

HOUSEHOLD WATER TREATMENT AND SAFE STORAGE OPTIONS IN DEVELOPING COUNTRIES: A REVIEW OF CURRENT IMPLEMENTATION PRACTICES

By Daniele S. Lantagne, Robert Quick, and Eric D. Mintz

The United Nations' International Drinking Water Supply and Sanitation Decade (1981–1990) failed to achieve its goal of universal access to safe drinking water and sanitation by 1990 (World Health Organization [WHO], 2003). Even though service levels rose by more than 10 percent during the decade, 1.1 billion people still lacked access to improved water supplies, and 2.4 billion people were without adequate sanitation, in 1990 (WHO/UNICEF, 2000). Reasons cited for the decade's failure include population growth, funding limitations, inadequate operation and maintenance, and continuation of a traditional “business as usual” approach (WHO/UNICEF, 1992).

The world is on schedule to meet the Millennium Development Goal (MDG), adopted by the UN General Assembly in 2000 and revised after the World Summit on Sustainable Development in Johannesburg, to “halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation” (World Bank Group, 2004; WHO/ UNICEF, 2004). However, success still leaves more than 600 million people without access to safe water in 2015 (WHO/ UNICEF, 2000). In addition, although the MDG

target specifically states the provision of “safe” drinking water, the metric used to assess the MDG target is the provision of water from “improved” sources, such as boreholes or household connections, as it is difficult to assess whether water is safe at the household level (WHO/UNICEF, 2004). Thus, many more people than estimated may drink unsafe water from improved sources.

HOUSEHOLD WATER TREATMENT AND SAFE STORAGE

To overcome the difficulties in providing safe water and sanitation to those who lack it, we need to move away from “business as usual” and research novel interventions and effective implementation strategies that can increase the adoption of technologies and improve prospects for sustainability. Despite general support for water supply and sanitation, the most appropriate and effective interventions in developing countries are subject to significant debate. The weak links among the water, health, and financial sectors could be improved by communication programs emphasizing health¹—as well as micro- and macroeconomic—benefits that could be gained.

1. The health consequences of inadequate water and sanitation services include an estimated 4 billion cases of diarrhea and 2.2 million deaths each year, mostly among young children in developing countries (WHO/UNICEF, 2000). In addition, water-borne diarrheal diseases lead to decreased food intake and nutrient absorption, malnutrition, reduced resistance to infection (Baqui et al., 1993), and impaired physical growth and cognitive development (Guerrant et al., 1999).

The new focus on novel interventions has led researchers to re-evaluate the dominant paradigm that has guided water and sanitation activities since the 1980s. A literature review of 144 studies by Esrey et al. (1991) represents the old paradigm, concluding that sanitation and hygiene education yield greater reductions in diarrheal disease (36 percent and 33 percent, respectively) than water supply or water quality interventions.² However, a more recent meta-analysis commissioned by the World Bank contradicted these findings, showing that hygiene education and water quality improvements are more effective at reducing the incidence of diarrheal disease (42 percent and 39 percent, respectively) than sanitation provision and water supply (24 percent and 23 percent, respectively) (Fewtrell & Colford, 2004).

The discrepancy between these findings can be attributed in part to a difference in intervention methodology. Esrey et al. (1991) reviewed studies that largely measured the impact of water quality improvements at the source (i.e., the wellhead or community tap). Since 1996, a large body of published work has examined the health impact of interventions that improve water quality at the point of use through household water treatment and safe storage (HWTS; Fewtrell & Colford, 2004). These recent studies—many of them randomized controlled intervention trials—have highlighted the role of drinking water contamination during collection, transport, and storage (Clasen & Bastable, 2003), and the health value of effective HWTS (Clasen et al., 2004; Quick et al.,

1999, 2002; Conroy et al., 1999, 2001; Reller et al., 2003).

In 2003, as the evidence for the health benefits of HWTS methods grew, institutions from academia, government, NGOs, and the private sector formed the International Network to Promote Household Water Treatment and Safe Storage, housed at the World Health Organization in Geneva, Switzerland. Its stated goal is “to contribute to a significant reduction in waterborne disease, especially among vulnerable populations, by promoting household water treatment and safe storage as a key component of water, sanitation, and hygiene programmes” (WHO, 2005).

HWTS OPTIONS

This article summarizes five of the most common HWTS options—chlorination, filtration (biosand and ceramic), solar disinfection, combined filtration/chlorination, and combined flocculation/chlorination—and describes implementation strategies for each option.³ We identify implementing organizations and the successes, challenges, and obstacles they have encountered in their projects. We consider sources of funding and the potential to distribute and sustain each option on a large scale, and propose goals for future research and implementation.

This article focuses on point-of-use drinking water treatment and safe storage options, which can accelerate the health gains associated with improved water until the longer-term goal of universal access to piped, treated water is achieved. By preventing disease, HWTS practices can contribute to poverty

2. This study reinforced previous work (Esrey, 1985) that led the water and sanitation sector to de-emphasize improving water quality as a way to reduce diarrheal disease incidence.
3. Space precludes exhaustive consideration of all HWTS options, and thus we have chosen those that are most widely used. For a thorough technical review of all HWTS options, see *Managing Water in the Home: Accelerated Health Gains From Improved Water Supply* (Sobsey, 2002). For reviews of safe storage options, see Mintz et al. (1995, 2001).

alleviation and development. Their widespread use, in conjunction with hygiene education and sanitation, could save millions of lives until the infrastructure to reliably deliver safe water to the entire world population has been created.

We use a consistent evaluation scheme for each of the HWTS options discussed (see Table 1):

1. Does the HWTS option remove or inactivate viral, bacterial, and parasitic pathogens in water in a laboratory setting?;
2. In the field, is the HWTS option acceptable, can it be used correctly, and does it reduce disease among users?; and
3. Is the HWTS option feasible at a large scale?

OPTION 1: CHLORINATION

Chlorination was first used to disinfect public water supplies in the early 1900s, and helped drastically reduce waterborne disease in cities in Europe and the United States (Gordon et al., 1987). Although there had been small trials of point-of-use chlorination (Mintz et al., 1995), larger-scale trials began in the 1990s as part of the Pan American Health Organization (PAHO) and the U.S. Centers for Disease Control and Prevention (CDC) response to epidemic cholera in Latin America (Tauxe, 1995). The Safe Water System (SWS) strategy devised by CDC and PAHO includes three elements:

TABLE 1: SUMMARY OF HWTS OPTION PERFORMANCE CRITERIA

Criterion	Lab Studies				Field Studies		Can intervention be brought to scale?
	Virus	Bacteria	Protozoa	Residual Protection?	Acceptable to users?	Health impact?	
Chlorination	Medium	High	Low	Chlorine	Yes	Yes (4 studies)	Yes (operates at village and national scale)
BioSand Filtration	Unknown	Medium-High	High	No	Yes	Unknown	Unknown (operates at village and regional scale)
Ceramic Filtration	Unknown	Medium-High	High	No	Yes	Yes (1 study with imported filters)	Unknown (operates at village and regional scale)
Solar Disinfection	High	High	High	Safe Storage	Yes	Yes (4 studies)	Unknown (operates at village and regional scale)
Filtration and Chlorination	Medium	High	Unknown	Chlorine	Yes	Yes (1 unpublished cross-sectional study)	Unknown (operates at village and regional scale)
Flocculation and Chlorination	High	High	High	Chlorine	Yes	Yes (5 studies)	Yes (operates at village and national scale)

- Treating water with dilute sodium hypochlorite⁴ at the point of use;
- Storing water in a safe container; and
- Educating users to improve hygiene, as well as water- and food-handling practices.

The sodium hypochlorite solution is packaged in a bottle with directions instructing users to add one full bottle cap of the solution to clear water (or two caps to turbid water) in a standard-sized storage container, agitate, and wait 30 minutes before drinking. In four randomized controlled trials, the SWS reduced the risk of diarrheal disease by 44–84 percent (Luby et al., 2004; Quick et al., 1999, 2002; Semenza et al., 1998). At concentrations used in HWTS programs, chlorine effectively inactivates bacteria and some viruses (American Water Works Association, 1999); however, it is not effective at inactivating some protozoa, such as cryptosporidium.⁵ Initial research shows water treated with the SWS does not exceed WHO guidelines for disinfection by-products, which are potentially cancer-causing agents (CDC, unpublished data). Because the concentration of the chlorine solution used in SWS programs is low, the environmental impacts of the solution are minimal.

Chlorination: Implementation Strategies

SWS implementation has varied according to local partnerships and underlying social and economic conditions. The disinfectant solution has been distributed at national and subnational levels in 13

countries through social marketing campaigns, in partnership with the NGO **Population Services International** (PSI). In Indonesia, the solution is distributed primarily by private sector efforts, led by a local manufacturing company. In several countries—including Ecuador, Laos, Haiti, and Nepal—the ministries of health or local NGOs run the SWS programs at the community level. In Kabul, Afghanistan, the SWS is provided at no charge to pregnant women receiving antenatal care. The SWS has also been distributed free of charge in a number of disaster areas, including Indonesia, India, and Myanmar following the 2004 tsunami, and also in Kenya, Bolivia, Haiti, Indonesia, and Madagascar after other natural disasters. When SWS programs are in place, the product's ready availability greatly facilitates emergency response. The CDC has developed an implementation manual and provides technical assistance to organizations implementing SWS projects (CDC, 2001).

PSI's Social Marketing of the SWS in Zambia

PSI is the largest social marketing NGO in the world, with offices in more than 70 countries. PSI designs a brand name and logo for health products; sells them at low prices; distributes them through wholesale and retail commercial networks; and generates demand for the products through behavior change communications such as radio and TV spots, mobile video units, point-of-sale materials, theater performances, and person-to-person communications.

4. Sodium hypochlorite (NaOCl) is a slightly yellow, transparent liquid. As a chlorine donor, it serves as a strong oxidizer, bleaching agent, and sterilizer.
5. Microscopic parasites of the genus *Cryptosporidium* cause a diarrheal disease called cryptosporidiosis. Once an animal or person is infected, the parasite lives in the intestine and passes in the stool. The parasite is protected by an outer shell that allows it to survive outside the body for long periods of time and makes it very resistant to chlorine-based disinfectants.



**Safe Water System reseller
in Jolivet, Haiti**
(courtesy of Daniele Lantagne)

In October 1998, PSI launched its Zambian SWS product, a bottle of sodium hypochlorite solution branded as “Clorin.” This program is one of the oldest PSI/CDC collaborations. Sales steadily increased from 732 bottles per month in October 1998 to 132,000 bottles per month in November 2003. A cholera epidemic in 1999 increased demand for Clorin; sustained social marketing and promotion in health centers and door-to-door visits stimulated further sales (Olembo et al., 2004). A population-based, cross-sectional study conducted by an independent agency reported that 42 percent of households said they were currently using Clorin, and 22 percent reported using it in the past (Olembo et al., 2004). However, only 13 percent of households had residual chlorine in their water at the time of the unannounced visit, indicating a discrepancy between reported and actual use. The study did not find a lower rate of reported diarrhea among users of Clorin as compared to non-users. However, using large cross-sectional studies to assess the efficacy of household water treatment options requires further refinement. The limitations of this study, which was the first large cross-sectional population study (as opposed to a randomized study with a controlled population), impacted the results.

The Clorin product is subsidized by USAID; the full cost of the 250-milliliter bottle—including production, marketing, distribution, and overhead—is US\$0.34, and the retail price is set at US\$0.12. The total program cost per person-month of protection from diarrhea is US\$0.045 (CDC, unpublished data). Increasing the price to recover full costs could have a negative impact on demand, particularly in a country like Zambia, which ranks 164th out of 177 on the Human Development Index (UN Development Programme, 2004). The program needs

studies of the price elasticity of demand for this product, and is currently implementing options to significantly lower costs.

PSI’s Zambia project is an example of a successful social marketing intervention that creates demand for a product and makes it widely available through the commercial sector. Interested NGOs can readily incorporate Clorin into their own programming. The two major challenges this program faces are achieving financial self-sufficiency while maintaining access to the product, and increasing demand among the highest-risk populations. With its wide Clorin use and distribution, Zambia is an ideal location for future research on program effectiveness in disease prevention, cost-effectiveness, and interventions to reduce economic and behavioral barriers to utilization.

Community-Based NGO Program in Northern Haiti

In contrast to PSI’s national-scale approach, the **Jolivert Safe Water for Families Project (JSWF)** produces its own disinfectant, “Dlo Pwòp,” at the Missions of Love Clinic in Jolivert, Haiti, for distribution in nearby communities. The JSWF Project installed a hypochlorite generator—a simple device that passes electric current through water and salt to generate hypochlorite—and trained two Haitian technicians to produce the disinfectant, sell it to families, provide educational support, and test for residual chlorine in users’ household water. Small-scale local production and distribution has ensured a continuous supply of disinfectant to families in spite of natural disasters and political upheavals.

JSWF spends about US\$7 to provide a bucket with a lid and spigot for safe storage, as well as

educational materials, for a family in the program. After that initial investment, disinfectant sales almost meet operating expenses. One month's supply of the disinfectant sells for US\$0.09, which is within the budget of most Haitian families. The project uses refillable bottles to reduce the cost of the disinfectant. JSWF began in September 2002 with 200 families; an independent evaluation four months later documented a reduction in diarrheal disease incidence of 55 percent (Brin, 2003). However, the data were from a cross-sectional survey, which is not as reliable for determining diarrheal disease outcomes as randomized, controlled, cohort studies. JSWF has expanded to more remote areas by transporting bulk disinfectant and distributing it through satellite refilling stations. Currently, the program distributes about 1,000 bottles of solution per month to approximately 1,200 participating families (7,200 people).

This type of program reaches rural populations in ways that are culturally appropriate and more cost-effective than many other programs. In addition, this program has created demand in surrounding communities via word-of-mouth advertising. The main drawbacks are the dependence on the hypochlorite generator and on outside programmatic support to enroll new families.

Chlorination: Benefits and Drawbacks of the SWS

The benefits of point-of-use chlorination include:

- Proven reduction of bacteria and most viruses;
- Residual protection against contamination;
- Ease of use and thus acceptability to users;
- Proven health impact in multiple randomized, controlled studies;

- Scalability; and
- Low cost.

The drawbacks include:

- Relatively low protection against some viruses and parasites;
- Lower effectiveness in water contaminated with organic and certain inorganic compounds;
- Potential objections to taste and odor; and
- Concerns about the potential long-term carcinogenic effects of chlorination by-products.

OPTION 2: FILTRATION

Porous stones and a variety of other natural materials have been used to filter visible contaminants from water for hundreds of years. These mechanical filters are an attractive option for household treatment because:

- There are many locally available and inexpensive options for filtering water;
- They are simple and easy to use; and
- Such filter media are potentially long-lived.

However, filtration is the least-studied HWTS intervention; and pathogen removal, filter maintenance, and the lack of residual protection pose challenges to implementation.

A recent health impact study in Bolivia documented a 64 percent reduction in diarrhea in users of 0.2 micron ceramic candle-shaped filters manufactured in Switzerland (Clasen et al., 2004).⁶ Users prevented recontamination by using a tight-fitting lid over the receptacle, a tight seal

6. Most currently used filtration options are locally manufactured.

to prevent leaking around the filters into the receptacle, and a spigot to access the water. In addition, users can clean the filters without removing them and potentially exposing the water in the receptacle to contaminants.

OPTION 2A: BIOSAND FILTRATION

The BioSand Filter (BSF) is a slow-sand filter adapted for use in the home. The most widely used version of the BSF is a concrete container approximately 0.9 meters tall and 0.3 meters square, filled with sand. The water level is maintained at 5–6 centimeters above the sand layer by setting the height of the outlet pipe. This shallow water layer allows a bioactive layer to grow on top of the sand, which helps reduce disease-causing organisms. A plate with holes in it is placed on the top of the sand to prevent disruption of the bioactive layer when water is added to the system. To use the system, users simply pour water into the BSF, and collect finished water from the outlet pipe in a bucket. In laboratory and field testing, the BSF consistently reduces bacteria, on average, by 81–100 percent (Kaiser et al., 2002) and protozoa by 99.98–100 percent (Palmateer et al., 1999). Initial research has shown that the BSF removes less than 90 percent of indicator viruses (Mark Sobsey, personal communication, March 20, 2005).

BioSand Filtration: Implementation Strategies

The BSF has been implemented through two main strategies. In the NGO model, employed in Cambodia and other countries, the cost of the filters is subsidized, and a NGO promotes the use of the BSF in the community and provides the filters. In the micro-entrepreneur model, used in Kenya and the Dominican Republic, local entrepreneurs construct the BSF, receive training and

start-up materials, and then develop micro-enterprises to sell filters within their communities.

Regional-Scale NGO Project in Cambodia

Samaritan's Purse, an international faith-based NGO, is one of the principal implementers of the BSF, responsible for the installation of approximately 30,000 of the 100,000 BSF filters in use worldwide. Samaritan's Purse has developed an implementation manual and employs a staff water expert to provide technical support to BSF projects across the world.

Samaritan's Purse has installed 15,000 filters in Cambodia, where it works with local partners to hold informational meetings for potential BSF users. Attendees interested in receiving a BSF are invited to a second training meeting to sign up for the program. This self-selected group is then asked to contribute a small amount of the cost of the BSF (about US\$3), attend focus group trainings on hygiene and use of the BSF, and send one family member to assist with the construction and transportation of the BSF. The full cost of installing a BSF in a home in Cambodia is US\$67; funding for this project primarily comes from the Canadian International Development Agency.

The success of this project is directly related to the strength of the cooperating staff in Cambodia (Kaida Liang, personal communication, December 24, 2004). Implementation challenges include human errors and the weight of the BSF (350 pounds), which makes transportation difficult and complicates installation in homes on stilts. Currently, 75,000 families are waiting to receive a filter, and lack of funding has limited expansion. As the project has grown, economies of scale and lessons learned have made installation more efficient and less costly.

BioSand Filtration: Benefits and Drawbacks

The benefits of the BSF include:

- Proven removal of protozoa and approximately 90 percent of bacteria;
- High user acceptability due to ease of use, and improved look and taste of water;
- Produced from locally available materials;
- One-time installation with few maintenance requirements; and
- Long life.

The drawbacks of the BSF include:

- Low rate of virus inactivation;
- Lack of residual protection and removal of less than 100 percent of the bacteria, which leads to recontamination;
- The current lack of studies proving health impact; and
- Difficulty in transport and high initial cost, which make scalability more challenging.

OPTION 2B: CERAMIC FILTRATION

Ceramic filters have traditionally been used for water treatment throughout the world. Currently, the most widely distributed ceramic filter is the **Potters for Peace** (PFP) filter, which is shaped like a flowerpot and impregnated with colloidal silver.⁷ Holding 8.2 liters of water, it sits inside a 20- to 30-liter plastic or ceramic receptacle with a spigot. Laboratory testing has shown that although the majority of the bacteria are removed mechanically through the filter's small (0.6–3.0 microns) pores, colloidal silver is necessary to inactivate 100 percent of the bacteria (Lantagne, 2001a). The filter removes 99.99 percent

of protozoa by mechanical processes (Lantagne, 2001a); however, the effectiveness of the filter in inactivating or removing viruses is unknown.

Ceramic Filtration: Implementation Strategies

PFP is a U.S.-based NGO whose mission is to build an international network of potters concerned with peace and justice issues. PFP helps potters learn appropriate technologies and marketing skills that improve their livelihoods and sustain their environment and cultural traditions. After staff members were introduced to the ceramic filter design, PFP established a filter-making factory in Managua, Nicaragua. Funding for the project initially came from private donations. The filter factory is now a self-financed micro-enterprise in Nicaragua. NGOs pay US\$10 per filter, and transport the filters themselves to project locations. From 1999–2004, PFP made and sold a total of 23,000 filters in Nicaragua. PFP has also established filter-making factories in 12 other countries, contracted by organizations that provide funding for technical assistance and factory construction.

In the current model, the factory sells filters to NGOs, who then implement a water program. This model is attractive to NGOs because they do not have to produce the filters, but it suffers from a lack of consistent training and education for both the NGO implementers and the users. Poor cleaning and maintenance of the filter often leads to recontamination of finished water (Lantagne, 2001b). To address this issue, PFP is working with cooperating NGOs to develop, implement,

7. Colloidal silver—tiny silver particles suspended in liquid—is a disinfectant, preventing bacterial growth in the ceramic filter and assisting in inactivating the bacteria in the filter. The use of colloidal silver in the PFP filter does not leave a residual in the drinking water.

and evaluate an educational program that includes safe storage, proper procedures for cleaning the filter, and follow-up visits to ensure proper use continues and broken filters are replaced. This educational component is critical for the real-world performance of the filter to match its effectiveness in the laboratory, and to test whether filters made with locally produced materials will prevent diarrhea.

Ceramic Filtration: Benefits and Drawbacks

The benefits of the PFP ceramic filter include:

- Proven reduction of bacteria and protozoa in the laboratory;
- Ease of use;
- Long life, if the filter remains unbroken; and
- Relatively low cost due to local production of the filter.

The drawbacks include:

- Unknown effectiveness against viruses;
- Lack of residual protection, leading to recontamination;
- Lack of health impact studies of this particular filter design;
- The need to educate the user to keep the filter and receptacle clean; and
- A low flow rate of 1–2 liters per hour.

OPTION 3: SOLAR DISINFECTION

Solar disinfection (SODIS) was initially developed to inexpensively disinfect water used for oral rehydration solutions (Acra et al., 1984). In 1991, the Swiss Federal Institute for Environmental Science and Technology began to investigate and implement solar disinfection as a HWTS option. Users of SODIS fill 0.3–2.0 liter plastic soda bottles with low-turbidity water, shake them to oxygenate the

water, and place the bottles on a roof or rack for six hours (if sunny) or two days (if cloudy). SODIS has been proven to inactivate bacteria and viruses (Wegelin et al., 1994; Sommer et al., 1997); the protozoa cryptosporidium and giardia are also sensitive to solar irradiation (Méndez-Hermida et al., 2005; Martin Wegelin & Regula Meierhofe, personal communication, March 8, 2005). Randomized controlled studies have shown SODIS to reduce diarrheal disease incidence by 9–86 percent (Conroy et al., 1996, 1999, 2001; Hobbins, 2003).

Solar Disinfection: Implementation Strategies

As a virtually zero-cost technology, SODIS faces marketing constraints. Since 2001, local NGOs in seven countries in Latin America—as well as in Uzbekistan, Pakistan, India, Nepal, Sri Lanka, Indonesia, and Kenya—are disseminating SODIS by training and educating users at the grassroots level, providing technical assistance to partner organizations, lobbying key players, and establishing information networks. The program has been funded by the AVINA and Solaqua Foundations, private and corporate sponsors, and official development assistance. The program has shown that SODIS is best promoted and disseminated by local institutions with experience in community health education. Creating awareness of the importance of treating drinking water and establishing corresponding changes in behavior requires a long-term training approach and repeated contact with the community. The Swiss Federal Institute for Environmental Science and Technology has developed an implementation manual, and provides technical assistance to NGOs implementing SODIS. The method, which has been disseminated in more than 20 developing countries, is regularly applied by more than one million users.

A NGO Project in East Lombok, Indonesia

After a successful pilot project, two local NGOs worked closely with the district health department in East Lombok, Indonesia, to promote SODIS (Meierhofer, 2005). This large-scale dissemination project worked through community health centers to train health officials, sanitarians, teachers, and community representatives in improved hygiene practices and use of SODIS. These trainers, in turn, trained 144 villages and 70 elementary schools in the use of SODIS, reaching 130,000 people in 14 months.

The project ensured sustainability by working closely with government partners. Integrating hygiene education and SODIS into the community health center structure provided long-term continuity for the project, which reduced bacterial contamination of household drinking water by 97 percent. Acquiring enough plastic bottles for each family was a challenge, so the project established a mechanism to transport and sell bottles. Georg Fischer AG, a German corporation, provided funding at a cost of US\$0.80 per capita.

Solar Disinfection: Benefits and Drawbacks

The benefits of SODIS include:

- Proven reduction of bacteria, viruses, and protozoa;
- Proven health impact;
- Acceptability to users because of the minimal cost to treat water, ease of use, and minimal change in water taste; and
- Unlikely recontamination because water is consumed directly from the small, narrow-necked bottles (with caps) in which it is treated.

8. Turbidities higher than 30 Nephelometric Turbidity Units.



Using solar disinfection (SODIS) in Nepal

(courtesy of EAWAG/Water and Sanitation in Developing Countries [SANDEC])

The drawbacks include:

- Need to pretreat water that appears slightly dirty;⁸
- Low user acceptability because of the limited volume of water that can be treated at one time and the length of time required to treat it; and
- Requires a large supply of intact, clean, and properly sized plastic bottles.

OPTION 4: FILTRATION AND CHLORINATION

Several systems incorporate both a physical filtration step for particle removal and a chlorination step (or steps) for disinfection. This dual approach produces high-quality finished water. The **Gift of Water, Inc.**, (GWI) purifier is a two-bucket system with a polypropylene string-wound filter in the top bucket and a granulated activated-carbon filter in the bottom bucket. Users collect water in the top bucket, add chlorine (purchased locally each month), wait 30 minutes, and then place the

top bucket on the bottom bucket, which activates a check-valve allowing water to flow through the two filters into the bottom bucket. Water is removed from the system via a tap in the bottom bucket, and a small amount of chlorine is added manually to the bottom bucket as residual protection. This system has been proven to reduce bacteria sufficiently to meet WHO guidelines (Varghese, 2002). Studies of protozoal removal have been inconclusive (Borucke, 2002); viral removal has not yet been studied.

Filtration and Chlorination: Implementation Strategies

GWI is a faith-based organization headquartered in Florida that assembles, distributes, and implements village-based programs with the GWI purifier. Church groups in the United States sponsor communities in Haiti, many through the Catholic Parish Twinning Program of the Americas.

Once a village is sponsored, Haitian GWI staff work with the community to establish a water committee and install purifiers in 200–400 homes. In addition, two local community health technicians are trained by master technicians to visit the users' homes weekly and perform maintenance and residual chlorine spot-checks. The purifier has garnered high levels of community acceptance, and an independent cross-sectional study found a 56 percent reduction in diarrheal disease incidence in users, with a 35 percent reduction when controlling for socio-economic status and hygiene practice (Varghese, 2002). As noted earlier, however, cross-sectional studies are not a reliable method for evaluating diarrheal disease. There are currently 70 sponsorships, covering 120 villages, and more than 16,000 purifiers, with 200 paid Haitian staff in the GWI program.

The program is expanding at a rate of 8,000–10,000 new families per year.

The program offers a successful product (water treatment for a village) to consumers (churches) who have resources and good intentions, but lack the technical capacity to implement a water intervention in a needy community. In July 2004, a church in Atlanta, Georgia, provided GWI with US\$5,600 to install 400 purifiers, train the community members and health technicians, and pay annual salaries for two of the technicians (Molly Brady, personal communication, December 29, 2004). By September 2004, the program had conducted the training and installed 200 filters; the church was very pleased with the program's progress, but was concerned about its ability to provide the technicians' salaries indefinitely. The drawbacks thus include the uncertainty of consistent support from community health technicians.

Filtration and Chlorination: Benefits and Drawbacks

The benefits of the GWI purifier are:

- High removal rates of bacteria, even in turbid waters;
- Residual protection;
- High acceptability among users due to the ease of use and visual improvement of the water; and
- Health impact, as measured by a cross-sectional study. (Internal GWI studies attribute their success to the program's community health technicians [Phil Warwick, personal communication, March 8, 2005].)

The drawbacks of the GWI purifier are:

- Unknown viral and protozoa removal; and

- The need for regular filter replacement, ongoing technical support, and continuing education, in addition to concurrent ongoing costs.

OPTION 5: FLOCCULATION AND CHLORINATION

Several systems incorporate both a chemical coagulation step for particle removal (flocculation⁹) and a chlorination step (or steps) for disinfection. This dual approach produces high-quality finished water. The **Procter & Gamble Company** (P&G) has developed a HWTS option for sale at no profit to users and NGOs, called PūR Purifier of Water. This small sachet contains powdered ferrous sulfate (a flocculant) and calcium hypochlorite (a disinfectant). To use PūR, users open the sachet, add the contents to an open bucket containing 10 liters of water, stir for five minutes, let the solids settle to the bottom of the bucket, strain the water through a cotton cloth into a second container, and wait 20 minutes for the hypochlorite to inactivate the microorganisms.

PūR incorporates both the removal of particles and disinfection. Because of this dual process treatment, PūR has high removal rates of bacteria, viruses, and protozoa, even in highly turbid waters (Souter et al., 2003; Le et al., 2003). Use of PūR reduced diarrheal disease incidence by 16 percent to more than 90 percent in five randomized controlled health intervention studies (Reller et al., 2003; Chiller et al., 2003; Crump et al., 2004; Agboatwalla 2004; Doocey, 2005). It also can remove heavy metals, such as arsenic. PūR is provided to global emergency relief groups for US\$0.035 per sachet, plus shipping.



Using solar disinfection (SODIS) in Nepal
(courtesy of EAWAG/Water and Sanitation in Developing Countries [SANDEC])

Flocculation and Chlorination: Implementation Strategies

P&G has recently moved from research and development of the PūR product to research into effective implementation strategies. P&G is investigating social marketing—in partnership with PSI—in Haiti, Pakistan, and Uganda, and distribution during emergency responses.

Emergency Response Using PūR

Three hundred thousand PūR sachets were distributed in response to the flooding after Hurricane Jeanne struck Gonaives, Haiti, in September 2004. PSI and CARE staff were trained in the use of the product and, within weeks of the flooding, distributed PūR and educational materials to affected communities.

9. In flocculation, fine particles in water are gathered together (aggregated) into larger particles by mixing water with coagulant chemicals.

As correct use of PūR requires several steps, the program's success in Haiti was due to well-trained staff who understood the product, "trained the trainers" (local community members), and provided them with the skills, knowledge, and materials to teach others through community demonstrations (Bowen et al., 2005). Adequate supplies of instructional and promotional materials in the local language were also very useful.

The lessons learned in Haiti helped inform emergency response procedures elsewhere. In refugee camps in Liberia, Johns Hopkins University researchers provided trainings, demonstrations, and the two buckets necessary to use the product. They documented a 93.6 percent reduction in diarrheal disease incidence among PūR users compared to a control group of safe storage users (Doocey, 2005). Before the South Asia tsunami in December 2004, 5 million sachets of PūR had been procured for emergency response (Greg Allgood, personal communication, February 3, 2005). Since then more than 16 million sachets have been purchased and transported to tsunami-affected areas in Indonesia, Sri Lanka, and the Maldives by Samaritan's Purse, AmeriCares, and PSI. Samaritan's Purse, UNICEF, World Vision, the International Rescue Committee, and the International Federation of the Red Cross have all mobilized and trained communities to use PūR, following an initial model established by Samaritan's Purse, which provides affected people a cloth, a spoon, soap, an instruction card, and 72 sachets of PūR packaged in two buckets.

Flocculation and Chlorination: Benefits and Drawbacks

The benefits of PūR are:

- Removal or inactivation of viruses, bacteria, parasites, heavy metals, and pesticides, even

in highly turbid waters;

- Residual protection;
- Proven health impact;
- User acceptability due to water's visual improvement;
- Ease of scalability or use in an emergency because the sachets are centrally produced, and easily transported (due to their small size, long shelf life, and classification as a non-hazardous material for air shipment); and
- Reduced concern about carcinogenic effects of chlorination because organic material is removed in the treatment process.

The drawbacks of PūR are:

- Multistep process requiring demonstrations for new users and a time commitment for water treatment from the users;
- Requires two buckets, a cloth, and a stirring device; and
- High relative cost per liter of water treated.

DISCUSSION

Many researchers, private companies, faith-based organizations, international and local NGOs, donors, ministries of health, and end users are interested in HWTS options and in mechanisms for their implementation. The evidence base for these interventions is well-established and growing, and an active program of further technical and operations research is being pursued on multiple fronts.

HWTS implementation has enjoyed numerous successes. First and foremost, field-based programs have documented reductions of diarrheal diseases in end users. Factors that contributed to successful programs include:

- The ability to obtain quality HWTS option components (and any replacement parts) locally;
- Behavior change communications including person-to-person communications and/or social marketing; and
- Availability of implementation materials and technical assistance to support on-the-ground implementers.

HWTS implementation projects have also encountered significant challenges, including:

- Questions regarding the health impact of these interventions in large-scale “real-world” situations;
- Long-term sustainability of the projects, especially long-term access to supplies; and
- Scaling up to efficiently reach people without access to improved water sources.

Larger studies will demonstrate the health impact of HWTS in real-world settings, and more time will tell us whether these programs are sustainable. Expanding efficiently to global scale will require a creative combination of market, micro-enterprise, and community-based approaches. The long-term goal of water infrastructure for all, however, should not be delayed by efforts to meet the short-term goal of health benefits from household water treatment. Research could help ensure that these two strategies can be implemented together to achieve both goals.

An additional challenge for implementers is choosing the best HWTS option in a given area. Important criteria to consider when selecting an HWTS option include:

- *Community specific needs and preferences:* For example, if the turbidity of the source water is

high, users should pretreat water with filtration or coagulation before disinfection and safe storage—or, if users prefer a current practice, such as storing water in ceramic pots, incorporate that practice into the project;

- *The mechanism to prevent recontamination of the treated water:* A number of HWTS options incorporate some form of residual protection (SWS, SODIS, GWI, PūR); safe storage or other mechanisms to prevent post-treatment contamination should be a part of every HWTS project; and
- *The mechanisms (financial and otherwise) to provide sustained availability:* Long-term access to the HWTS option requires not only activating some type of supply chain, but also ensuring that once activated, access is uninterrupted.

Unfortunately, these criteria may not be systematically considered when HWTS interventions are implemented. We studied a BioSand Filter installation in a peri-urban slum with access to piped, processed, municipal water—likely not the most cost-appropriate or effective intervention for this setting. An investigation of source water quality before implementation would have discovered this, and potentially a more appropriate intervention—such as improving the local water supply, educating users about safe water storage to prevent recontamination, or using chlorination alone—could have been implemented.

In some situations, there may not be an appropriate HWTS option. While accompanying a U.S. school group on a trip to Mexico to plan a joint Mexico-U.S. student-run SWS project, an investigation showed the project communities’ existing piped, treated water was of good quality, though with sub-optimal residual chlorine (Lantagne,

TABLE 2: COST OF HWTS OPTIONS

HWTS Option	Project Location and Implementer	Cost of Product to User	Full Cost of Product*	
			Initial equipment	Ongoing Cost
Chlorination	Zambia, PSI	1 bottle of chlorine solution at US\$0.12 per family per month	Accounted for in cost of bottle	US\$0.37 per bottle of chlorine solution (US\$0.25 per bottle subsidized by donor)
Chlorination	Haiti, JSWF	1 bottle of chlorine solution at US\$0.09 per family per month	US\$7 start-up fee per family paid by NGO	US\$0.09 per family per month for chlorine solution (no subsidy)
BioSand Filtration	Cambodia, Samaritan's Purse	One-time cost of US\$3 to family for BSF	US\$67 per BSF paid by NGO covers all expenses	None
Ceramic Filtration	Nicaragua, Potters for Peace	Zero	US\$10 for filter paid by NGO covers all factory expenses	Unknown
Solar Disinfection	Indonesia, local NGOs	Zero	Zero	US\$0.80 paid by NGO per person reached in 14-month project
Filtration and Chlorination	Haiti, GWI	US\$1.71 per family for filter US\$0.12–0.34 per family per month for chlorine	US\$12-15 paid by NGO per family for filter	US\$4 paid by NGO per family per year for education and replacement filters
Flocculation and Chlorination	South Asia tsunami emergency response	Zero	Unknown	US\$0.07 per day per family for sachets

*Including delivery, installation, distribution, education, marketing, overhead, and other costs.

Source: Costs reported in this table are self-reported by program coordinators.

2004). Although the SWS project was well-intentioned, it was not an appropriate intervention for these communities. Instead, investigators recommended improving the existing water treatment and distribution infrastructure.

A critical piece of every development program is cost (see Table 2). Costs are highly program-spe-

cific; they vary with location, implementation strategy, and desired endpoint, and cannot be generalized. For example, in comparing the GWI and JSWF projects, both of which operate in rural Haiti, we find that the JSWF project requires a smaller subsidy and thus appears the better option. However, the GWI project incorporates a filtra-

tion step that the JSWF project does not, and thus treats turbid water more effectively. Program planners must evaluate both the costs and the treatment needs in a community to determine the most cost-effective and appropriate intervention.

When reviewing cost data, it is important to compare them to the costs of other water and sanitation improvements. A recent cost-benefit evaluation found that all water and sanitation improvements analyzed were cost-beneficial in all regions of the world, with returns of US\$1.92–\$15.02 on each US\$1 invested, depending on region and type of improvement (Hutton & Haller, 2004). However, disinfection at the point of use (the only HWTS option considered in the analysis) had the lowest cost per person when compared with all non-HWTS interventions to provide improved water supply or sanitation. This initial work indicates that HWTS options are cost-effective mechanisms for providing improved water to households.

FUTURE WORK

Although much research has been completed on HWTS options, more is needed, including:

- Health impact studies:
 - Of the HWTS options that are widely distributed but have not yet been proven effective at reducing disease;
 - Of a large-scale real-world project, such as one of the national or sub-national PSI SWS projects; and
 - With longer-term endpoints in children, including growth, cognitive development, and mortality.
- Development of real-term, practical parameters and performance measures to predict safety of drinking water in developing countries;

- Investigations of the economics of moving to large-scale projects, including cost analysis, economic demand assessment, and sustainability; and
- Determination of the relative and absolute impact of HWTS options and other water, sanitation, and hygiene (WASH) interventions, and research investigating optimal combinations of HWTS and WASH interventions.

In addition, important operational research questions remain, including:

- What motivates users to purchase and use a HWTS option?;
- What are current purchase (use) and re-purchase (sustained use) rates in different demographic, socio-economic, and cultural groups; and how do these correlate with water-borne disease prevalence rates?;
- What is the health impact of routine versus sporadic use of HWTS options in the home?;
- What are optimal behavior-change strategies for hygiene and sanitation practices; and how do we best incorporate these into different HWTS implementation strategies?;
- What are the most sustainable and cost-effective ways to reach rural and remote areas?

To address these research questions, the HWTS community should continue to work with academic institutions that provide technical knowledge and student labor. The University of North Carolina, Emory University, MIT, Johns Hopkins University, and the London School of Hygiene and Tropical Medicine, among others, have existing programs in public health or engineering departments that research HWTS options. This path has resulted in numerous successes, such as

the development of a computer model to ascertain SODIS appropriateness for any area of the world using NASA data (Oates et al., 2002).

One question to ponder: are students being trained for job opportunities that do not yet exist? The interest in HWTS options is very high at the student level. The HWTS community should seek to identify and coordinate future human resources with the growing number of graduates with relevant field experience.

Lastly, HWTS options need to be implemented at scale, and in conjunction with other water and sanitation programming to help reduce disease burden and alleviate poverty. A diverse array of creative partners, with adequate capital and technical support, will be needed to complete this work.

CONCLUSION

HWTS systems are proven, low-cost interventions that have the potential to provide safe water to those who will not have access to safe water sources in the near term, and thus significantly reduce morbidity due to waterborne diseases and improve the quality of life. HWTS implementations have developed from small pilot projects into national-scale programs, and now face the challenge of reaching the more than 1.1 billion in need of safe drinking water, and effectively working with other water, sanitation, and hygiene programs to achieve the greatest health impact. The active, diverse, and expanding community of researchers, private companies, faith-based organizations, international and local NGOs, and donors interested in answering these questions can play a major role in helping the world achieve the Millennium Development Goal to halve, by 2015, the proportion of people without access to safe water (World Bank Group, 2004). Achieving this goal, and surpassing it, will require

continued collaboration, investment, and research and development, but it is our best hope for rapidly reducing waterborne disease and death in developing countries.

BIOGRAPHIES

Daniele S. Lantagne, Dr. Robert Quick, and Dr. Eric D. Mintz work for the Foodborne and Diarrheal Diseases Branch of the U.S. Centers for Disease Control and Prevention (CDC). Lantagne is an environmental engineer with more than 10 years of experience in water treatment. She has evaluated and implemented household water treatment options in more than 30 developing countries, first as a lecturer with the MIT Department of Civil and Environmental Engineering and with her own consulting firm, and for the last three years with the CDC. Medical epidemiologists Dr. Quick and Dr. Mintz, who also work at the Center for Global Safe Water at Emory University, have been with the CDC for more than 15 years. Both were involved in the initial cholera epidemic investigations that led to the development of the Safe Water System, and have been evaluating and implementing the Safe Water System since 1995.

ACKNOWLEDGMENTS

The authors would like to thank Bill Gallo, Sr. (Jolivet Safe Water for Families Program), Ron Rivera (Potters for Peace), Kaida Liang (Samaritan's Purse), Martin Wegelin and Regula Meierhofer (Swiss Federal Institute for Environmental Science and Technology), Phil Warwick (Gift of Water, Inc.), and Greg Allgood (Procter & Gamble Company) for providing information and for fact-checking their respective implementation sections.

REFERENCES

- Acra, Aftim, Zeina Raffoul, & Yester Karahagopia. (1984). *Solar disinfection of drinking water and oral rehydration solutions – Guidelines for household application in developing countries*. Beirut, Lebanon: UNICEF, American University of Beirut.
- Agboatwalla, Mubina (2004, May). “Health intervention trial in Karachi with new household water treatment method.” Paper presented at International Symposium on Safe Drinking Water, Karachi, Pakistan.
- American Water Works Association. (1999). *Water quality and treatment: A handbook of community water supplies* (Fifth Ed.). New York: McGraw-Hill, Inc.
- Baqi, Abdullah H., Robert E. Black, R. Bradley Sack, Hafizur R. Chowdhury, Mohammad Yunus, & A. Kasem Siddique (1993). “Malnutrition, cell-mediated immune deficiency and diarrhea: A community-based longitudinal study in rural Bangladeshi children.” *American Journal of Epidemiology* 137, 355–365.
- Borucke, Michael (2002). *Filtration of Giardia cysts from Haitian drinking water*. Unpublished master’s thesis, Massachusetts Institute of Technology, Cambridge.
- Bowen, Anna, Romulo Colindres, & Seema Jain. (2005, January 12). *Epi-Aid #2005-009 trip report: Assessment of post-Hurricane Jeanne disease surveillance and emergency PūR distribution—Gonaives, Haiti, 2004*. Atlanta, GA: Centers for Disease Control and Prevention.
- Brin, Genevieve (2003). *Evaluation of the Safe Water System in Joliver Haiti by bacteriological testing and public health survey*. Unpublished master’s thesis, Massachusetts Institute of Technology, Cambridge, MA.
- Centers for Disease Control and Prevention (CDC). (2001). *Safe water systems for the developing world: A handbook for implementing household-based water treatment and safe storage projects*. Atlanta, GA: CDC. Available online from <http://www.cdc.gov/safewater>
- Chiller, Thomas M., Carlos E. Mendoza, M. Beatriz Lopez, Maricruz Alvarez, Robert Michael Hoekstra, Bruce H. Keswick, & Stephen P. Luby (2003, December). “Taking the dirt out of dirty water: Introducing a new flocculent-disinfectant for household treatment of drinking water dramatically reduces diarrhea in rural Guatemala.” Paper presented at the American Society of Tropical Medicine and Hygiene Annual Meeting, Philadelphia, PA. Abstract available online from http://www.pghsi.com/safewater/pur_abstracts.html
- Clasen, Thomas F., & Bastable, Andrew (2003). “Faecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use.” *Journal of Water and Health* 1(3), 109–115.
- Clasen, Thomas F., Joseph Brown, Simon Collin, Oscar Suntura, & Sandy Cairncross. (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(6), 651–657.
- Conroy, Ronán M., Michael Elmore-Meegan, Tina Joyce, Kevin McGuigan, & Joseph Barnes. (1996). “Solar disinfection of drinking water and diarrhoea in Maasai children: A controlled field trial.” *Lancet (N. American edition)* 348(9043), 1695–1697.
- Conroy, Ronán M., Michael Elmore-Meegan, Tina Joyce, Kevin McGuigan, & Joseph Barnes. (1999). “Solar disinfection of water reduces diarrhoeal disease: An update.” *Archives of Disease in Childhood* 81(4), 337–338.
- Conroy, Ronán M., Michael Elmore-Meegan, Tina Joyce, Kevin McGuigan, & Joseph Barnes. (2001). “Solar disinfection of drinking water protects against cholera in children under 6 years of age.” *Archives of Disease in Childhood* 85(4), 293–5.

- Crump, John A., Peter O. Otieno, Laurence Slutsker, Bruce H. Keswick, Daniel H. Rosen, John M. Vulule, & Stephen P. Luby. (2004, March). "Trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in the setting of highly turbid source water in rural Kenya." Paper presented at the International Conference on Emerging Infectious Diseases, Atlanta, Georgia. Abstract available online from http://www.pghsi.com/safewater/pur_abstracts.html
- Doocey, S. (2005). *Report of PwR effectiveness trial in a refugee camp in Liberia*. Monrovia, Liberia: Unpublished report. Available via email from allgood.gs@pg.com
- Esrey, Steve A., Richard G. Feachem, & James M. Hughes. (1985). "Interventions for the control of diarrhoeal diseases among young children: Improving water supplies and excreta disposal facilities." *Bulletin of the World Health Organization* 63 (4), 757–772.
- Esrey, Steve A., James B Potash, Leslie Roberts, & Clive Shiff. (1991). "Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma." *Bulletin of the World Health Organization* 69(5), 609–621.
- Fewtrell, Lorna, & John M. Colford (2004). *Water, sanitation and hygiene: Interventions and diarrhoea: A systemic review and meta-analysis* (Health, Nutrition, and Population Discussion Paper). Washington, DC: World Bank. Available online at <http://siteresources.worldbank.org/HEALTHNUTRITIONANDPOPULATION/Resources/281627-1095698140167/Fewtrell&ColfordJuly2004.pdf>
- Gordon, Gilbert, W.J. Cooper, R.G. Rice, & G.E. Pacey. (1987). *Disinfectant residual measurement methods*. Denver, CO: AWWA Research Foundation, American Water Works Association.
- Guerrant, David I., Sean F. Moore, Aldo A. Lima, Peter D. Patrick, John B. Schorling, & Richard L. Guerrant. (1999). "Association of early childhood diarrhoea and cryptosporidiosis with impaired physical fitness and cognitive function for seven years later in a poor urban community in northeast Brazil." *American Journal of Tropical Medicine and Hygiene* 61, 707–713.
- Hobbins, Michael (2003). *The SODIS health impact study*. Unpublished doctoral dissertation, Swiss Tropical Institute, Basel, Switzerland.
- Hutton, Guy, & Laurence Haller. (2004). *Evaluation of the costs and benefits of water and sanitation improvements at the global level*. Geneva: World Health Organization. Available online at http://www.who.int/water_sanitation_health/wsh0404/en/
- Kaiser, Nathan, Kaida Liang, Marianne Maertens, & Ryan Snider. (2002). *2002 BSF evaluation report: Summary of all Lab and Field Studies*. Samaritan's Purse, Canada. Available online at <http://www.cawst.org/technology/watertreatment/summaryoflabandfield.php>
- Lantagne, Daniele S. (2001a). *Investigation of the Potters for Peace colloidal silver impregnated ceramic filter: Report 1: Intrinsic effectiveness*. Boston, MA: Alethia Environmental. Available via email from daniele@alethia.cc
- Lantagne, Daniele S. (2001b). *Investigation of the Potters for Peace colloidal silver impregnated ceramic filter: Report 2: Field investigations*. Boston, MA: Alethia Environmental. Available via email from daniele@alethia.cc
- Lantagne, Daniele S. (2004). *Mexico trip report, August 8–15th, 2004*. Available via email from dlantagne@cdc.gov
- Le, B.T., J.G. Jacangelo, & K.J. Schwab. (2003, May). "Viral inactivation in surface water using a metal coagulant combined with granular slow-release chlorine." Paper presented at American Society for Microbiology

- Annual Meeting, Washington, DC. Abstract available online from: http://www.pghsi.com/safewater/pur_abstracts.html
- Luby, Stephen P., Mubina Agboatwalla, Robert Michael Hoekstra, Mohammad Rahbar, Ward Billhimer, & Bruce H. Keswick. (2004). "Delayed effectiveness of home-based interventions in reducing childhood diarrhea, Karachi, Pakistan." *American Journal of Tropical Medicine and Hygiene* 71(4), 420–427.
- Meierhofer, Regula (2005). *A case example of water quality improvement through SODIS from East Lombok, Indonesia*. Available via email from regula.meierhofer@eawag.ch
- Méndez-Hermida, F., J.A. Castro-Hermida, E. Arez-Mazás, S.C. Kehoe, & Kevin G. McGuigan. (2005). "Effect of batch process solar disinfection (SODIS) on the survival of *Cryptosporidium parvum* oocysts in drinking water." *Applied Environmental Microbiology* 71(3), 1653–4.
- Mintz, Eric, Fred Reiff, & Robert Tauxe. (1995). "Safe water treatment and storage in the home: A practical new strategy to prevent waterborne disease." *Journal of the American Medical Association* 273(12), 948–953.
- Mintz, Eric, Jamie Bartram, Peter Lochery, & Martin Wegelin. (2001). "Not just a drop in the bucket: Expanding access to point-of-use water treatment systems." *American Journal of Public Health* 91(10).
- Oates, Peter, Pete Shanahan, & Martin Polz. (2003). "Solar disinfection (SODIS): Simulation of solar radiation for global assessment and application for point-of-use water treatment in Haiti." *Water Research* 37(1), 47–54.
- Olembo, Lynette, F.A.D. Kaona, Mary Tuba, & Gilbert Burnham. (2004, September). *Safe water systems: An evaluation of the Zambia CLORIN Program* (Final Report). U.S. Agency for International Development, through the Environmental Health Project. Available online at <http://www.ehproject.org/PDF/Others/Zambia%20Report%20Format.pdf>
- Palmateer, G., David Manz, A. Jurovic, R. McInnis, S. Unger, K. Kwan, & B. Dutka. (1999). "Toxicant and parasite challenge of Manz Intermittent Slow Sand Filter." *Environmental Toxicology* 14, 217–225.
- Quick, Robert E., Linda Venczel, Eric Mintz, L. Soletto, J. Aparicio, M. Gironaz, et al. (1999). "Diarrhea prevention in Bolivia through point-of-use disinfection and safe storage: a promising new strategy." *Epidemic Infections* 122, 83–90.
- Quick, Robert E., Akiko Kimura, Angelica Thevos, Mathias Tembo, Isidore Shamputa, Lori Hutwagner, & Eric D. Mintz. (2002). "Diarrhea prevention through household-level water disinfection and safe storage in Zambia." *American Journal of Tropical Medicine and Hygiene* 66(5), 584–589.
- Reller, Megan E., Carlos E. Mendoza, M. Beatriz. Lopez, Maricruz Alvarez, Robert Michael Hoekstra, Christy A. Olson, et al. (2003). "A randomized controlled trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in rural Guatemala." *American Journal of Tropical Medicine and Hygiene* 69(4), 411–419.
- Semenza, Jan, Leslie Roberts, A. Henderson, J. Bogan, & Carol Rubin. (1998). "Water distribution system and diarrheal disease transmission: A case study in Uzbekistan." *American Journal of Tropical Medicine and Hygiene* 59(6), 941–6.
- Sobsey, Mark D. (2002). *Managing water in the home: Accelerated health gains from improved water supply* (WHO/SDE/ WSH/02.07). Geneva: World Health Organization. Available online at http://www.who.int/water_sanitation_health/dwq/en/WSH02.07.pdf
- Sommer, B., A. Marino, Y. Solarte, M. Salas, C. Dierolf, C. Valiente, et al. (1997). "SODIS: An emerging water treatment process." *Aqua (Oxford)* 46(3), 127–137.
- Souter, Philip F., Graeme D. Cruickshank, Melanie Z. Tankerville, Bruce H. Keswick, Brian D. Ellis, Don E.

- Langworthy, 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 and Health* 1(2), 73–84.
- Tauxe, Robert (1995). "Epidemic cholera in the new world: Translating field epidemiology into new prevention strategies." *Emerging Infectious Diseases* 1(4), 141–146.
- United Nations Development Program. (2004). *Human development report: Human development index table*. Available online at http://hdr.undp.org/statistics/data/indic/indic_8_1_1.html
- Varghese, Arun (2002). *Point-of-use water treatment systems in rural Haiti: Human health and water quality impact assessment*. Unpublished master's thesis, Massachusetts Institute of Technology, Cambridge, MA.
- Wegelin, Martin, S. Canonica, K. Mechsner, T. Fleischmann, F. Pesaro, & A. Metzler. (1994). "Solar water disinfection: Scope of the process and analysis of radiation experiments." *Aqua (Oxford)* 43(4), 154–169.
- World Bank Group. (2004). *Millennium Development Goals: About the goals*. Retrieved February 14, 2004, from http://www.developmentgoals.org/About_the_goals.htm
- World Health Organization (WHO). (2003). *Looking back: Looking ahead: Five decades of challenges and achievements in environmental sanitation and health*. Geneva: Available http://www.who.int/water_sanitation_health/hygiene/envsan/en/Lookingback.pdf
- WHO (2004). *Draft research agenda: International network to promote safe household water treatment and storage* (Mark Sobsey and Stephen Gundry, revised June, 2004).
- WHO. (2005). *The international network to promote household water treatment and safe storage*. Retrieved February 14, 2005, from http://www.who.int/household_water/en/
- WHO/UNICEF. (1992). *Water supply and sanitation monitoring report 1990*. New York: WHO & UNICEF.
- WHO/UNICEF. (2000). *Global water supply and sanitation assessment 2000 report*. Geneva: WHO & UNICEF. Available online from http://www.who.int/water_sanitation_health/monitoring/globalassess/en/
- WHO/UNICEF. (2004). *Meeting the MDG drinking water and sanitation target: A mid-term assessment of progress*. Geneva: WHO & UNICEF. Available online at http://www.who.int/water_sanitation_health/monitoring/en/jmp04.pdf