the lowest copays is not near a bus route, making it difficult for those who use public transportation to access the lowest prices. One may also find connections between the boxes; patients who are college educated are more likely to adhere, because they have more knowledge, and perhaps better organizational skills (Figure 13). Using the HBM as an example, one would recognize the context issues as 'barriers' to adherence, and would see education, knowledge, and skills as the construct of 'self-efficacy.' Creating an intervention that would decrease barriers and increase self-efficacy would result in an overall behavior change in individuals.

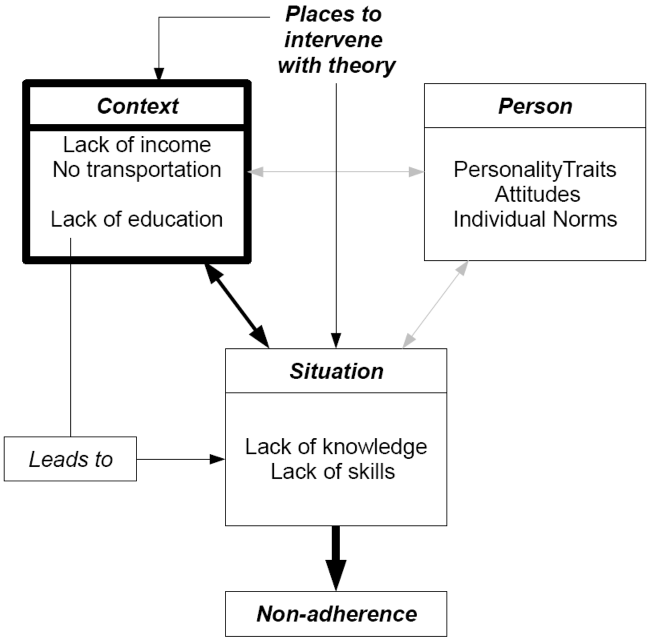

Figure 13. Behavioral model of where to intervene with theory.

Often, researchers are likely to attempt to intervene at the level of the person, without first taking into account the context and situation. In the previous example of adherence, one may place blame on basic individual traits, such as laziness or forgetfulness. While these may, in fact, be contributing factors to low adherence, it is important to examine the relative weight of each factor in producing the behavioral outcome. Obviously, deciding which factors are prioritized and which factors are not is subjective. Identifying the highest priority for intervention is a challenge, and one reference suggests the following four steps to doing so (Stanton et al., 1992):

1) Identify health promoting or demoting behaviors and beliefs.
2) Identify behaviors that are alterable.
3) Define the frequency and distribution of risk (protective) behaviors.
4) Assess severity of outcome of risk (protective) behaviors.

In the above scenario, the combined effects of *context* out-weighed prioritization of the effects of *person* or *situation*, due to their strong health demoting effects and high frequency. Policy changes could resolve the issues surrounding lack of income and transportation, and improved patient education could resolve lack of knowledge and improve skills, leading to changes in behavior.

2.1.3.1 Theoretically Based Studies Related to Diarrhea Prevention

Several studies in developing countries have used health behavior theory to design, implement, and evaluate diarrhea prevention programs. Theories utilized include the knowledge deficit model, HBM, Motivational Interviewing (a derivative of the Trans-theoretical model), and the Theory of Planned Behavior. The results of these studies are briefly summarized below.

In its most simplistic form, the theory of planned behavior (TPB) states that three main factors predict a person's intention to carry out a particular behavior: the person's attitude towards the behavior, the subjective norm (i.e., the perception that other people approve of the behavior), and perceived behavioral control (i.e., the perception that one is able to carry out the behavior) (Glanz et al., 2002). "Attitude" is operationalized as the amount of affect for or against some object; a field study that examined differences between SODIS users and non-users in Nicaragua, this evaluated this factor by looking at the overall emotional attitude toward a technology (in this case, the SODIS system of water disinfection) (Altherr et al., 2006).

"Subjective norms" in the Nicaragua study included three variables: 1) perceived social pressure, 2) SODIS behaviors of neighbors (as perceived by the individual), and 3) the perceived number of neighbors who were SODIS users. "Perceived behavioral control" was measured only on external factors (self-efficacy, or the perceived internal ability to carry out the behavior, was not evaluated). External factors under perceived behavioral control included "the perceived availability of the resources necessary to use SODIS, such as enough sunny periods, sufficiently clear water, and most important, enough bottles" (Altherr et al., 2006).

Despite the fact that numerous studies have reported a link between perceived behavioral control and behavioral intention or action (Glanz et al., 2002), the Nicaragua study found no such relationship. Only attitude and subjective norms were found to be significant predictors of intention. The authors explain the lack of association between behavioral control and action by suggesting that both SODIS users and non-users in their study perceived external factors, such as availability of bottles, as equally low; or conversely, their evaluation that SODIS is easy to use was equally high. However, it was having a positive attitude towards SODIS and perhaps the modeling effect of neighbors' behavior that differentiated SODIS users from non-users and correlates with action (Altherr et al., 2006).

A second study of SODIS in Nepal, utilizing the HBM, aimed to determine the acceptability of the technology with local residents. The HBM (Glanz et al., 2002) explains health behaviors by postulating that disease is a function of four beliefs of an individual: 1) vulnerability ('Can I get the disease?'); 2) severity ('Will the disease have a negative impact on my life?'); 3) efficacy ('Do preventive measures exist?'); and 4) barriers ('Will it be worth it for me to take action against this disease?'). Efficacy may be divided into 'response' efficacy or benefits ('Does the intervention work?') and "self" efficacy ('Will I succeed at the intervention?'). In addition, "diverse demographic, sociopsychological, and structural variables may affect the individual's perceptions, and thus indirectly influence health related behavior" (Glanz et al., 2002). These variables may be referred to as "modifying factors" (Stanton et al., 1992*;* Rainey & Harding, 2005)*,* and provide the context for health behavior (Rainey & Harding, 2005).

In the Nepal study (Rainey & Harding, 2005)*,* the authors found that despite high perceived efficacy (benefits) from SODIS water, perceived vulnerability and severity were low (most people did not understand what caused diarrhea, leading to an inability to perceive vulnerability as related to water), and perceived barriers were high (heavy workload by women, no bottles available, taste of water is different). All of these factors taken together could lead to a low likelihood of adoption in the study community, and indeed, only 9% of households adopted the SODIS system during the study period. In addition, modifying factors (common to many rural areas in developing countries) were listed, such as low level of education and literacy and poor sanitation practices, which further decreased support for adoption.

The results of the Nepal study were consistent with previous findings by the SODIS project initiators (EAWAG, 2008) that barriers to the adoption of SODIS include "unpleasant taste of water," "no bottles available," and "don't trust the method." However, the main barrier in the Nepal study (83% of respondents) was the workload of women. In addition, cultural factors played an important role in this study; beliefs surrounding hot and cold food and drink may have played into "the participants' perception that drinking warm SODIS-treated water served as an instigator of illness" (Rainey & Harding, 2005). In this example, using constructs of the HBM, the researchers were able to explain the low adoption rates of SODIS in the study population, indicating that this theory may be useful for understanding behavior related to the adoption of SODIS.

One study examined the use of Motivational Interviewing and its effect on the adoption of chlorination in rural Zambia (Thevos, Kaona, Siajunza, & Quick, 2000). Motivational Interviewing is an approach that incorporates the trans-theoretical model's (TTM) stages of change concept. The TTM posits that people move through "stages of change" with varying levels of readiness, or willingness, to change behavior over time (Glanz et al., 2002). The five main stages include pre-contemplation (not ready to consider change), contemplation (ambivalent about change), preparation (open to changing, may be ready for change), action (bringing about change), and maintenance.

Motivational Interviewing (MI) is "a directive, client-centered counseling style for eliciting behavior change by helping clients to explore and resolve ambivalence" (Emmons & Rollnick, 2001). Generally speaking, MI is a person-oriented, stage-based approach to using a person's own arguments for change to enhance motivation to change. By eliciting the argument for change from the client herself, counselors can be more effective than by simply trying to convince a client to change (Emmons & Rollnick, 2001). One of the critical components of MI is the quality of the client-counselor interaction, and remembering that "readiness to change is not a client trait, but a fluctuating product of interpersonal interaction" (Emmons & Rollnick, 2001).

The Zambia study is the first to employ MI to prevent diarrheal diseases in a developing country. Using nurses trained in MI, two field trials were conducted to determine if MI significantly improved health outcomes over health education alone. The first field trial resulted in near equal outcomes for both groups, possibly for methodological reasons (i.e., chlorine tablets were provided free of charge to both groups), and possibly due to stages of change (the community had reported a high concern with water quality and may have been in the "preparation" and "action" stages in both groups). The second field trial, however (where chlorine tabs were not free), sales of chlorine were significantly higher in the treatment group than in the education only group, despite the fact that households would have had to spend a considerable portion of their income on the disinfectant.

The results of the Zambia trial lend credence to appropriate use of the trans-theoretical model and the stages of change, which are operationalized through MI. The final aspect of the TTM is "maintenance," where people attempt to prevent relapse into previous behaviors (Glanz et al., 2002). In Zambia, the rates of chlorine purchase were sustained throughout the eight month course of the trial in the MI group. Although this particular publication did not specifically address cases of diarrhea as an outcome measure, the authors reference unpublished data (which they collected during an efficacy study of sodium hypochlorite) that show that the POU treatment decreased diarrheal incidence in the community (Thevos et al., 2000)

Finally, a study conducted in the Dominican Republic assessing knowledge, practices, and barriers related to diarrhea prevention, also examined the Knowledge Deficit Model (KDM), and the HBM. The KDM is based on the idea that knowledge, or lack of it, contributes to poor hygiene behavior. For example, if a caretaker does not know that untreated drinking water is potentially contaminated, that contamination can cause diarrhea, and that the treatment of water can reduce contamination and the occurrence of diarrhea, then behavior will reflect a lack of actions to prevent diarrhea (McLennan, 2000). Many interventions assume that 1) high rates of diarrhea are due to deficiencies in prevention practices of caregivers and 2) that these deficiencies are due to a lack of knowledge by the caretaker.

The Dominican Republic study interviewed 582 caretakers of children under five years of age and found that support for the first assumption is high: most caretakers do not utilize good preventive practices. However, support for the second assumption was low: there was a high level of biomedical knowledge given for reasons behind preventive practices. For example, 74% of respondents indicated that the reason they chlorinated drinking water was to “kill ‘germs,’ ‘bacteria,’ ‘parasites,’ or ‘micro-organisms’” (McLennan, 2000, pg. 17). Therefore, it may be inappropriate to assume that a lack of knowledge is responsible for high diarrhea rates in developing countries, although one can presume the lack of correlation between biomedical knowledge and translating this knowledge into preventive practice may play an important role in high rates. The key may be to find relevant theories that explain the lack of correlation between the two.

The barriers to preventive practice elucidated in this study are similar to the findings of the SODIS trial that also examined constructs of the HBM, although some new barriers were discovered in practicing general hygiene behaviors. Resource limitation was noted as a barrier, in the form of lack of money and time, similar to the SODIS study. Child-based barriers were identified, in which the parent placed the onus of hygiene practice on the child. For example, respondents indicated that children did not want to wash their hands, and so they did not enforce hand-washing. Another frequent response was a “lapse in caregiving” (McLennan, 2000, pg. 19). While the authors simply point to these as barriers, it is suggested here that these are evidence of low self-efficacy, as seen by the HBM. Increasing self-efficacy in parenting skills and beliefs might be one way to intervene using theory in this example.

2.1.3.2 Choosing an Appropriate Theory

Selection of theory may vary according to discipline of the investigator, timing of use, or consistency with previously collected data (Stanton et al., 1992). The finding that mothers are more likely to treat their child's 'serious diarrhea' with oral rehydration solution than 'mild diarrhea' is an indication that the HBM may be applicable to diarrhea-related behaviors (construct of perceived severity) (Stanton et al., 1992). To date, a specific methodology for selection of theories and models has not been developed. Some authors offer various approaches to theory selection, but none have been universally accepted. It is recommended that one looks both within one's field, and also outside the confines of one's discipline for relevant theories. It is suggested to consider the application of multiple theories to a single problem, as well. Where one theory falls short, another may prove to be explanatory. For now, selection of theory is largely a matter of personal choice, but careful thought should be given to how the theory may be relevant to the target population.

2.1.4 Component Four: Program Design

Once a CHA has been conducted, the community has assisted in choosing a WQT, and an appropriate theory has been selected, one must consider specifics of intervention program design. This includes operationalizing one's theory of choice, and choosing an appropriate planning model to help guide program design.

Consider the first two steps in operationalizing theory: define the components of the selected model or theory, and translate each component for targeted behavior within the culture or population one wishes to reach (Stanton et al., 1992). For example, using the HBM and examining mother's diarrhea prevention seeking behaviors, one must define what is meant by ‘perceived severity.’ This construct may be broken down into two (or more) components: mothers’ biomedical knowledge of diarrhea, and mothers’ cultural norms about diarrhea (Stanton et al., 1992). In Zaire, mothers recognize five separate illnesses associated with diarrhea, and results of a survey revealed that they were four times as likely to provide oral rehydration to children suffering from what they termed ‘ordinary diarrhea’ than to those suffering from dysentery or dehydration (Yoder, 1997). Therefore, in translating perceived severity into cultural behaviors, one must examine the biomedical understandings of diarrhea as mothers see it (Do they know that diarrhea is a risk to health?), but must also take into consideration what their culture tells them about severity (Which type of diarrhea is a risk to my child?).

Next, one must determine options for the intervention design (Stanton et al., 1992). Now that the constructs of the theory have been translated into culturally applicable questions or items, the investigators should attempt to answer such questions with multiple possibilities for intervention. In the example above, perhaps one has found, either during the CHA or in follow-up surveys, that while mothers understand that ‘germs’ or ‘micro-organisms’ from contaminated water may cause diarrhea in children, they do not believe that all diarrhea is necessarily dangerous to the health of the child. One must consider possible routes for intervention, keeping in mind the heuristic framework given previously in Section 2.1.3. Figure 14 shows the framework modified for this example.

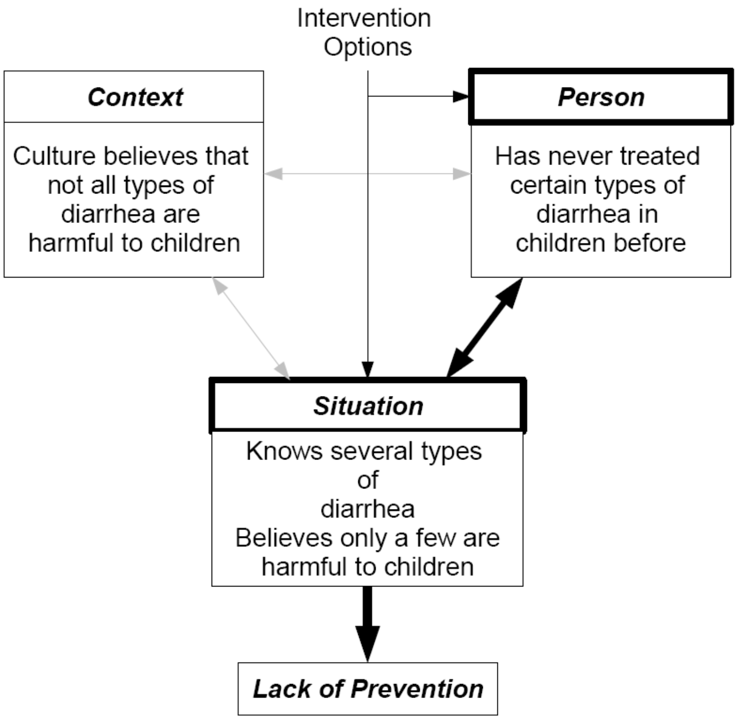

Figure 14. Modified framework showing health seeking behaviors of mothers and intervention options.

In this case, the context consists of cultural beliefs, which may be difficult to change. More appropriate options might be to intervene either at the level of the person or the situation. Knowledge is already high, but perceived severity of all types is low. An intervention aimed at increasing perceived severity may be effective here. In addition, because mothers have not traditionally treated certain types of diarrhea, their individual norms relating to this practice may not support appropriate treatment. This could relate to increasing self-esteem or self-efficacy, the mother's internal belief that she is able to complete a certain task.

In determining options for intervention design, remember that some constructs may translate relatively easily and reveal only one or two simple options for intervention, whereas others may yield multiple exploratory routes (Stanton et al., 1992). For example, recalling the study of SODIS acceptance in Nepal, where the primary barrier to use was the high workload of women, steps to reduce the workload of women, such as improvements in technology, or moving water sources closer to villages, might be examined. However, other constructs, efficacy for example, have larger theoretical issues involved, such as how self-efficacy may vary in societies where self-action is mediated through elders versus a relatively independent society.

Finally, the content of the intervention itself must be determined; that is, what exactly will take place to improve health related disease outcomes in the population? This involves choosing one of the options laid out above, selecting the target population, and implementing the strategy. This process requires creative insight, and each intervention obviously has a 'blueprint' that establishes it as unique. However, as listed by one author, several principles and strategies are common to any effective intervention;

1) Tailoring to a specific population.
2) Involving participants in planning, implementation, and evaluation
3) Integrating efforts to change individuals, social and physical environments, communities, and policies.
4) Using existing resources.
5) Building on strengths (capacities).
6) Preparing participants to become leaders.
7) Supporting the diffusion of innovations to wider populations.
8) Seeking to institutionalize successful components and replicate them in other settings (Freudenberg et al., 1994).

Several planning models can assist the practitioner in creating programs that meet the above requirements. There may be some confusion regarding terminology; the Health Belief Model as a behavior change theory should not be confused with the following discussion of planning models. Planning models are not theories, in that they do not "predict or explain factors linked to the outcomes of interest, but offer a framework for identifying intervention strategies to address these factors" (NIH, 2005, pg. 39). Some examples of these models include PRECEDE-PROCEED, Intervention Mapping, and the CDC's PATCH framework. Again, a full review of these models is beyond the scope of this work, but the PRECEDE-PROCEED model will be reviewed briefly as an example.

The model is divided into two segments; PRECEDE stands for Predisposing, Reinforcing, and Enabling Constructs in Educational Diagnosis and Evaluation; and PROCEED stands for Policy, Regulatory, and Organizational Constructs in Educational and Environmental Development. A schematic of the PRECEDE-PROCEED framework is given in Figure 15.

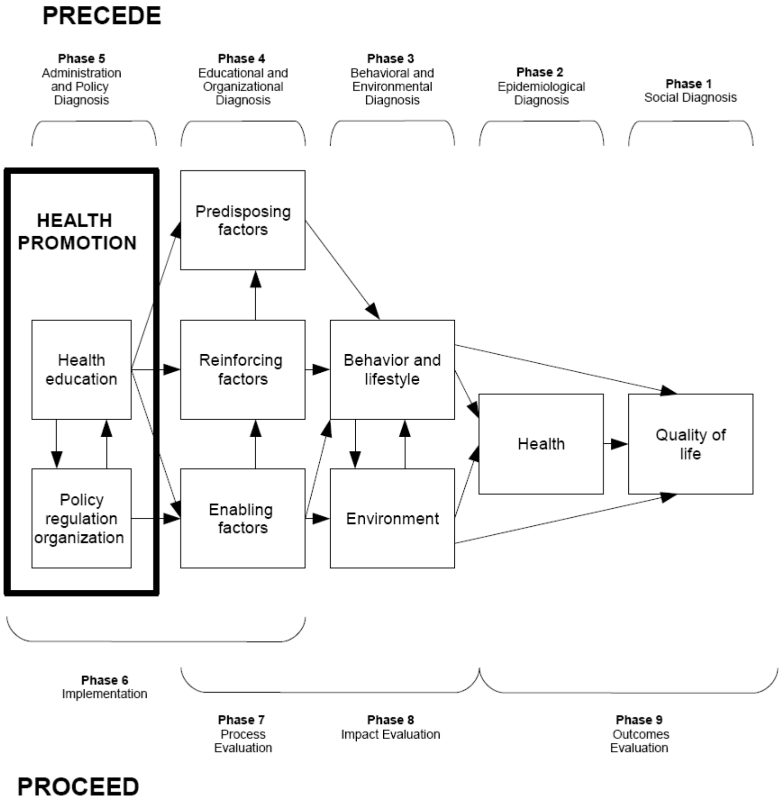

Figure 15. PRECEDE-PROCEED Framework

PRECEDE is diagnostic in nature, and much of the work specified in these phases may have already been conducted during the CHA. For example, Phase One consists of a needs assessment to determine quality of life of the target population, according to the community one is assessing. Phase Two is simply an epidemiological assessment of the health of the community. Both of these Phases should have been completed as part of the CHA. Phases Three, Four and Five may or may not have been completed as part of the CHA, but it is in these Phases where theory will be most useful (NIH, 2005). In Phase Four, in which an assessment of the predisposing, reinforcing, and enabling factors that affect behavior is conducted, the individual level theories of behavior change are especially pertinent, as these factors are often amenable to change (NIH, 2005). Phase Five may be more relevant for organizational level theories, such as the Diffusion of Innovations, or Organization Theory.

By utilizing the PRECEDE framework, one can gather enough information on the target community to decide which intervention to implement. For example, continuing with the example of mothers' health seeking behavior for diarrhea in children and the HBM, perceived severity (how serious she believes diarrhea to be) is a predisposing factor, the motivation or reason behind a behavior (NIH, 2005). Reinforcing factors are important after a behavior has begun, and provide rewards or incentives; they contribute to repetition or persistence of behaviors. Social support, praise, reassurance, and symptom relief might all be reinforcing factors. Self-efficacy could be a reinforcing factor in this scenario, and the two factors influence behavior and lifestyle, with an ultimate impact on health and quality of life. Looking at the model, one can see that enabling factors influence both reinforcing and predisposing factors, and that health education, in turn, influences all three. Enabling factors make it possible for a behavior to be realized; they include available resources, supportive policies, assistance, and services (NIH, 2005). Suppose an intervention was created that used midwives as the primary proponents of an oral rehydration therapy (ORT) education campaign in a developing country. If the mid-wives were provided with the resources necessary to teach others about ORT, they and their resources would become the enabling factors necessary to improve self-efficacy and increase perceived severity among mothers of young children. Their social support would also be a reinforcing factor, which would change the status of the predisposing factor.

Following the framework, one will see that Phase Six is actual implementation of the intervention. Phases Seven through Nine deal with an important step in any intervention: evaluation. These Phases, as well as evaluation, will be covered following Section 2.1.5.

2.1.5 Component Five: Community Mobilization

Ideally, community mobilization will have already begun before Phase Five by including the community in the CHA process, having community members help with selection of a technology, and developing a theory- based intervention. However, in this phase, formal methods of communication, social mobilization, social marketing, and advocacy are utilized.

Communication includes the types of strategies used to raise awareness of hygiene practices and behaviors (Storti, 2004). There are a variety of communication channels, such as "traditional media, music, song and dance, community drama, literacy materials, leaflets, posters, pamphlets, videos, and home visits" (Storti, 2004, pg. 12). It is important to think about the target population when developing materials. For example, written materials may not be appropriate in areas in which literacy rates are very low. Music and dance may be done in the customs and traditions of the target community, so as to be culturally relevant to the population.

Social mobilization includes involving various members or groups in the community in the intervention (Storti, 2004). From the example of the mothers' health seeking behavior in previous sections, it might be appropriate to mobilize a women's group to develop a peer education program to inform other mothers about the risks of childhood diarrhea.

Social marketing uses marketing principles and strategies to "achieve social goals such as better sanitation and hygiene" (Storti, 2004, pg. 13). This may involve partnering with an agency or manufacturing company to spread key messages related to a product. For example, in Kenya, sodium hypochlorite is marketed as Klorin (Garrett et al., 2008), while in Madagascar, it is marketed as Sur D'eau (Ram et al., 2007). The creation of media materials that target specific populations creates demand for the product and is beneficial for both production agencies and consumers (Storti, 2004).

Advocacy is a process during which one may lobby for improved hygiene policies to government and agency stakeholders. Advocacy often involves giving voice to those who are under-represented or otherwise incapable of representing themselves. Advocates may includes donors, community representatives, or program designers and managers (Storti, 2004).

Figure 16 shows a conceptual framework for how community mobilization integrates into interventions and combines with choice of WQT for diarrheal disease improvement. The intervention chosen, the theory behind the intervention, and the planning model used will help determine how hygiene behavior change is operationalized. This will relate directly to one's choice of WQT, as seen in the upper left box, and also impacts the choice of channels and materials one uses for community mobilization, as seen in the upper right box. As seen by the dotted arrow leading from the intervention to disease improvement, it is not the theory nor

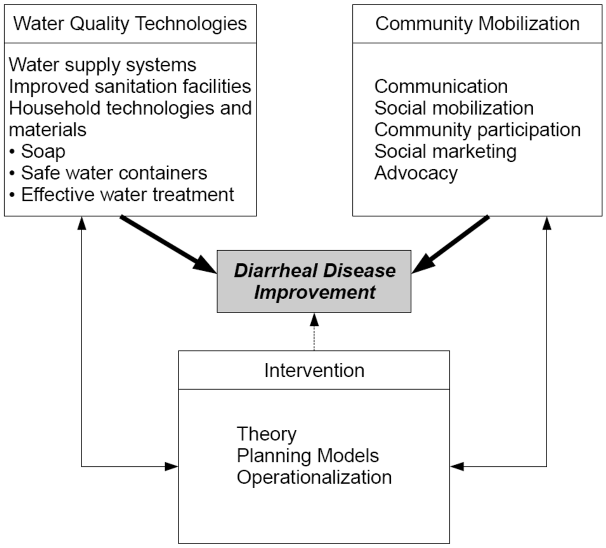

Figure 16. Conceptual model for integrating community mobilization into water quality interventions. Adapted from Storti, 2004

planning model that directly leads to disease outcomes, but the operationalization of such constructs as choice of WQT and method of community mobilization that directly improve hygiene behaviors and thus lead to decreased diarrheal disease (indicated by the bold arrows).

At this point, full project implementation has occurred, and the community members should be fully engaged in active learning, moving towards behavior change. This may continue for several months to several years, depending on the intended length of project and project funding sources. Although the next stage (Six) formally includes evaluation, the evaluation process will have started before, and continued throughout, the project implementation.

2.1.6 Component Six: Evaluation

Evaluation, according to the model presented in PRECEDE-PROCEED, can be broken into three distinct components: process evaluation, impact evaluation, and outcome evaluation (See Figure

15). The creators of the model note, “listing evaluation as the last phase is misleading, for evaluation is an integral and continuous process from the beginning through all phases of implementation” (Green & Kreuter, 1999, pg. 42). Data collection processes should be in place before program implementation, so that monitoring may begin at the onset of the project activities.

Process evaluation, or formative evaluation, “focuses on what services were provided to whom and how. Its purpose is to describe how the program was implemented- who was involved and what problems were experienced. A process evaluation is useful for monitoring program implementation; for identifying changes to make the program operate as planned; and, generally, for program improvement” (Gomby & Larson, 1992, pg. 71).

Impact evaluation looks at the changes in individuals, communities, or other populations that can be attributed to an intervention (World Bank, 2008). Impact tries to assess if a program has made a change in a target group relative to what would have happened had there been no intervention. This type of evaluation, in the PRECEDE-PROCEED model, assesses changes in predisposing, reinforcing, and enabling factors, and also in behavioral and environmental factors (Glanz et al., 2002).

Outcome evaluation is different from outcome monitoring. Monitoring shows if the expected outcomes occurred, whereas evaluation shows if the intervention was the cause of the expected outcomes (CDC, 2007). For example, hygiene behaviors may increase over a set amount of time, but outcome evaluation can determine if the increase is due to the program or to external factors. Outcome evaluation assesses the effect of the program on health and quality-of-life indicators, as seen in the PRECEDE-PROCEED model.

The three types of evaluation described here will give the program staff a complete view of the intervention, and will help to determine if the program is meeting stated goals and objectives. However, evaluation is complex and time-consuming. Careful planning will ensure that evaluation is not an after-thought, but becomes a useful tool for program monitoring throughout the implementation process.

3.0 CONCLUSION

Dr. Lee Jong-Wook, former Director-General of the World Health Organization, said, “Water and Sanitation is one of the primary drivers of public health. I often refer to it as ‘Health 101,’ which means that once we can secure access to clean water and to adequate sanitation facilities for all people, irrespective of the difference in their living conditions, a huge battle against all kinds of diseases will be won" (WHO, 2008). This statement could not be more relevant, but the question that remains to be answered is, “How?” How does one provide water that is safe and affordable for all people? If a technology promises to do so, how does one ensure the use of such a technology in a population?

Point-of-use water treatment technologies have been shown to be more effective than treatment at the water source (Clasen et al., 2001), and many reviewed here utilize local resources and are within the limits of affordability for many communities. Moreover, many of them are designed to be more time efficient than traditional methods of water treatment (such as boiling). These facets of the technology may reduce the workload of women and girls, allowing women to participate in other work, such as income generating activities, and allowing girls to attend school more frequently. They may also use sustainable resources, may be more “environmentally friendly” than burning traditional wood fuels, and may indirectly impact health by reducing indoor air pollution associated with fires.

Several steps must be taken in order to achieve water and sanitation for all. First, laboratory tests that indicate potential success of a new technology must be translated into action in community-based research studies that examine the technology's impact on populations (Montgomery & Elimelech, 2007). In addition, research should be conducted examining the effects of multiple technologies or combining multiple interventions. Thus far, there is little evidence to show that combined interventions are more effective than a single intervention, but the studies to back this statement are few. Perhaps most importantly, the interaction between educational interventions (hand washing interventions, or hygiene behavior interventions), and technologies should be examined to determine how education impacts the uptake and diffusion of technologies.

Methodology should be improved and standardized so as to accurately compare studies. Studies have shown that significant differences in diarrhea morbidity are seen in publications due to differences in "case definitions, recall periods for reporting episodes, reported vs. clinically confirmed cases, age, seasonality, ambient level of contamination, and pathogenicity of the etiological agent" (Clasen & Carincross, 2004, pg. 189). Indicators for quantifying "improved health" should be developed that are suitable for monitoring in community settings (Montgomery & Elimelech, 2007), and can be monitored over the long term. More randomized, controlled trials would be helpful in "understanding health outcomes from different interventions, especially among key subgroups, such as children or immuno-compromised individuals" (Montgomery & Elimelech, 2007, pg. 23). While blinding is often difficult in such studies, due to visible changes in water that may occur with the implementation of a technology, further trials in which participants and researchers are blinded to the treatment may be useful in determining the relative effects of interventions. In addition, multi-year studies and follow-up evaluations are critical for determining the long-term effects of interventions.

Interventions based on sound theoretical principles are needed, and should be tailored with the specific community's skills and capacities in mind. Multiple theories may be combined to address the host of issues surrounding water and sanitation in developing countries. The influence of social, demographic, environmental, economic, and policy factors must be explored as they relate to improving hygiene conditions and changing hygiene behaviors (Montgomery & Elimelech, 2007).

Researchers from several fields should work together to integrate their knowledge, including those from engineering, public health, marketing, and the biological sciences. Collaboration between fields is necessary due to the multi-disciplinary nature of the problems surrounding water quality. Interventions and programs that involve experts from multiple disciplines as consultants or program managers will most likely have better success than those that do not.

Despite the wealth of information presented here regarding water quality technologies and interventions, there remains a great deal left unknown. However, it is of the utmost importance that research continues, both in developing new cost-effective technologies, and in finding ways to integrate them into the lives of those who need them most. Of the 2.2 million deaths that occur each year due to diarrheal diseases, most are needless and preventable. Finding new and innovative ways to integrate technology into communities could save millions of lives, and thus should be considered a public health priority.

BIBLIOGRAPHY

Acra, A. R. (1984). *Solar disinfection of drinking water and oral rehydration solutions. Guidelines for household application in developing countries.* Beruit, Lebanon: UNICEF.

Aikhomu, S. E., Brieger, W. R., & Kale, O. O. (2000). Acceptance and use of communal filtration units in guinea worm eradication. *Tropical Medicine and International Health , 5* (1), 47-52.

Altherr, M., Mosler, H., Tobias, R., & Butera, F. (2006). Attitudinal and Relational Factors Predicating the Use of Solar Water Disinfection: A Field Study in Nicaragua. *Health Education and Behavior Online* .

Arnold, B., & Colford, J. M. (2007). Treating water with chlorine at point-of use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. *Am. J. Trop. Med. Hyg , 76* (2), 354-364.

Bandura, A. (2002). Social Cognitive Theory in Cultural Context. *Applied Psychology: An International Review, 51*(2), 269-290.

Berney, M. W., Simonetti, A., & Egli, T. (2006). Efficacy of solar disinfection of *Escherichia coli, Shigella flexneri, Salmonella typhimurium* and *Vibrio cholerae*. *Journal of Applied Microbiology , 101*(4), 828-836.

Bohrerova, Z., & Linden, K. G. (2007). Standardizing photoreactivation: Comparison of DNA photorepair rate in *Escherichia coli* using four different fluorescent lamps. *Water Research, 41*, 2832-2838.

Bratby, J. (1980). *Coagulation and flocculation: with an emphasis on water and wastewater treatment.* Croydon, England: Uplands Press.

Brown, J. (2007). Effectiveness of ceramic filtration for drinking water treatment in Cambodia. *Doctoral Dissertation*. University of North Carolina Chapel Hill .

Burch, J., & Thomas, K. (1998). Water Disinfection for Developing Countries and Potential for Solar Thermal Pasteurization. *Solar Energy, 64*, 87-97.

Burgess, S., & Onyonge, C. (2004). Solar Disinfection of Water (A case study from Kenya). *Waterlines, 4*(1), 22-25.

Cairncross, S. (1989). Water supply and sanitation: an agenda for research. *Journal of Tropical Medicine and Hygiene, 92*, 301-314.

CAWST. (2007). *Center for Affordable Water and Sanitation Technology*. Retrieved March 27, 2008, from Filtration Technologies : www.cawst.org

Centers for Disease Control and Prevention. (2007). CDC Evaluation Web Site. Retrieved March 24, 2008, from CDC Web Site: http://www.cdc.gov/hiv/topics/evaluation

Centers for Disease Control and Prevention. (2001). Safe Water System Web site. Retrieved March 24, 2008, from CDC Web site: http://www.cdc.gov/safewater

Centers for Disease Control and Prevention. (2008). *Safe Water System Site* . Retrieved March 24, 2008, from CDC Web Site : http://www.cdc.gov/safewater/

Clasen, T., & Carincross, S. (2004). Household water management, refining the dominant paradigm. *Tropical Medicine and International Health, 9*(2), 87-191.

Clasen, T., Brown, J., Collin, S., Suntura, O., & Cairncross, S. (2004). Reducing diarrhea through the use of household based ceramic water filters: A randomized, controlled trial in rural Bolivia. *American Journal of Tropical Medicine and Hygiene , 70*, 651-657.

Clasen, T., Haller, L., Walker, D., Bartram, J., & Cairncross, S. (2007). Cost-effectiveness of water quality interventions for preventing diarrhoeal disease in developing countries. *Journal of Water and Health, 5*(4), 599-608.

Clasen, T., Parra, G., Boisson, S., & Collin, S. (2005). Household-based ceramic water filters for the prevention of diarrhea: a randomized, controlled trial of a pilot program in Columbia. *American Journal of Tropical Medicine and Hygiene, 73*(4), 790-795.

Clasen, T., Roberts, I., Rabie, T., Schmidt, W., & Cairncross, S. (2001). Cochrane review: Interventions to improve water quality for preventing diarrhoea. *Evidence-Based Child Health: A Cochrane Review Journal, 2*(1), 226-329.

Cohn, A. (2002, May). The UV-Tube as an appropriate water disinfection technology: an assessment of technical performance and potential for dissemination. *Master's thesis.* University of California, Berkeley.

Colindres, R., Jain, S., Bowen, A., Domond, P., & Mintz, E. (2007). After the flood: an evaluation of in-home drinking water treatment with combined flocculant-disinfectant following Tropical Storm Jeanne- Gonaives, Haiti, 2004. *Journal of Water and Health, 5* (3), 367-274.

Conroy, M., Elmore-Meegan, M., Joyce, T., McGuigan, K., & Barnes, J. (1996). Solar Disinfection of Drinking Water and Diarrhoea in Maasai Children: a Controlled Field Trial. *Lancet, 348*, 1695-1697.

Conroy, R., Elmore-Meegan, M., Joyce, T., McGuigan, K., & Barnes, J. (1999). Solar disinfection of water reduces diarrhoeal disease: an update. *Arch Dis Child, 81*, 337-338.

Crump, J. A., Mendoza, C. E., Priest, J. W., Glass, R. I., Monroe, S. S., Dauphin, L. A., et al. (2007). Comparing serologic response against enteric pathogens with reported diarrhea to assess the impact of improved household drinking water quality. *American Journal of Tropical Medicine and Hygiene, 77*(1), 136-141.

Crump, J., Okoth, G., Slutsker, L., Ogaja, D., Keswick, B., & Luby, S. (2004). Effect of point-of-use disinfection, flocculation and combined flocculation-disinfection on drinking water quality in western Kenya. *Journal of Applied Microbiology, 97*, 225-231.

Crump, J., Otieno, P., Slutsker, L., Keswisk, B., Rosen, D., Hoekstra, R., et al. (2005, July 26). Household based treatment of drinking water with flocculant-disinfectant for preventing diarrhoea in areas with turbid source water in rural western Kenya: cluster randomised controlled trial. *BMJ, 331*(7515), 478-482.

Curtis, V., & Cairncross, S. (2003). Effect of washing hands with soap on diarrhoea risk in the community: a systematic review. *The Lancet Infectious Diseases, 3*, 275-280.

Curtis, V., Cairncross, S., & Yonli, R. (2000). Domestic hygiene and diarrhoea- pinpointing the problem. *Tropical Medicine and International Health, 5*(1), 22-32.

Curtis, V., Kanki, B., Cousens, S., Diallo, I., Kpozehouen, A., Sangare, M., et al. (2001). Evidence of behaviour change following a hygiene promotion programme in Burkina Faso. *Bulletin of the World Health Organization, 79*(6), 518-527.

Dalsgaard, A., Reichert, P., & Mortensen, H. F. (1997). Application of Lime (*Citrus aurantifolia*) juice to drinking water and food as a cholera-preventive measure. *Journal of Food Protection, 60*, 1329-1333.

Deb, B. C., Sircar, B. K., Sengupta, P. G., Mondal, S. K., Gupta, D. N., & Saha, N. C. (1986). Studies on interventions to prevent eltor cholera transmission in urban slums. *Bulletin of the World Health Organization , 64* (1), 127-131.

Deb, B. C., Sircar, B. K., Sengupta, P. G., Mondal, S. K., Gupta, D. N., & Saha, N. C. (1986). Studies on interventions to prevent eltor cholera transmission in urban slums. *Bulletin of the World Health Organization, 64*(1), 127-131.

Doocy, S., & Burnham, G. (2006). Point-of-use water treatment and diarrhoea reduction in the emergency context: an effectiveness trial in Liberia. *Tropical Medicine and International Health, 11*(1), 1542-1552.

Duffy, E. F., Al Touati, F., Kehoe, S. C., McLoughlin, O. A., Gill, L. W., Gernjak, W., et al. (2004). A novel TiO_2-assisted solar photocatalytic batch-process disinfection reactor for the treatment of biological and chemical contaminants in domestic drinking water in developing countries. *Solar Energy, 77*(5), 649-656.

EAWAG. (2008). *SODIS Technical Notes 1-17 and FAQ.* Retrieved February 24, 2008, from SODIS Web Site: www.sodis.ch

Eisenberg, J. N., Scott, J. C., & Porco, T. (2007). Integrating disease control strategies: balancing water sanitation and hygiene interventions to reduce diarrheal disease burden. *American Journal of Public Health, 97*(5), 846-852.

Ejemot, R. I., Ehiri, J. E., Meremikwu, M. M., & Critchley, J. A. (2008). Handwashing for preventing diarrhoea. *Cochrance Database of Systematic Reviews*. DOI: 10.1002/14651858.CD004265.pub2.

Elimelech, M. (2006). The Global Challenge for Adequate and Safe Water. *Journal of Water Supply Research, 55*, 3-10.

Elliott, M. A., Stauber, C. E., Koksal, F., DiGiano, F. A., & Sobsey, M. D. (2008). Reductions of *E. coli,* echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter. *Water Research*, *42* (10), 2662-2670

Emmons, K., & Rollnick, S. (2001). Motivational Interviewing in Health Care Settings: Opportunities and Limitations. *Amer. Journal of Preventive Medicine, 20*(1), 68-74.

Esrey, S., & Habicht, J. (1986). Epidemiologic evidence for health benefits from improved water and sanitation in developing countries. *Epidemiologic Reviews, 8*, 117-128.

Fayer, R. (2004). Cryptosporidum: a water-borne zoonotic parasite. *Vet. Parasitol., 126*, 37-56.

Feng, Q. L., Wu, J., Chen, G. Q., Cui, F. Z., Kim, T. N., & Kim, J. O. (2000). A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. *J. Biomed. Mat. Res., 52*(4), 662-668.

Fewtrell, L., Kaufmann, R., Kay, D., Enanoria, W., Haller, L., & Colford, J. J. (2005). Water, Sanitation, and Hygiene Interventions to Reduce Diarrhoea in Less Developed Countries: a Systemic Review and Meta-Analysis. *Lancet Infect Dis, 5*, 42-52.

Flores, X. (2003). Feasibility of semi-continuous solar disinfection system for developing countries at a household level. *Doctoral Dissertation*. Massechusetts Institute of Technology.

Freudenberg, N., Eng, E., Flay, B., Parcel, G., Rogers, T., & Wallerstein, N. (1994). Strengthening Individual and Community Capacity to Prevent Disease and Promote Health:

In Search of Relevant Theories and Principles. *Health Education & Behavior, 22*(3), 290-306.

Gadgil, A. (1998). Drinking Water in Developing Countries. *Annu. Rev. Energy Environ., 23*, 253–286.

Garrett, V., Ogutu, P., Mabonga, P., Ombeki, S., Mwaki, A., Aluoch, G., et al. (2008). Diarrhoea prevention in a high-risk rural Kenyan population through point-of-use chlorination, safe water storage, sanitation, and rainwater harvesting. *Epidemiol. Infect*. Retrieved March 13, 2008 from doi:10.1017/S095026880700026X

Gilmore, G. D., & Campbell, M. D. (2005). *Needs and Capacity Assessment Strategies for Health Education and Health Promotion* (3 ed.). (G. D. Gilmore, & M. D. Campbell, Eds.) Boston: Jones and Bartlett Publishers.

Glanz, K., Lewis, F. M., & Rimer, B. K. (2002). *Health Behavior and Health Education: Theory, Research, and Practice* (3 ed.). (K. Glanz, F. M. Lewis, & B. K. Rimer, Eds.) San Fransisco, CA: Jossey-Bass.

Gomby, D., & Larson, C. (1992). Evaluation of school-linked services. *The Future of Children, 2*, 68-84.

Good, B. (1994). *Medicine, rationality, and experience.* Cambridge: Cambridge University Press.

Green, L., & Kreuter, M. (1999). *Health promotion planning: An educational and ecological approach.* Mountain View: Mayfield Publishing Company.

Hancock, T., & Minkler, M. (1997). Community Health Assessment of Health Community Assessment: Whose Community? Whose Health? Whose Assessment? In T. Hancock, M. Minkler, & M. Minkler (Ed.), *Community Organizing and Community Building for Health* (pp. 139-155). New Brunswick, NJ: Rutgers University Press.

Heaselgrave, W. P., Kilvington, S., Kehoe, S. C., & McGuigan, K. G. (2006). Solar disinfection of poliovirus and *Acanthamoeba polyphaga* cysts in water – a laboratory study using simulated sunlight. *Letters in Applied Microbiology , 43* (2), 125-135.

Hoque, B. A., Juncker, T., Sack, R. B., Ali, M., & Aziz, K. M. (1996). Sustainability of a water, sanitation and hygiene education project in rural Bangladesh: a 5 year follow-up. *Bulletin of the World Health Organization , 74* (4), 431-439.

Huisman, L., & Wood, W. E. (1974). *Slow sand filtration.* Geneva, Switzerland: WHO.

Hunter, P. (1997). *Waterborne Disease Epidemiology and Ecology.* Chichester: John Wiley and Sons .

Huq, A., Xu, B., Chowdhury, M. R., Islam, M. S., Montilla, R., & Colwell, R. R. (1996). A simple filtration method to remove plankton-associated *Vibrio cholerae* in raw water supplies in developing countries. *Applied and Environmental Microbiology, 62*(7), 2508-2512.

Israel, B., Lichtenstein, R., Lantz, P., McGranaghan, R., Allen, A., Guzman, J., et al. (2001). The Detroit Community Academic Urban Research Center: Development, Implementation, and Evaluation. *Journal of Public Health Management and Practice, 7*, 1-19.

Jensen, P. K., Ensink, J. H., Jayasinghe, G., van der Hoek, W., Cairncross, S., & Dalsgaard, A. (2003). Effect of chlorination of drinking-water in water quality and childhood diarrhoea in a village in Pakistan. *J. Health Popul. Nutr, 21*(1), 26-31.

Joyce, T., McGuigan, K. G., Elmore-Meegan, M., & Conroy, R. M. (1996). Prevalence of enteropathogens in stools of rural Maasai children under five years of age in the Maasailand Region of the Kenyan Rift Valley. *East African Medical Journal, 73*(1), 59-62.

Joyce, T., McGuigan, K., Elmore-Meegan, M., & Conroy, R. (1996). Inactivation of Fecal Bacteria in Drinking Water by Solar Heating. *Applied and Environmental Microbiology*, 399-402.

Jungfer, C., Schwartz, T., & Obst, U. (2007). UV-Induced dark repair mechanisms in bacteria associated with drinking water. *Water Research, 41*, 188-196.

Kehoe, S. C., Barer, M. R., Devlin, L. O., & McGuigan, K. G. (2004). Batch process solar disinfection is an efficient means of disinfecting drinking water contaminated with *Shigella dysenteriae* type 1. *Letters in Applied Microbiology, 48*, 410-414.

Kerwick, M., Reddy, S., Holt, D., & Chamberlain, A. (2005). A methodology for the evaluation of disinfection technologies. *Journal of Water and Health, 3*(4), 393-403.

Kirchoff, L. V., McClelland, K. E., Pinho, M. D., Araujo, J. G., De Sousa, M. A., & Guerrant, R. L. (1985). Feasibility and efficacy of in-home water chlorination in rural North-eastern Brazil . *The Journal of Hygiene*, *94*(2), 173-180

Kolvin, J. L., & Roberts, D. (1982). Studies on the growth of *Vibrio cholerae* biotype E1 Tor and biotype classical in foods. *Journal of Hygiene (Cambridge), 89*, 243-252.

Lantagne, D. (2001). *Alethia Environmental.* Retrieved March 24, 2008, from Investigation of the Potters for Peace colloidal silver impregnated ceramic filter: Report 1: Intrinsic effectiveness.: www.alethia.cc

Latagne, D., Quick, R., & Mintz, E. (2008). Household water treatment and safe storage options in developing countries: a review of current implementation practices.. Retrieved March 4, 2008, from Environmental Change and Security Program: http://www.wilsoncenter.org/topics/pubs/WaterStoriesHousehold.pdf

Leavens, T., Blount, B., DeMarini, D., Madden, M., Valentine, J., & Case, M. (2007). Disposition of Bromodichloromethane in Humans Following Oral and Dermal Exposure. *Toxicological Sciences, 99* (2), 432-445.

Leclerc, H., Schwartzbrod, L., & Dei-Cas, E. (2002). Microbial agents associated with waterborne diseases. *Critical Reviews in Microbiology, 28*, 371-409.

Linden, K., Thurston, J., Shcaefer, R., & Malley, J. (2007). Enhanced UV Inactivation of Adenoviruses under Polychromatic UV Lamps. *Applied and Environmental Microbiology, 73*(23), 7571-7574.

Loevinsohn, B. (1990). Health education interventions in developing countries: a methodological review of published articles. *International Journal of Epidemiology, 19*, 788-794.

Logan, A. J., Stevik, T. K., Siegrist, R. L., & Ronn, R. N. (2005). Transport and fate of *cryptosporidium parvum* oocysts in intermittent sand filters. *Water Research, 35* (18), 4359-4369.

Lonnen, J., Kilvington, S., Kehoe, S. C., Al Touati, F., & McGuigan, K. G. (2005). Solar and photocatalytic disinfection of protozoan, fungal and bacterial microbes in drinking water. *Water Research, 39*, 877-883.

Luby, S. P., Agboatwalla, M., Feikin, D. R., Painter, J., Billhimer, W., Altaf, A., et al. (2005). Effect of handwashing on child health: a randomised controlled trial. *Lancet, 366*, 225-233.

Luby, S. P., Agboatwalla, M., Hoekstra, R. M., Rahbar, M. H., Billhimer, W., & Keswick, B. (2004). Delayed effectiveness of home-based interventions in reducing childhood diarrhea, Karachi, Pakistan. *American Journal of Tropical Medicine and Hygiene, 71*(4), 420-427.

Luby, S. P., Agboatwalla, M., Painter, J., Altaf, A., Billhimer, W., & Hoekstra, R. M. (2004). Effect of intensive handwashing promotion on childhood diarrhea in high-risk communities in Pakistan. *JAMA, 291*(21), 2547-2554.

Luby, S. P., Agboatwalla, M., Painter, J., Altaf, A., Billhimer, W., Keswick, B., et al. (2006). Combining drinking water treatment and hand washing for diarrhoea prevention, a cluster randomised controlled trial. *Tropical Medicine and International Health, 11*(4), 479-489.

Lule, J. R., Mermin, J., Ekwaru, J. P., Malamba, S., Downing, R., Ransom, R., et al. (2005). Effect of home-based water chlorination and safe storage on diarrhea among persons with human immunideficiency virus in Uganda. *Am. J. Trop. Med. Hyg., 73*(5), 926-933.

Makutsa, P., Nzaku, K., Ogutu, P., Barasa, P., Ombeki, S., Mwaki, A., et al. (2001). Challenges in Implementing a Point-of-Use Water Quality Intervention in Rural Kenya. *American Journal of Public Health, 91*(10), 1571-1573.

Mani, S. K., Kanjur, R., Singh, I. S., & Reed, R. H. (2006). Comparative effectiveness of solar disinfection using small-scale batch reactors with reflective, absorptive and transmissive rear surfaces. *Water Research, 40*, 721-727.

Manz, D. H., Buzunis, B. J., & Morales, C. (1993). *Final report on the Nicaragua household water supply and testing project.* Calgary, AB, Canada: University of Calgary.

Marti-Costa, S., & Serrano- Garcia, I. (2001). Needs assessment and community development: An ideological perspective. In J. Rothman, J. Erlich, & J. Tropman (Eds.), *Strategies of community intervention* (6 ed.). Itasca, IL: F.E. Peacock.

Martin-Dominquez, A., Alarcon- Hererra, M., Martin-Dominquez, I., & Gonzalez- Hererra, A. (2005). Efficiency in the disinfection of water for human consumption in rural communities using solar radiation. *Solar Energy, 78*, 31–40.

Mata, L., Vargas, C., Saborio, D., & Vives, M. (1994). Extinction of *Vibrio cholerae* in acidic substrata: contaminated cabbage and lettuce treated with lime juice. *Review of the Biology of the Tropics, 42*, 487-492.

McGuigan, K. G., Méndez-Hermida, F., Castro-Hermida, J. A., Ares-Mazás, E., Kehoe, S. C., Boyle, M., et al. (2006). Batch solar disinfection (SODIS) inactivates oocysts of *Cryptosporidium parvum* and cysts of *Giardia muris* in drinking water. *J. Appl. Microbiol., 10* (2), 453-463.

McGuigan, K., Joyce, T., Conroy, R., Gillespie, J., & Elmore-Meegan, M. (1998). Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. *Journal of Applied Microbiology, 84*, 1138-1148.

McKnight, J., & Kretzmann, J. (1990). *Building communities from the inside out.* Evanston, IL: Center for Urban Affairs and Policy Research, Northwestern University.

McLennan, J. D. (2000). Prevention of diarrhea in a poor district of Santo Domingo, Dominican Republic: Practices, knowledge, and barriers. *J. Health Popul. Nutr., 18*(1), 15-22.

Méndez-Hermida, F. A.-M., McGuigan, K. G., Boyle, M., Sichel, C., & Fernández-Ibáñez, P. (2007). Disinfection of drinking water contaminated with *Cryptosporidium parvum* oocysts under natural sunlight and using the photocatalyst TiO_2. *Journal of Photochemistry & Photobiology B: Biology, 88*(2/3), 105-112.

Migele, J., Ombeki, S., Ayalo, M., Biggerstaff, M., & Quick, R. (2007). Short report: Diarrhea prevention in a Kenyan school through the use of a simple safe water and hygiene intervention. *Am. J. Trop. Med. Hyg., 76*(2), 351-353.

Mintz, E., Bartram, J., Lochery, P., & Wegelin, M. (2001). Not Just a Drop in the Bucket: Expanding Access to Point-of-Use Water Treatment Systems. *American Journal of Public Health, 91*(10), 1565-1570.

Mong, Y., Kaiser, R., Ibrahim, D., Rasoatiana, E. K., & Quick, R. (2001). Impact of the Safe Water System on water quality in cycline-affected communities in Madagascar. *American Journal of Public Health, 91*(10), 1577-1579.

Montgomery, M., & Elimelech, M. (2007). Water and Sanitation in Developing Countries: Including Health in the Equation. *Environmental Science and Technology, 41*(1), 17-24.

Mutanda, L., Gemert, W., Kangethe, S., & Juma, R. (1986). Seasonal patterns of some causative agents of childhood diarrhoea in Nairobi. *East African Medical Journal, 63*(6), 373-381.

Nguyen, T. V., Van, P. L., Huy, C. L., Gia, K. N., & Wientraub, A. (2006). Etiology and epidemiology of diarrhea in children in Hanoi, Vietnam. *International Journal of Infectious Diseases, 10*, 298-208.

National Institute of Health. (2005). *Theory at a Glance.* Retrieved March 16, 2008, from US Department of Health and Human Services Web site: www.cancer.gov/theory

Nimri, L. F., & Meqdam, M. (2004). Enteropathogens associated with cases of gastroenteristis in a rural population in Jordan. *Clin Microbiol Infect, 10*, 634-639.

Oates, P. M., Shanahan, P., & Polz, M. F. (2003). Solar disinfection (SODIS): simulation of solar radiation for global assessment and application for point-of-use water treatment in Haiti. *Water Research, 37*, 47-54.

Olsen, A., Magnussen, P., & Anemana, S. (1997). The acceptability and effectiveness of a polyester drinking-water filter in a dracunculiasis-endemic village in northern region, Ghana. *Bulletin of the World Health Organization, 75*(5), 449-452.

Prrocter & Gamble. (2008). *Procter and Gamble PUR Website*. Retrieved April 2, 2008 , from Procter and Gamble Website : www.purpurifierofwater.com

Palmateer, G., Manz, D. H., Jurkovic, A., McInnis, R., Unger, S., & Kwan, K. K. (1999). Toxicant and Parasite Challenge of Manz Intermittent Slow Sand Filter. *Environ. Toxicol, 14*, 217-225.

Parker, A. A., Stephenson, R., Riley, P. L., Ombeki, S., Komolleh, C., Sibley, L., et al. (2006). Sustained high levels of stored drinking water treatment and retention of hand-washing knowledge in rural Kenya households following a clinic-based intervention. *Epidemiol. Infect., 134*, 1029-1036.

Peterson, E. A., Roberts, L., Toole, M. J., & Peterson, D. E. (1998). The effect of soap distribution on diarrhoea: Nyamithuthu Refugee Camp. *International Journal of Epidemiology, 27*, 520-524.

Pick, S., Poortinga, Y., & Givaudan, M. (2003). Integrating Intervention Theory and Strategy in Culture-Sensitive Health Promotion Programs. *Prof. Psych.: Research and Practice, 34* (4), 422-429.

Pinfold, J., & Horan, N. (1996). Measuring the effect of a hygiene behavior intervention by indicators of behavior and diarrhoeal disease. *Transactions of the Royal Society fo Tropical Medicine, 90*, 366-371.

Potters for Peace. (2006). *Potters for Peace Website* . Retrieved March 20, 2008, from Potters for Peace : http://www.pottersforpeace.org/

Pozzo, R. L., Baltanas, M. A., & Cassano, A. E. (1997). Supported titanium dioxide as a photocatalyst in water decontamination. *Catal. Today, 39*, 219-231.

Prashar, U., Bresee, J., Gentsch, J., & Glass, R. (1998). Rotavirus. *Emerging Infectious Diseases, 4*, 561-570.

Prashar, U., Gibson, C., Bresee, J., & Glass, R. (2006). Rotavirus and severe childhood diarrhea. *Emerging Infectious Diseases, 12*(2), 304-306.

Pryer, J. (1993). The impact of adult ill health on household income and nutrition in Khulna, Bangladesh. *Environ. Urbaniz, 5*(2), 35–49.

Quick, R., Venczel, L., & Mintz, E. (1999). Diarrhea prevention in Boliva through point-of-use disinfection and safe storage: a promising new strategy. *Epidemiology Infections, 122*, 83-90.

Rainey, R., & Harding, A. (2005). Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *International Journal of Environmental Health Research, 15* (5), 361-372.

Ram, P., Rasoatiana, E. K., Miarintsoa, R. R., Rakotomalala, O., Dunston, C., & Quick, R. (2007). Bringing safe water to remote populations: An evalutation of a portable point-of-use intervention in rural Madagascar. *American Journal of Public Health, 97* (3), 398-400.

Reed, R. (1997). Solar inactivation of faecal bacteria in water: the critical role of oxygen. *Letters in Applied Microbiology, 24*, 276-280.

Reller, M. E., Mendoza, C. E., & Lopez, M. B. (2003). A randomized controlled trial of household based flocculant-disinfectant drinking water for diarrhea prevention in rural Guatemala. *The American Journal of Tropical Medicine and Hygiene, 69*, 411-419.

Rincon, A. G., & Pulgarin, C. (2003). Photocatalytical inactivation of *E. coli*: effect of (continuous–intermittent) light intensity and of (suspended–fixed) TiO_2 concentration. *Applied Catalysis B: Environmental, 44*, 263-284.

Roberts, L., Chartier, Y., Chartier, O., Malenga, G., Toole, M., & Rodka, H. (2001). Keeping clean water clean in a Malawi refugee camp: a randomized intervention trial. *Bulletin of the World Health Organization, 79*, 280-287.

Rodgers, E. (2003). *Diffusion of Innovations* (5th ed.). New York: Free Press.

Rodrigues, A., Sandstrom, A., Ca, T., Steinsland, H., Jensen, H., & Aaby, P. (2000). Protection from cholera by adding lime juice to food- results from community and laboratory studies in Guinea-Bissau, West Africa. *Tropical Medicine and International Health, 5*(6), 418-422.

Rose, A. (2006). Solar disinfection of water for diarrhoeal prevetion in southern India. *Arch Dis Child, 91*, 139-141.

Rothman, J. (2001). Approaches to Community Intervention. In J. Rothman, et. al (Eds.), *Strategies of Community Intervention* (6th ed., pp. 27–64). Itasca, IL: F. E. Peacock.

Saidi, S., Iijima, Y., Sang, W., Mwangudza, A., Oundo, J., Taga, K., et al. (1997). Epidemiological study on infectious diarrheal diseases in children in a coastal rural area of Kenya. *Microbiology and Immunology, 41*(10), 773-778.

Saito, T., Iwase, T., Horie, J., & Morioka, T. (1992). Mode of photolytic bactericidal action of powdered semiconductor TiO_2 on mutans streptococci. *Journal of Photochemistry and Photobiology B: Biology, 14*, 369-379.

Salih, F. M. (2002). Enhancement of solar inactivation of *Escherichia coli* by titanium dioxide photcatalytic oxidation. *Journal of Applied Microbiology, 92*, 920-926.

SANDEC . (2008). *SODIS Manual (English).* Retrieved April 1, 2008, from SODIS Web Site: www.sodis.ch

Schwab, K. (2007). Waterborne Gastroenteritis Viruses. In A. Bosch (Ed.), *Human Viruses in Water* (pp. 27-38). Oxford: Elsevier.

Semenza, J. C., Robert, L., Henderson, A., Bogan, J., & Rubin, C. H. (1998). Water distribution system and diarrheal disease transmission: a case study in Uzbekistan. *Am. J. Trop. Med. Hyg., 59*(6), 941-946.

Sharpless, C. M., & Linden, K. G. (2001). UV Photolysis of Nitrate: Effects of Natural Organic Matter and Dissolved Inorganic Carbon and Implications for UV Water Disinfection. *Environ. Sci. Technol, 35*(14), 2949-2955.

Silvestry-Rodriguez, N., Bright, K. R., Uhlmann, D. R., Slack, D. C., & Gerba, C. P. (2007). Inactivation of *Pseudomonas aeruginosa* and *Aeromonas hydrophila* by silver in tap water. *Journal of Environmental Science and Health Part A, 42*, 1579-1584.

Smith, R. J., Kehoe, S. C., McGuigan, K. G., & al, e. (2000). Effects of simulated solar disinfection of water on infectivity of *Salmonella typhimurium*. *Letters in Applied Microbiology, 31*, 284-288.

Sobel, J., Mahon, B., Mendoza, C. E., Passaro, D., Cano, F., Baier, K., et al. (1998). Reduction of fecal contamination of street-vended beverages in Guatemala by a simple system for water purification and storage, handwashing, and beverage storage. *Am. J. Trop. Med. Hyg, 59*(3), 380-387.

Sobsey, M. D., Handzel, T., & Venczel, L. (2003). Chlorination and safe storage of household drinking water in developing countries to reduce waterborne disease. *Water Science and Technology, 47*(3), 221-228.

Sobsey, M. (1989). Inactivation of health-related microorganisms in water by disinfection processes. *Water Sci Technol, 21*, 179-195.

Sobsey, M. (2002). *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply.* Retrieved February 18, 2008, from WHO Web Site: http://www.who.int/water_sanitation_health/dwq/wsh0207/en/

Sommer, B. (1997). SODIS- an emerging water treatment process. *Journal of Water Supply Research Technology Aqua, 46*, 127-137.

Souter, P., Cruickshank, G., Tankerville, M., Keswick, B., Ellis, B., Langworthy, D., et al. (2003). Evaluation of a New Water Treatment for Point-of-Use Household Applications to Remove Microorganisms and Arsenic from Drinking Water. *Journal of Water Health, 3*, 73-84.

Stanton, B., Black, R., Engle, P., & Pelto, G. (1992). Theory-driven behavioral intervention research for the control of diarrheal diseases. *Social Science and Medicine, 35*(11), 1405-1420.

Stauber, C. E., Elliot, M. A., Koksal, F., Ortiz, G. M., DiGiano, F. A., & Sobsey, M. D. (2006). Characterisation of the biosand filter for *E. coli* reductions from household drinking water under controlled laboratory and field use conditions. *Water Sci Technol, 54*(3), 1-7.

Stohl, E. A., Brockman, J. P., Burkle, K. L., Morimatsu, K., Kowalczykwski, S. C., & Seifert, H. S. (2003). *Escherichia coli* RecX inhibits RecA recombinase and coprotease activities in vitro and in vivo. *J.Biol. Chem, 278*, 2278-2285.

Storti, C. (2004). *The Hygiene Improvement Framework: A Comprehensive Approach for Preventing Childhood Diarrhea.* Washington, DC: U.S. Agency for International Development.

Thevos, A. K., Kaona, F. D., Siajunza, M. T., & Quick, R. E. (2000). Adoption of safe water behaviors in Zambia: Comparing educational and motivational approaches. *Education for Health, 13*(3), 366-376.

Torres, M. E., Pirez, M. C., Varela, G., Parodi, V., Allende, F., & al, e. (2001). Etiology of Children's Diarrhea in Montevideo, Uruguay: Associated Pathogens and Unusual Isolates. *Journal of Clinical Microbiology, 39*(6), 2134-2139.

Tumwine, J. (2005). Clean drinking water for homes in Africa and other less developed countries. *BMJ, 331*, 468-469.

Tumwine, J., Thompson, J., Katua-Katua, M., Mujwajuzi, M., Johnstone, N., Wood, E., et al. (2002). Diarrhoea and Effects of Different Water Sources, Sanitation and Hygiene Behavior in East Africa. *Tropical Medicine and International Health, 7*(9), 720-756.

United Nations. (2008). *UN Web Site*. Retrieved February 24, 2008, from Millennium Development Goals Indicators Website-Kenya: http://mdgs.un.org/unsd/mdg/default.aspx.

Vanderslice, J., & Briscoe, J. (1993). All coliforms are not created equal- a comparison of the effects of water source and in-house water contamination on infantile diarrheal disease. *Water Resouces Research, 29*, 1983-1995.

Weglin, M. (2001). Does sunlight change the material and content of polyethylene terephthalate (PET) bottles? *Journal of Water Supply Research and Technology-AQUA, 50*(3), 125-133.

Weglin, M. (2001). Solar water disinfection (SODIS): a simple water treatment process. *Journal of Water Supply Research Technology Aqua, 50*, 125-134.

Wegmann, M., Michen, B., Luxbacher, T., Fritsch, J., & Graule, T. (2008). Modification of ceramic microfilters with colloidal zirconia to promote the adsorption of viruses from water. *Water Research*, *42*(6-7), 1726-1734

Whittington, D., Mu, X., & & Roche, R. (1990). Calculating the Value of Time Spent Collecting Water: Some Estimates for Ukunda, Kenya. *World Development, 18*(2), 269-280.

World Health Organization. (2008). *Global Burden of Disease Web site*. Retrieved April 1, 2008, from WHO Web site: http://www.who.int/healthinfo/bodestimates/en/index.html

World Health Organization. (2004). *Guidelines for Drinking Water Quality* (3rd ed.). Geneva: World Health Organization.

World Health Organization. (2006). *Water, Sanitation, and Health Web site.* Retrieved April 1, 2008, from WHO Web site: http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html

World Health Organization. (2008). *Water, sanitation and hygiene links to health site.* Retrieved March 18, 2008, from WHO Web site: http://www.who.int/water_sanitation_health/publications/facts2004/en/

WHO/UNICEF. (2004). *Meeting the MDG Drinking Water and Sanitation Target:A Mid-Term Assessment of Progress.* Geneva: World Health Organization

WHO/UNICEF. (2005). *Water for Life: Making it happen.* Retrieved April 1, 2008, from WHO Web site: http://www.who.int/water_sanitation_health/monitoring/jmp2005/en/

Wigle, D., Arbuckle, T., Walker, M., Wade, M., Liu, S., & Krewski, D. (2007). *Environmental Hazards: Evidence for Effects on Child Health.* Retrieved February 12, 2008, from http://dx.doi.org/10.1080/10937400601034563

Wilderer, P. (2005). UN Water Action Decade: A Unique Challenge and Chance for Water Engineers. *Water Science and Technology, 51*, 99-107.

Wilhelmi, I., Roman, E., & Sanchez-Fauquier, A. (2003). Viruses causing gastroenteritis. *Clin. Microbiol. Infect., 9*, 247-262.

World Bank. (2004). *Rural Water Supply and Sanitation in Africa; Case Study.* Washington, D.C.: World Bank.

World Bank (2008). *World Bank Impact Evaluation.* Retrieved April 4, 2008, from World Bank Impact Evaluation Site: http://web.worldbank.org

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 and International Health, 9*(1), 106-117.

Yang, L., Ning, X., Xiao, Q., Chen, K., & Zhou, H. (2007). Development and characterization of porous silver-incorporated hydroxyapatite ceramic for separation and elimination of microorganisms. *Journal of Biomedical Materials Research Part B: Applied Biomaterials , 81*(B), 50-56.

Yoder, P. S. (1997). Negotiating relevance: Belief, knowledge, and practice in international health projects. *Medical Anthropology Quarterly, 11*(2), 131-146.

Yousafzai, M. A., & Bhutta, Z. A. (2000). Global epidemiology of childhood diarrhoea at the turn of the millennium. In Z. Bhutta (Ed.), *Contemporary Issues in Childhood Diarrhoea and Malnutrition* (pp. 1-22). Oxford: Oxford University Press.