

Alternatives for safe water provision in urban and peri-urban slums

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ABSTRACT

In response to rapid urbanization throughout the global South, urban and peri-urban slums are expanding at an alarming rate. Owing to inadequate financial and institutional resources at the municipal level, conventional approaches for safe water provision with centralized treatment and distribution infrastructure have been unable to keep pace with rapidly growing demand. In the absence of alternatives to centralized systems, a global public health emergency of infectious water-related diseases has developed. Alternative decentralized water treatment systems have been promoted in recent years as a means of achieving rapid health gains among vulnerable populations. Though much work with decentralized systems, especially in urban environments, has been at the household level, there is also considerable potential for development at the community level. Both levels of approach have unique sets of advantages and disadvantages that, just as with treatment technologies, may make certain options more appropriate than others in a particular setting. Integrating community, government and other relevant stakeholders into the process of systems development and implementation is essential if the outcome is to be appropriate to local circumstances and sustainable in the long term.

Key words | appropriate technology, point-of-use, slum rehabilitation, urban services, water treatment, waterborne disease

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INTRODUCTION

Slums are a ubiquitous part of the urban landscape throughout the underdeveloped South. At the confluence of overpopulation, economic deprivation and environmental degradation, people living in slums occupy a precarious position at the very fringes of urban life. Human health risks arising from unsafe water and environmental degradation are exacerbated by the poverty and social marginalization people living in slums face. As urban population growth continues to far outpace development, migrants to cities will continue to improvise at the margins. And as the world's slums continue to grow, the environmental and social pressures that threaten the health and well-being of people living within them will only intensify.

Of the 3.2 billion people living in cities around the world today, one in three live in slum conditions, which the

UN (2007) defines as lacking at least one of four basic amenities: adequate sanitation, safe water supply, durable housing material and adequate living space. Deprivation of these basic amenities gives rise to a host of negative health outcomes. Infectious water-related diseases, particularly the diarrhoeal diseases, are among the leading risks facing people living in slums.

The diarrhoeal diseases are those illnesses that induce diarrhoea as a major symptom, including, but not limited to, cholera, dysentery and typhoid (Butterton & Calderwood 2004). With an estimated 4 billion cases annually throughout the world, the diarrhoeal diseases are the most detrimental of all ailments related to water, sanitation and hygiene (Schuster-Wallace *et al.* 2008). Every year, the diarrhoeal diseases are responsible for more than 1.5 million

deaths and the loss of 52 million DALYs (disability-adjusted life years) globally. Tragically, these diseases disproportionately affect impoverished children under the age of five, particularly those living in slums (Marsh *et al.* 1995). Almost 1.4 million of the deaths caused by diarrhoeal diseases are among children (Prüss-Üstün *et al.* 2008). A study in Dhaka, Bangladesh, on the determinants of child mortality in urban slums indicated that diarrhoea was the leading cause of death among children one to five years of age, and was second, after tetanus, among infants under one year of age (Hussain *et al.* 1999). In South Asia, which has the greatest proportion of slum-dwellers anywhere in the world (UNFPA 2007), the diarrhoeal diseases account for an alarming 24% of total child mortality (Black *et al.* 2003). Diarrhoeal diseases also have serious non-fatal implications. Often associated with malnutrition, the diarrhoeal diseases can result in life-long impacts for children by stunting growth, impairing cognitive development and weakening immune resistance (Baqui *et al.* 1993; Berkman *et al.* 2002). The diarrhoeal diseases exert a tragic and excessive toll among the most vulnerable sectors of the population in the underdeveloped world.

The urgency of this global public health crisis has found expression in the UN Millennium Development Goals (MDGs). Two targets under MDG 7 aim to reduce the burden associated with diarrhoeal diseases. One seeks to halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation. The second aims to achieve, by 2020, a significant improvement in the lives of at least 100 million slum-dwellers through improved sanitation, safe water provision and durable housing with sufficient living area. Furthermore, MDG 4 seeks to reduce by two-thirds, between 1990 and 2015, the under-five mortality rate, for which diarrhoeal diseases are a major cause (UN 2008). Controlling the global diarrhoeal diseases pandemic is central to the realization of the MDGs.

The present paper explores alternatives for safe water provision in urban and peri-urban slums in the underdeveloped world. First, it will discuss the importance of safe water for the protection of public health. It will then appraise challenges facing centralized water systems and consider decentralized approaches for safe water provision. Treatment technologies amenable to decentralized

applications will be surveyed, as will factors pertaining to the sustainability of alternative safe water systems. Through this exploration, alternative approaches for safe water provision in slums will be developed.

SAFE WATER FOR PROTECTING PUBLIC HEALTH IN SLUMS

The essential tragedy of the pandemic of diarrhoeal diseases lies in that it is almost entirely preventable. Caused by various bacterial, viral and protozoan pathogens, diarrhoeal diseases are communicated via complex and manifold faecal-oral pathways. Pathogens in human and animal excreta are transmitted by soil, surface and groundwater, flies, hands or other vectors. Humans ultimately become exposed via the ingestion of contaminated water, food or by direct unsanitary contact. All of these pathways may be found to be active in slums. Slums often occupy marginal urban lands—those adjacent to wastelands at the urban periphery, along the banks of sewage-polluted rivers, or other contaminated sites—where faecal contamination in the ambient environment may be considerable. In these places, drinking water, food, hands and utensils are readily contaminated. It is the uncontrolled transmission of faecal-oral pathogens that is at the root of the diarrhoeal diseases pandemic. However, the introduction of various barriers can serve to disrupt pathogenic transmission and prevent infection (see Figure 1).

Fundamental barriers to the transmission of faecal-oral pathogens include: sanitation and source water protection; hygiene and food safety; and water treatment and safe distribution. Sanitation preserves environmental hygiene by preventing faecal contamination of source waters and the ambient environment. Along with the promotion of hygienic practices, supplying an adequate quantity of water is a necessary precondition for the maintenance of personal and domestic hygiene and food safety, which protect against direct unsanitary and food-borne transmission. For this reason, the dominant paradigm with regard to water has hitherto been largely focused on increasing the quantity of water available—irrespective of its quality (Esrey *et al.* 1991; Esrey 1996). Drinking water is, however, a key pathway by which individuals become exposed to faecal-oral

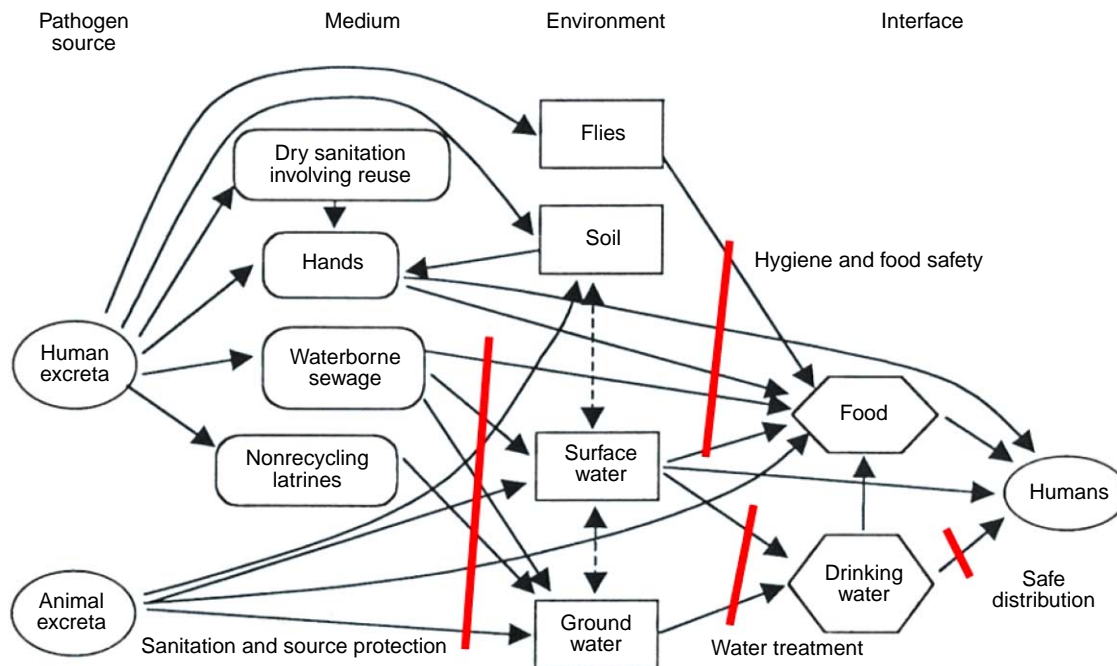


Figure 1 | Pathways and barriers in the transmission of faecal-oral pathogens (modified after Prüss *et al.* 2002).

pathogens. It has been observed that in places where drinking water quality is good to moderate (i.e. <1 *Escherichia coli* per 100 ml and 2–100 *E. coli* per 100 ml respectively), non-drinking water pathways—that is, food-borne or direct unsanitary transmission—may be more important for the spread of diarrhoeal disease. However, where drinking water is highly contaminated (i.e. >1,000 *E. coli* per 100 ml), drinking water becomes a dominant transmission route (Moe *et al.* 1991). This threshold suggests that where drinking water quality is highly compromised, water treatment and safe distribution are a leading concern. Recent epidemiological evidence highlights the importance of drinking water quality in preventing diarrhoeal disease.

Clasen & Cairncross (2004) observe that, since the mid-1990s, there have been substantial global reductions in mortality due to diarrhoeal diseases, whereas morbidity has remained largely unchanged (Kosek *et al.* 2003). The widespread introduction of effective case management techniques, such as oral rehydration therapy, has been implicated in the observed decline in mortality. However, the quantity-centric paradigm has not made similar strides in reducing transmission, infection and subsequent

morbidity. Though this is an ecological observation, it is corroborated by further evidence coming from intervention studies.

Gundry *et al.* (2004) observe that the review by Esrey *et al.* (1991) examined water quality studies that focused on quality *at source* rather than *at point of use*. This, they suggest, is responsible for the dismal performance of the water quality interventions in the review by Esrey *et al.* Water treated at source is subject to recontamination during distribution, collection, storage and the drawing of water in the home (Ahmed *et al.* 1998; Brick *et al.* 2004; Wright *et al.* 2004). If recontamination is likely to occur, treatment at or near the point of use becomes necessary in order to assure safe drinking water quality (Luby *et al.* 2001). In light of this observation, Gundry *et al.* systematically review the impact of point-of-use (PoU) water quality interventions—rather than at-source interventions—on cholera and diarrhoeal diseases in general. Their findings indicate that PoU water quality interventions have a significant positive effect, especially in households that have adequate sanitation. With regard to cholera, the authors estimate a pooled odds ratio of 0.35 (95% CI: 0.21–0.56). For diarrhoeal diseases in general, PoU interventions

were found to be effective, but featured significant heterogeneity between studies, suggesting the influence of unknown confounding factors.

The importance of drinking water quality is further supported by other meta-analyses of diarrhoeal disease prevention studies. Clasen *et al.* (2007) report a pooled rate ratio of 0.62 (95% CI: 0.47–0.82) for PoU water quality interventions compared with 0.87 (95% CI: 0.74–1.02) for at-source water quality interventions. Fewtrell *et al.* (2005) similarly report an overall relative risk of 0.65 (95% CI: 0.48–0.88) with PoU water quality interventions, compared with 0.89 (95% CI: 0.42–1.90) for those at source. Fewtrell *et al.* also examine the effectiveness of PoU water quality interventions in different settings. From those PoU water quality intervention studies deemed to be of good quality conducted in urban, peri-urban, and refugee camp settings, the authors estimate a relative risk of 0.74 (95% CI: 0.65–0.85), suggesting that PoU water quality interventions may be somewhat less effective in densely populated areas.

The epidemiological evidence suggests that the quantity-centric paradigm is not incorrect so much as it is incomplete. Ensuring safe drinking water quality is also important for the protection of public health. Altogether, there are several components that are necessary—but alone are insufficient—for the prevention of diarrhoeal diseases. These include sanitation, hygiene, PoU water quality and sufficient quantity of water supply. Esrey *et al.* (1991) report that improved water and sanitation produced a median reduction of 65% (95% CI: 43–79) in mortality due to diarrhoeal diseases, and a 22% (95% CI: 0–100) in morbidity across all reviewed studies. Curtis & Cairncross (2003), in a systematic review of studies examining hand-washing with soap, report a relative risk of 0.53–0.58 for diarrhoeal disease across all reviewed studies. Fewtrell *et al.* (2005) in their systematic review and meta-analysis of water supply, water quality, sanitation and hygiene interventions find that all of the interventions are relatively equal at controlling diarrhoeal diseases. In addition to the relative risk figures for at-source and household water quality improvements given above, Fewtrell *et al.* also report that hygiene interventions were associated with an overall relative risk of 0.63 (95% CI: 0.52–0.77); sanitation interventions, 0.68 (95% CI: 0.53–0.87); and water supply

interventions, 0.75 (95% CI: 0.62–0.91). Interestingly, the authors also find that multiple interventions, those combining one or more interventions, performed no better than individual interventions, with a relative risk of 0.67 (95% CI: 0.59–0.76). Altogether, effective sanitation, adequate quantities of water supply, and hygiene promotion are all necessary, along with improving safe drinking water quality at its point of consumption, for protecting public health.

CHALLENGES FACING CENTRALIZED WATER SYSTEMS

Many strategies for development in the South are modelled on the historical experience of the modern industrialized North. However, these strategies may not necessarily be appropriate to the particular contexts found in the South (Schumacher 1973). For this reason, a major challenge for the realization of the MDGs is the development of contextually appropriate approaches for water and sanitation. Some progress has been made in this regard. In South Asia, community-led sanitation projects have met with considerable success in both urban and rural areas (Khan 1996; Kar & Pasteur 2005). These projects represent models that may be adapted with good effect elsewhere in the South.

While alternative approaches have been developed for sanitation in low-income settings, alternative approaches for ensuring safe drinking water quality in slums are lacking. Centralized water treatment and distribution systems, a standard approach imported from the North, continue to be sought despite having largely fallen short of expectations. Today, coverage from centralized systems remains inadequate in the rapidly expanding cities of the underdeveloped South, leaving millions without access to safe water. Even where such systems are in place, they are plagued with operational challenges that exemplify their inappropriateness to the context. The reasons for this are manifold but the most apparent are resource and institutional limitations at the municipal level. Whereas centralized treatment and distribution systems require considerable capital investments, the limited availability of public sector capital remains a definitive constraint on

infrastructural development in the South (Illich 1997). Municipal authorities in many cities in the South are faced with unprecedented urban population growth and, as such, the demand for essential services, of which water is but one, far outstrips available resources (Elimelech 2006). The expansion of centralized water systems into urban slums is, for this reason, unfortunately unlikely in the foreseeable future.

Even where centralized systems do exist, inadequate institutional resources at the municipal level may give rise to ongoing problems. Generally speaking, in the North, centralized systems supply treated water without substantial change in microbiological quality between the treatment plant and the consumer. Even so, on infrequent occasions, operational inadequacies result in the recontamination of treated water during distribution, resulting in outbreaks of various infectious waterborne diseases (LeChevallier *et al.* 2003). Unfortunately, in much of the South, operational inadequacies are the rule, not the exception. A study of centralized water supply infrastructure in Karachi, Pakistan, revealed that though finished water leaving treatment plants may be of adequate quality, water is readily recontaminated during distribution. Urban water distribution infrastructure is widely compromised because of inadequate institutional capacity for ongoing repairs and maintenance. Sewerage and water lines are laid in close proximity and, being highly deteriorated, leak profusely. Frequent power outages and inadequate supply relative to demand result in low flow rates and low pressure in water distribution lines, whereas flow rates and pressure are consistently high in sewerage lines. The high pressure and compromised containment in sewerage lines leads to the ubiquitous contamination of the subsurface with sewage, while chronically low pressure and the dilapidated condition of water distribution lines result in the widespread ingress of sewage-contaminated groundwater. Ultimately, the water arriving to the urban consumer is unfit for consumption. The financial costs associated with rehabilitating deteriorated centralized infrastructure is likewise prohibitive (Rahman *et al.* 1997). Distribution system failures are widespread in the underdeveloped South and are caused by an array of deficiencies including: improper disinfection and inadequate disinfection residual; low pipeline pressure; intermittent service; illegal connections

and excessive network leakages; system corrosion; inadequate sewage containment and removal; inequitable pricing and usage of water (Lee & Schwab 2005).

While many of the challenges facing centralized distribution systems in the South may appear to arise from technical and financial inadequacies, the experience in Phnom Penh, Cambodia, indicates that these factors may obscure a larger and more fundamental issue. The Phnom Penh Water Supply Authority (PPWSA) has, under extremely difficult circumstances, within a decade developed an effective centralized water system, through its good governance practices. Without effective governance within municipal institutions, infinite resources are not sufficient to build and maintain effective urban water infrastructure (Biswas & Tortajada 2009). Because of considerable resource and institutional limitations at the municipal level, effective centralized water systems remain a distant prospect for slums throughout the South.

In the absence of piped water supply in slums, people are forced to improvise to meet their daily needs. Water in slums, in large part, comes from four sources: groundwater, local surface water, vendors, or illegal connections to nearby municipal water mains. The first two sources are almost universally compromised owing to the under-coverage of sanitation in many cities in the underdeveloped world, while the latter two may also be for reasons discussed above. Water sold by vendors may be of unknown provenance, and though it is often drawn from the municipal supply, at times it can be of worse quality (Hutin *et al.* 2003). Though vendors selling water from carts or water trucks in bottles and small tanks/drums are filling a critical gap in municipal service delivery, vended water is considered an unimproved source of water (UNDP 2006).

For those slum settlements that are in central districts of cities or otherwise have access to municipal water lines, illegal connections are also a major source of water. Often these sources are controlled by criminal elements who retail water at exorbitant rates to slum-dwellers. Water in distribution lines may already be contaminated, but because reduced flows are often routed to low-income areas where illegal connections may be widespread and because of pressure losses from excessive tapping, water quality in mains that serve slums or low-income areas may be even more deteriorated. Irrespective of source, water supply in

slums is likely to be unfit for consumption. It is in the absence of alternatives to centralized treatment and distribution systems that the immense public health emergency brought on by diarrhoeal diseases is allowed to persist.

DECENTRALIZED ALTERNATIVES FOR SAFE WATER PROVISION

The critical vulnerability with centralized water systems in the South lies not with treatment, but with distribution. It is possible then to conceive of alternatives that circumvent recontamination vulnerabilities by having decentralized treatment capacity closer to end-users. Alternative safe water systems for urban and peri-urban slums could see treatment capacity shifted from centralized plants to points at or near where drinking water is consumed, at either the household or community level. Decentralized systems would be amenable to treating water drawn from different sources, as often is the case for water supply in slums. The capital costs associated with decentralized systems may also be substantially lower than those for centralized systems, owing to savings on distribution networks. Decentralized systems are, for these reasons, increasingly being advocated as a means to fill the safe water gap before the extension of effective centralized water networks. Such systems may be able to achieve immediate public health gains among vulnerable populations throughout the South presently lacking access to safe water (Mintz *et al.* 2001; Sobsey 2002; Thompson *et al.* 2005; NRC 2006; Montgomery & Elimelech 2007).

Though alternative decentralized safe water systems can be deployed at either the household or community level, much of the work done thus far, particularly in urban areas, has been at the former. Various water treatment technologies—from chlorine and UV disinfection to ceramic filtration to simplified coagulation-flocculation—have been developed into bench-top systems that can purify enough water to meet the drinking water needs of a single family. These small-scale systems are typically owned and operated by individual households, who may receive some ongoing material or operational support from public or private agencies, but are otherwise responsible for the systems themselves. Examples of household systems are numerous

(for instance, see Chiller *et al.* 2006; Rose *et al.* 2006; Arnold & Colford 2007; Brown *et al.* 2008).

Decentralized treatment systems may also be applied at the community/neighbourhood level, that is, in a 'semi-centralized' manner. As with household systems, community systems are amenable to a range of treatment technologies. Treatment occurs in a small-scale treatment facility centrally located in the community it serves, from where safe water is distributed to community members. A similar concept for potable water sustainability in industrialized countries has been proposed by Weber (2002) with *distributed optimal technology networks* (DOT-NET). Much of the work done with community-level treatment systems in the South has been in rural areas. An illustrative example comes from the village of Bomminampadu in the Krishna District of Andhra Pradesh, India, where a community safe water system (CSWS) is run by the Naandi Foundation and WaterHealth India (NF 2007). The CSWS utilizes simplified filtration and UV disinfection technology developed by Gadgil *et al.* (1998). The system is housed in a small-scale treatment plant at a central location in the village, from where community members collect drinking water in safe storage containers. The CSWS is implemented and managed as a public–private–community partnership in which the beneficiaries contribute a portion of the capital costs and ongoing user fees—typically Rs. 1 (Indian rupees) per 12–15 l of drinking water—and the local government and NGO actors provide technology, technical support and additional financing while facilitating social mobilization, behavioural change and management. There is significant potential for the development of community-level safe water systems, particularly for peri-urban slums, where centralized networks do not yet reach.

Benefits and drawbacks of household and community systems

Household and community systems differ in some important respects. Depending on the context, one may be more appropriate than the other. With household systems there are some important and apparent benefits, perhaps the most relevant of which is the lack of physical infrastructure. Whereas a community system requires capital investment for the creation of a small-scale treatment

facility, household systems do not. Similarly, household systems do not have ongoing infrastructural upkeep costs, beyond material inputs, as community systems may have with distribution networks. The development of community infrastructure typically requires a significant level of community mobilization for systems sustainability, as the involvement of community members is fundamental to systems development, operation and maintenance. Mobilizing community resources and support for the development of communal infrastructure may well be a challenge, particularly in slums where there is high population turnover or nascent levels of community organization. In these situations, household systems may be easier to apply. Household systems may also benefit from lower levels of recontamination risk as purification occurs closer to the time of consumption. This risk, however, can and should be ameliorated in either household or community systems by distributing, storing and dispensing water from safe water storage containers (Clasen & Bastable 2003). One of the most significant concerns surrounding slum rehabilitation is land tenure. Individuals without title to the land they inhabit are less likely to invest in its improvement, as they could be stripped of it without warning or opportunity for compensation (Davis 2006). Household systems, compact and without infrastructure, may be more appropriate than community systems in slums where land tenure is highly insecure.

In some situations, community-based systems may be advantageous compared with household systems. Community systems may be able to realize economies of scale through the semi-centralization of treatment that household systems cannot. Furthermore, the complexity of treatment could be greater with community systems, as semi-centralization may allow for trained personnel to operate and maintain them. Community safe water systems may also have associated benefits relating to community organization and development. Technological systems are not inert, but actively influence, and are influenced by, the social environment in which they exist (Franklin 1990). Household systems individualize what are in fact collective issues—the degradation of the environment and public safe water supply—reducing the social and political impetus to protect the environment and public health. As the level of responsibility for the provision of safe drinking water

is devolved to individual households, the collective responsibility for providing safe water to the public is undone; as a consequence, the poorest and most vulnerable members of the public tend to be those left without access. Whereas household systems tend towards individualization, community systems collectivize the response to common problems. Community systems are also better positioned to assure that all members of the public have access, though there is also the potential for community participation to become dominated by local elites (Sahu 2008). Even in those cases where user fees are sought for capital recovery and maintenance costs, progressive fee structures can be adopted to ensure accessibility to lower-income users. Furthermore, a community safe water system, in both the social and physical sense, can act as a space for community organization and action by facilitating communication and cooperation among community members (J. Janakiram, personal communication 2009).

Community systems, more so than household systems, may also lend themselves to effective public monitoring to ensure a universal standard of water quality, whereas compliance and operational issues are a perennial concern with household systems (Luby *et al.* 1999). Community systems may also be more sustainable than household systems. Usage of household systems has been seen to decline once external supports are removed as individual households perceive costs to outweigh benefits (Luby *et al.* 2008). Community systems, though initially facing greater challenges in mobilizing support from diverse actors, may be more sustainable in the long term as responsibility can be distributed among several groups including individual households, community groups, NGOs and governmental authorities, through a tripartite arrangement such as a public–private–community partnership. Furthermore, governments are the primary agent of development within their jurisdiction and bear a responsibility to the public for the provision of public goods, including safe water (Leftwich 2000). Community systems, by virtue of semi-centralization, may be able to more effectively integrate the government in development and operations, and thereby, reaffirm the responsibility of the government to the public. The relative advantages and drawbacks of household and community approaches are summarized in Table 1.

Table 1 | Advantages and drawbacks of household and community systems in different circumstances

Criteria	Application level	
	Household	Community
Capital requirements	None	Necessary
Upkeep requirements	Materials	Infrastructure and materials
Demand on individuals	High	Low
Demand on community	Low	High
Control of safe water system	Individual household	Cooperation at community level
Locus of responsibility	Individual household	Community and/or municipal government
Recontamination risk	Lower as treatment closer to time of use	May be higher as more opportunities
Suitability to land tenure status	More appropriate to low tenure security	High tenure security necessary
Treatment complexity	Low with untrained lay-people	Medium with trained personnel
Economies of scale	None	Possible
Social impact on common issues	Individualizes	Collectivizes
Community organization	May or may not be fostered, depending on approach of intervening party	Tends to foster cooperation
Public monitoring of quality	Infeasible	Feasible
Management system	NGO–public partnerships or commercial approaches generally	Public–NGO–government and other multi-stakeholder partnerships possible

Household and community level approaches to decentralized safe water systems are differently suited to different circumstances. The decision about the level at which a safe water system should be deployed is a fundamental one and should be taken with careful consideration of the particular setting. This is best done through a participatory process involving community members, government agencies and other relevant stakeholders.

CANDIDATE WATER TREATMENT TECHNOLOGIES

There is an array of water treatment technologies available for decentralized safe water applications. Sobsey *et al.* (2008) critically examine five key PoU technologies including chlorination with safe storage, combined coagulant-chlorine disinfectant systems, SODIS, ceramic filters, and biosand filters on the basis of several criteria relevant to low-income contexts in the South. The criteria they consider include: microbial efficacy under real field and ideal lab conditions (for bacteria, viruses and protozoa); health impacts (i.e. percentage reduction in diarrhoeal disease reported from controlled studies in the literature); and sustainability (comprising several factors including quantity of water

produced; robustness of treatment with respect to influent water quality variability; ease of process use and time required to treat water; cost of treatment; and supply chain requirements). Their findings are summarized in Table 2.

On the basis of their evaluation, Sobsey *et al.* recommend ceramic and biosand household filters as being the most effective and having the greatest potential to become widely used at the household level. This analysis is, however, criticized by Lantagne *et al.* (2009) as: 1) being subject to bias due to vague and incomplete definitions of ranking system criteria; 2) having scores assigned from insufficient evidence; and 3) lacking key sustainability criteria including consumer preference, economic considerations and local water quality. Lantagne *et al.* recommend that more complex water treatment selection tools be developed that give greater consideration to the local context of a given application instead of the ‘silver bullet’ approach taken by Sobsey *et al.* (2009). They respond to Lantagne *et al.* by stating that their evaluation is a ‘starting point’, based on the best available evidence, in the effort to develop fundamental and uniform criteria applicable to all situations in order to assist policy-makers and programme implementers in evaluating available options.

Table 2 | Key PoU technologies assessed for microbial efficacy, health impact and sustainability (adapted from Sobsey *et al.* 2008)

Treatment technology	Microbial efficacy (log ₁₀ reduction values)			Health impacts (estimate of diarrhoeal disease reduction, 95% CI)	Sustainability criteria (scored 1–3 for low to good performance)				
	Microbe class	Field	Lab		Quantity	Quality	Ease of use	Cost	Supply chain
Chlorination with safe storage	Bacteria	3	6 +	37% (25–48%)	3	1	3	Liquid: 3	1
	Viruses	3	6 +	29%				Tablets: 2	
	Protozoa	3	5 +						
Combined coagulant- chlorine disinfection	Bacteria	7	9	31% (18–42%)	2	3	1	1	1
	Viruses	2–4.5	6	29%					
	Protozoa	3	5						
SODIS (solar UV + thermal effects)	Bacteria	3	5.5 +	31% (26–37%)	1	1	1	3	3
	Viruses	2	4 +						
	Protozoa	1	3 +						
Ceramic filters	Bacteria	2	6	Candle filters: 63% (51–72%)	2	3	2	3	2
	Viruses	0.5	4						
	Protozoa	4	6	Ceramic purifiers: 46% (29–59%)					
Biosand filters	Bacteria	1	3	47% (21–64%)	3	3	2	2	3
	Viruses	0.5	3						
	Protozoa	2	4						

Context-specific assessment is necessary in order to determine the most appropriate option for a particular setting. An ideal treatment option would satisfy all possible evaluation criteria; however, no one technology can do that. By integrating two or more complementary technologies into a treatment chain, a combined system may be better able to satisfy the necessary criteria. Such a system could distribute treatment processes at both levels of approach; that is, at the household and the community levels. Treatment to improve the microbiological quality of water can be thought to have two basic stages: first turbidity control, to reduce suspended solids and other materials that can interfere with disinfection; and second, disinfection to inactivate waterborne pathogens. In all situations, a detailed analysis of local water quality and contextual factors with local stakeholders must inform the selection of the most appropriate level of approach and the treatment processes to be utilized.

SUSTAINABLE IMPLEMENTATION OF ALTERNATIVE SAFE WATER SYSTEMS IN SLUMS

Water, environment and public health in urban slums is a complex issue that requires the consideration of a range of factors for the development and sustainable implementation of appropriate technologies. Building on Sobsey *et al.* (2008) and Murphy *et al.* (2009), for an alternative safe water system to be effective and sustainable, it should meet several criteria including:

- effectiveness at reducing turbidity;
- effectiveness at improving microbiological quality;
- affordability with respect to the capacity and willingness to pay among the targeted socio-economic strata;
- simplicity and ease of use in operations and maintenance;
- availability of materials and parts in local supply chain;
- reliability;

- adjustability and flexibility for variable influent water quality;
- residual protection against recontamination;
- production of adequate quantities of safe drinking water;
- without offensive taste, odours or other objectionable qualities; and
- contextually appropriate.

Meeting the technical criteria given above may be challenging, but perhaps not as much as the final criterion, that the system should be contextually appropriate. This criterion demands that a system be appropriate to the economic and socio-cultural context in which it is situated. It has implications for systems management, community mobilization and the approach taken to systems development. The importance of this criterion necessitates a participatory approach to systems development, as these factors cannot be fully understood by external actors *a priori*. Further criteria, specific to a particular locale, may be identified by various stakeholders in the community in which a safe water system is being developed. Assessment of potential treatment options against local circumstances and subsequent decision-making should likewise be done in a participatory fashion with community members and other relevant stakeholders. This is an important step for assuring that systems development is appropriate to the realities of the community in which it is situated (Kelly & Farahbakhsh 2008). The following section attempts to shed some light on the complexity and centrality of contextual considerations by exploring some previous applications of PoU water treatment technologies.

Economic considerations

Chemical coagulation-disinfection is one of the treatment options considered by Sobsey *et al.* (2008). In addition to contributing to the microbiological quality of drinking water, coagulation-flocculation may also have the added benefit of improving the chemical quality of water by removing suspended solids, heavy metals and other chemical agents. Reller *et al.* (2003) conducted the first major epidemiological field study of a combined system utilizing chemical coagulation-disinfection. Their study in rural Guatemala realized significant reductions in diarrhoeal

diseases among the intervention population. The combined chemical treatment in their study included several coagulation, flocculation and disinfection agents commonly found in large-scale municipal water treatment plants (Souter *et al.* 2003). As a proprietary technology of the Procter & Gamble Co., the precise formulation of the chemical cocktail is not published; however Reller *et al.* (2003) indicate that it contains ferric sulphate, bentonite, sodium carbonate, chitosan, polyacrylamide, potassium permanganate and calcium hypochlorite. This proprietary technology has been applied elsewhere in intervention studies and has similarly met with positive results (Crump *et al.* 2005; Chiller *et al.* 2006).

Despite initial successes, follow-up on the Guatemalan study revealed that the relatively high cost of the commercial product resulted in the rapid decline of its use once institutional supports were removed (Luby *et al.* 2008). The Guatemalan example is hardly unique: many PoU safe water systems undergo rapid declines in usage following study completion. In a 5-year follow-up to a community-based safe water intervention in rural Mexico, deWilde *et al.* (2008) observed that there was no impact on diarrhoeal incidence; their study revealed that household priorities and preferences are a crucial factor in maintaining compliance with safe drinking water practices and user convenience is a major factor controlling uptake. In another study evaluating long-term uptake and use of locally produced ceramic water filters in rural Cambodia, Brown *et al.* (2009) observed a 2% decline in filter usage per month among households that had been targeted for the water quality intervention. This begs the question of who pays for safe water, from initial financing through operations to ongoing upkeep. It also raises questions on how best to manage household and community-based safe water systems in order to sustain them indefinitely. The question of sustainably scaling-up household water treatment systems among low-income populations has recently been explored by Clasen (2009).

Given the resource and institutional limitations facing the public sector, market-based approaches are often sought because they are seen to promote financial sustainability while minimizing implementation, administrative and financial burdens on the intervening group. However, in low-income settings, market-based approaches are

hardly a panacea; in fact, they give rise to a unique set of complexities that must be addressed should sustainability be sought. There have been several attempts to utilize a purely commercial approach for household PoU water treatment systems, but most have met with low levels of adoption and use (Harris 2005). From those attempts that have approached commercial viability, Harris identifies six factors that have contributed to financial sustainability. These are: refining and improving product positioning (i.e. marketing); leveraging existing health awareness; offering a smorgasbord of PoU options for different market segments; hybridizing business practices with donor-based approaches; finding alternative models of financial viability; and focusing on key product improvements. These steps may promote the financial sustainability of household PoU systems should a commercial approach be applied in their implementation.

Instead of a purely commercial approach, approaches that integrate the public and private sectors with the citizenry in tripartite partnerships could also be structured. Whereas household PoU systems more readily lend themselves to a commercial approach, community systems may be more amenable to such hybrid frameworks. Most often it is the case that the public and private sectors collaborate, while the community is overlooked. However, citizen involvement can contribute to service delivery, not just through the payment of service charges, but also by enhancing the monitoring of service quality on the part of the public and private sectors. Tripartite partnerships can 'democratize' service delivery by bringing citizens, politicians and service providers to face one another in discussion, enhancing the transparency, accountability and responsiveness of urban service delivery (Ahmed & Ali 2006). The Community Safe Water System developed by the Naandi Foundation and WaterHealth India discussed above is an example of such a tripartite framework.

Further research into management frameworks for decentralized systems is necessary. Public sector, commercial and tripartite approaches may be suitable for different contexts. The decision on which approach to take and how to structure the framework is influenced by local economic and political factors. It is an issue requiring the participation of community members, government agencies and other relevant stakeholders. Appropriate management

frameworks are necessary to ensure that decentralized safe water systems are sustainable in the communities in which they are implemented.

Socio-cultural considerations

The use of local natural materials is often encouraged as a means to reduce costs and integrate local and traditional knowledge into the development process. Whereas the proprietary technology discussed above contains industrial coagulation-flocculation agents, similar effects can also be achieved with plant materials that may be relatively inexpensive and widely available in certain locales. There are several plant-based materials with such properties available in tropical areas, including *Moringa oleifera*. *M. oleifera*, or the 'drumstick' tree, is found widely throughout South Asia and West Africa. At first glance, *Moringa* appears to be an interesting candidate for PoU applications throughout tropical areas. However, regional differences in socio-cultural context may make *Moringa* more amenable to certain locales over others. While *Moringa* grows widely throughout South Asia, its use varies between regions. For example, in southern India, the fruit is used widely in local cuisine, whereas in northern India, it is not. For water purification purposes, mature seeds are necessary, but in southern India, much of the *Moringa* crop is harvested early for food purposes. Because of this, mature seeds are not widely available. Conversely, in northern India, the *Moringa* fruit is not harvested for food so the seeds reach maturity. Having few competing uses, *Moringa* seeds are widely available and inexpensive. For this reason, *M. oleifera* may be more appropriate for PoU safe water applications in northern India than in southern India. This example illustrates the influence of the socio-cultural context on the selection of appropriate treatment technologies. For a decentralized, safe water system to be effective and sustainable, it must be suited to the social and cultural milieu of the community in which it is situated. Utilizing a participatory process with a range of stakeholders will encourage the identification of socio-cultural issues, which are important in the design process but easily overlooked by technical teams.

The uptake of behavioural changes into the social fabric of a community is also a prerequisite for the

sustainability of decentralized safe water systems; however, how this occurs is not yet fully understood (Zwane & Kremer 2007). Social marketing techniques have previously been employed for the promotion of PoU systems and have met with considerable success (Lantagne *et al.* 2007). In a social marketing campaign for a chlorine-based household PoU system in Kenya, focus groups identified community meetings, schools and community health training workshops to be favourable venues to promote behavioural change. Further factors identified as being important for influencing uptake included: having local health promoters and support from respected community leaders; increasing perceived need among the community for water treatment to prevent diarrhoea; promoting the interest in disinfection and willingness to pay; facilitating ease of access and use of the system; affordability; and building trust with the project implementers (Makutsa *et al.* 2001). Taking a participatory approach to systems development may encourage the realization of these factors.

Gender is also a critical issue in the development and implementation of decentralized safe water systems. As the primary collectors and managers of water in the household, women's participation in systems development and implementation is crucial for sustainability. Women may be more knowledgeable about sources of water and their quality and the implications of unsafe water to health than men. Women are also usually the ones who care for sick children and seek medical attention, and, as such, may be sensitized to preventive measures. With basic training in water, sanitation and hygienic practices, women can become the health promoters necessary for behavioural change in their community. Women should, for all these reasons, be involved in the development and management of safe water systems (Serafini 2005). This is not to say that men should be excluded from the process, particularly from promotional activities. Men typically control household spending and also need to be sensitized to the issues in order to promote sustainability (Harris 2005). Follow-up on a water, sanitation and hygiene intervention in rural Bangladesh indicated that women's participation contributed to project sustainability by promoting behavioural uptake. Involvement of women, along with the support of men, led to a positive attitude among the whole community toward improving water, sanitation and hygiene practices

(Hoque *et al.* 1996). Development and implementation of decentralized safe water systems, including the structuring of management frameworks, must be sensitive to gender. Men and women have different roles in the community and the household, and both should be included in a participatory process to ensure that the outcome meets their needs, while not over-burdening one group over another.

More generally, attention must also be given to marginalized groups within a given community. Low-income communities are hardly homogeneous; within them there can be considerable stratification due to class, caste, race, religion, age or disability. Marginalized groups may have particular needs for which they are unable to effectively self-advocate. Moreover, marginalized groups can be excluded from participatory community development if facilitators are not aware of the power dynamics within a community and then work actively to redress such issues. Certain groups may not be able to provide the necessary financial or human resources for systems development and management, and may become excluded from benefits. Their constraints and needs must be given due consideration in order to ensure that alternative safe water systems are inclusive and no one is locked out of the benefits.

CONCLUSION

Alternative decentralized safe water systems may be able to achieve rapid health gains among people living in urban and peri-urban slums throughout the South that presently lack access to safe water. Alternative safe water systems can be applied at either the household or the community/neighbourhood level, either of which has different benefits and drawbacks and are differently suited to particular settings. While much of the work done thus far in urban slums has focused on household systems, there is considerable potential for the development of community systems as well. Shifting treatment capacity from large-scale, centralized plants to small-scale, decentralized facilities in individual neighbourhoods may represent an alternative model for sustainable safe water provision in rapidly expanding cities in the South. The level at which a safe water system is deployed is, however, highly dependent on the particular circumstances of a given community.

This is one of three factors that are crucial for appropriate, decentralized, safe water systems development:

1. Selection of an appropriate level of approach—household vs. community.
2. Selection and development of appropriate treatment technology options.
3. Selection and development of an appropriate operations and management framework.

These decisions require considerable assessment and comparison of available options. This requires the integration of community members, government agencies, researchers and other relevant stakeholders into a participatory process that facilitates multi-disciplinary collaborative learning and the creation of adaptive capacity in the community. Such a process will encourage the development of safe water systems that, in being appropriate to the context in which they are situated, are effective and sustainable.

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REFERENCES

- Ahmed, S. & Ali, S. 2006 People as partners: facilitating people's participation in public-private partnerships for solid waste management. *Habitat Int.* **30**, 781–796.
- Ahmed, S., Hoque, B. & Mahmud, A. 1998 Water management practices in rural and urban homes: a case study from Bangladesh on ingestion of polluted water. *Public Health* **112**, 317–321.
- Arnold, B. & Colford, J., Jr 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.
- Baqui, A., Black, R., Sack, B., Chowdhury, H., Yunus, M. & Siddique, A. 1993 Malnutrition, cell-mediated immune deficiency, and diarrhea: a community-based longitudinal study in rural Bangladeshi children. *Am. J. Epidemiol.* **137**(3), 355–365.
- Berkman, D., Lescano, A., Gilman, R., Lopez, S. & Black, M. 2002 Effects of stunting, diarrhoeal disease, and parasitic infection during infancy on cognition in late childhood: a follow-up study. *Lancet* **359**(9306), 564–571.
- Biswas, A. & Tortajada, C. 2009 *Water Supply of Phnom Penh: A Most Remarkable Transformation*. Institute of Water Policy, Lee Kuan Yew School of Public Policy, Singapore.
- Black, R., Morris, S. & Bryce, J. 2003 Where and why are 10 million children dying every year? *Lancet* **361**, 2226–2234.
- Brick, T., Primrose, B., Chandrasekhar, R., Roy, S., Muliylil, J. & Kang, G. 2004 Water contamination in urban South India: household storage practices and their implications for water safety and enteric infections. *Int. J. Hyg. Environ. Health* **207**, 473–480.
- Brown, J., Sobsey, M. & Loomis, D. 2008 Local drinking water filters reduce diarrheal disease in Cambodia: a randomized, controlled trial of the ceramic water purifier. *Am. J. Trop. Med. Hyg.* **79**(3), 394–400.
- Brown, J., Proum, S. & Sobsey, M. 2009 Sustained use of a household-scale water filtration device in rural Cambodia. *J. Water Health* **7**(3), 404–412.
- Butterton, J. R. & Calderwood, S. B. 2004 Acute infectious diarrheal diseases and bacterial food poisoning. In *Harrison's Principles of Internal Medicine*, 16th Edition. McGraw-Hill Professional, UK.
- Chiller, T., Mendoza, C., Lopez, M., Alvarez, M., Hoekstra, R., Keswick, B. & Luby, S. 2006 Reducing diarrhoea in Guatemalan children: randomized controlled trial of flocculant-disinfectant for drinking-water. *Bull. World Health Org.* **84**(1), 28–35.
- Clasen, T. 2009 *Scaling up Household Water Treatment Among Low-Income Populations*. World Health Organization, Geneva.
- Clasen, T. & Bastable, A. 2003 Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use. *J. Water Health* **1**(3), 109–115.
- Clasen, T. & Cairncross, S. 2004 Editorial: household water management: refining the dominant paradigm. *Trop. Med. Int. Health* **9**(2), 187–191.
- Clasen, T., Schmidt, W., Rabie, T., Roberts, I. & Cairncross, S. 2007 Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. *Brit. Med. J.* **334**, 782–785.
- Crump, J., Otieno, P., Slutsker, L., Keswick, B., Rosen, D., Hoekstra, R., Vulule, J. & Luby, S. 2005 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. *Brit. Med. J.* **331**, 478–484.
- Curtis, V. & Cairncross, S. 2003 Effect of washing hands with soap on diarrhoea risk in the community: a systematic review. *Lancet Infect. Dis.* **3**, 275–281.
- Davis, M. 2006 *Planet of Slums*. Verso, London.
- deWilde, C., Milman, A., Flores, Y., Salmeron, J. & Ray, I. 2008 An integrated method for evaluating community-based safe water programmes and an application in rural Mexico. *Health Policy Plann.* **23**, 452–464.

- Elimelech, M. 2006 The global challenge for adequate and safe water. *J. Water Suppl. Res. Technol.* **55**(1), 3–10.
- Esrey, S. 1996 Water, waste, and well-being: a multicountry study. *Am. J. Epidemiol.* **143**(6), 608–623.
- Esrey, S. A., Potash, J. B., Roberts, L. & Shiff, C. 1991 Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. *Bull. World Health Org.* **69**(5), 609–621.
- Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L. & Colford, J. M., Jr 2005 Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infect. Dis.* **5**, 42–52.
- Franklin, U. 1990 *The Real World of Technology*. CBC Enterprises, Toronto.
- Gadgil, A., Greene, D., Drescher, A., Miller, P. & Kibata, N. 1998 *Low Cost UV Disinfection System for Developing Countries: Field Tests in South Africa*. First International Symposium on Safe Drinking Water in Small Systems, Washington, DC.
- Gundry, S., Wright, J. & Conroy, R. 2004 A systematic review of the health outcomes related to household water quality in developing countries. *J. Water Health* **2**(1), 1–13.
- Harris, J. 2005 *Challenges to the Commercial Viability of Point-Of-Use (POU) Water Treatment Systems in Low-Income Settings*. MSc Thesis, School of Geography and Environment, Oxford University, UK.
- Hoque, B. A., Juncker, T., Sack, R. B., Ali, M. & Aziz, K. M. A. 1996 Sustainability of a water, sanitation, and hygiene education project in rural Bangladesh: a 5-year follow-up. *Bull. World Health Org.* **74**(4), 431–437.
- Hussain, A., Ali, S. & Kvale, G. 1999 Determinants of mortality among children in the urban slums of Dhaka City, Bangladesh. *Trop. Med. Int. Health* **4**(11), 758–764.
- Hutin, Y., Luby, S. & Paquet, C. 2003 A large cholera outbreak in Kano City, Nigeria: the importance of hand washing with soap and the danger of street-vended water. *J. Water Health* **1**(1), 45–52.
- Illich, I. 1997 Development as planned poverty. In *The Post-Development Reader* (ed. M. Rahnema & V. Bawtree), pp. 94–101. Zed Books, London.
- Kar, K. & Pasteur, K. 2005 *Subsidy or Self-Respect? Community-led Total Sanitation*, IDS Working Paper 257. Institute of Development Studies, Brighton, UK.
- Kelly, B. & Farahbakhsh, K. 2008 Innovative knowledge translation in urban water management: an attempt at democratizing science. *Int. J. Technol. Know. Soc.*, **4**.
- Khan, A. 1996 *Orangi Pilot Project: Reminiscences and Reflections*. Oxford University Press, Karachi.
- Kosek, M., Bern, C. & Guerrant, R. L. 2003 The global burden of diarrhoeal disease, as estimated from studies published between 1992 and 2000. *Bull. World Health Org.* **81**(3), 197–204.
- Lantagne, D., Quick, R. & Mintz, E. 2007 Household water treatment and safe storage options in developing countries: a review of current implementation practices. In *Water Stories: Expanding Opportunities in Small-Scale Water and Sanitation Projects* (ed. M. Parker, A. Williams & C. Youngblood), pp. 17–308. Environmental Change & Security Program, Woodrow Wilson International Center for Scholars, Washington, DC.
- Lantagne, D., Meierhofer, R., Allgood, G., McGuigan, K. & Quick, R. 2009 Comment on 'Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world'. *Environ. Sci. Technol.* **43**(3), 968–969.
- LeChevallier, M., Gullick, R., Karim, M., Friedman, M. & Funk, J. 2003 The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. *J. Water Health* **1**(1), 3–14.
- Lee, E. & Schwab, K. 2005 Deficiencies in drinking water distribution systems in developing countries. *J. Water Health* **3**(2), 109–127.
- Leftwich, A. 2000 *States of Development: On the Primacy of Politics in Development*. Polity Press, Cambridge, UK.
- Luby, S. P., Syed, A. H., Atiullah, N., Faizan, M. K. & Fisher-Hoch, S. 1999 Limited effectiveness of home drinking water purification efforts in Karachi, Pakistan. *Int. J. Infect. Dis.* **4**, 3–7.
- Luby, S., Agboatwalla, M., Raza, A., Sobel, J., Mintz, E., Baier, K., Rahbar, M., Qureshi, S., Hassan, R., Ghouri, F., Hoekstra, R. M. & Gangarosa, E. 2001 A low-cost intervention for cleaner drinking water in Karachi, Pakistan. *Int. J. Infect. Dis.* **5**, 144–150.
- Luby, S., Mendoza, C., Keswick, B., Chiller, T. & Hoekstra, R. 2008 Difficulties in bringing point-of-use water treatment to scale in rural Guatemala. *Am. J. Trop. Med. Hyg.* **78**(3), 382–387.
- Makutsa, P., Nzaku, K., Ogotu, P., Barasa, P., Ombeki, S., Mwaki, A. & Quick, R. E. 2001 Challenges in implementing a point-of-use water quality intervention in rural Kenya. *Am. J. Public Health* **91**(10), 1571–1573.
- Marsh, D., Husein, K., Lobo, M., Shah, M. A. & Luby, S. 1995 Verbal autopsy in Karachi slums: comparing single and multiple cause of child deaths. *Health Policy Plann.* **10**(4), 395–403.
- Mintz, E., Bartram, J., Lochery, P. & Wegelin, M. 2001 Not just a drop in the bucket: expanding the access to point-of-use water treatment systems. *Am. J. Public Health* **91**(10), 1565–1570.
- Moe, C., Sobsey, M., Samsa, G. & Mesolo, V. 1991 Bacterial indicators of risk of diarrhoeal disease from drinking-water in the Philippines. *Bull. World Health Org.* **69**(3), 305–317.
- Montgomery, M. & Elimelech, M. 2007 Water and sanitation in developing countries: including health in the equation. *Environ. Sci. Technol.* **41**(1), 17–24.
- Murphy, H., McBean, E. & Farahbakhsh, K. 2009 Appropriate technology: a comprehensive approach for water and sanitation in the developing world. *Technol. Soc.* **31**, 158–167.
- NF 2007 *Changing Lives: Making Safe Drinking Water and Sanitation for all a Reality*. Naandi Foundation and Waterhealth India, Hyderabad, Andhra Pradesh.

- NRC 2006 *Drinking Water Distribution Systems: Assessing and Reducing Risks*. National Academies Press, Washington, DC.
- Prüss, A., Kay, D., Fewtrell, L. & Bartram, J. 2002 Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Environ. Health Perspect.* **110**(5), 537–542.
- Prüss-Üstün, A., Bos, R., Gore, F. & Bartram, J. 2008 *Safer Water, Better Health: Costs, Benefits, and Sustainability of Interventions to Protect and Promote Health*. World Health Organization, Geneva.
- Rahman, A., Lee, H. & Khan, M. 1997 **Domestic water contamination in rapidly growing megacities of Asia: case of Karachi, Pakistan**. *Environ. Monit. Assess.* **44**, 339–360.
- Reller, M. E., Mendoza, C. E., Beatriz Lopez, M., Alvarez, M., Hoekstra, R. M., Olson, C. A., Baier, K., Keswick, B. H. & Luby, S. 2003 A randomized controlled trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in rural Guatemala. *Am. J. Trop. Med. Hyg.* **69**(4), 411–419.
- Rose, A., Roy, A., Abraham, V., Holmgren, G., George, K., Balraj, V., Abraham, S., Muliylil, J., Joseph, A. & Kang, G. 2006 **Solar disinfection of water for diarrhoeal prevention in southern India**. *Arch. Dis. Child.* **91**, 139–141.
- Sahu, B. 2008 **Pani Panchayat in Orissa, India: The practice of participatory water management**. *Development* **51**, 121–125.
- Schumacher, E. F. 1973 *Small Is Beautiful: Economics as If People Mattered*. Harper Perennial, London.
- Schuster-Wallace, C., Grover, V., Adeel, Z., Confalonieri, U. & Elliott, S. 2008 *Safe Water as the Key to Global Health*. United Nations University International Network on Water, Environment, and Health (UNU-INWEH), Hamilton.
- Serafini, M. 2005 *Promotion and Microfinance of Kanchan Arsenic Filter in Rural Terai Region of Nepal*, Final Report. Stanford University, California.
- Sobsey, M. 2002 Managing water in the home: accelerated health gains from improved water supply. In *Protection of the Human Environment: Water, Sanitation and Health*. World Health Organization, Geneva.
- Sobsey, M., Stauber, C., Casanova, L., Brown, J. & Elliott, M. 2008 **Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world**. *Environ. Sci. Technol.* **42**, 4261–4267.
- Sobsey, M., Stauber, C., Casanova, L., Brown, J. & Elliott, M. 2009 **Response to comment on 'Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world'**. *Environ. Sci. Technol.* **43**(3), 970–971.
- Souter, P., Cruickshank, G., Tankerville, M., Keswick, B., Ellies, B., Langworthy, D., Metz, K., Appleby, M., Hamilton, N., Jones, A. & Perry, J. 2003 Evaluation of a new water treatment for point-of-use household applications to remove microorganisms and arsenic from drinking water. *J. Water Health* **1**(2), 73–84.
- Thompson, T., Sobsey, M. & Bartram, J. 2003 **Providing clean water, keeping water clean: an integrated approach**. *Int. J. Environ. Health Res.* **13**, S89–S94.
- UN 2007 *The Millennium Development Goals Report*. United Nations Department of Economic and Social Affairs, New York.
- UN 2008 *The Millennium Development Goals Report*. United Nations Department of Economic and Social Affairs, New York.
- UNDP 2006 *Human Development Report 2006–Beyond Scarcity: Power, Poverty, and the Global Water Crisis*. Palgrave Macmillan, New York.
- UNFPA 2007 *State of the World Population 2007: Unleashing the Potential for Urban Growth*. United Nations Population Fund, New York.
- Weber, W., Jr 2002 Distributed optimal technology networks: a concept and strategy for potable water sustainability. *Water Sci. Technol.* **46**(6–7), 241–246.
- 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**. *Trop. Med. Int. Health* **9**(1), 106–117.
- Zwane, A. & Kremer, M. 2007 **What works in fighting diarrheal diseases in developing countries? a critical review**. *World Bank Res. Obser.* **22**(1), 1–24.

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