Vaccine xxx (xxxx) xxx

Contents lists available at ScienceDirect

Vaccine

journal homepage: www.elsevier.com/locate/vaccine

Broad approaches to cholera control in Asia: Water, sanitation and handwashing

Stephen P. Luby [a,*], Jennifer Davis [a], Rebekah R. Brown [b], Steven M. Gorelick [a], Tony H.F. Wong [c]

[a] Woods Institute for the Environment, Stanford University, Stanford, CA 94305, United States
[b] Monash Sustainable Development Institute, Monash University, Clayton, Australia
[c] Cooperative Research Centre for Water Sensitive Cities, Monash University, Clayton, Australia

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Cholera
Sanitation
Asia
Drinking water
Government

ABSTRACT

Cholera has been eliminated as a public health problem in high-income countries that have implemented sanitation system separating the community's fecal waste from their drinking water and food supply. These expensive, highly-engineered systems, first developed in London over 150 years ago, have not reached low-income high-risk communities across Asia. Barriers to their implementation in communities at highest risk for cholera include the high capital and operating costs for this technological approach, limited capacity and perverse incentives of local governments, and a decreasing availability of water. Interim solutions including household level water treatment, constructing latrines and handwashing promotion have only marginally reduced the risk of cholera and other fecally transmitted diseases. Increased research to develop and policy flexibility to implement a new generation of solutions that are designed specifically to address the physical, financial and political constraints of low-income communities offers the best prospect for reducing the burden of cholera across Asia.

1. Background

Fear of cholera contributed importantly to the development of modern sanitation systems. In the middle of the 19th century, recurrent cholera outbreaks in London resulted in thousands of deaths [1,2]. In the hot summer of 1858 when the smell of open sewage in the Thames River became so intolerable ("The Great Stink") that several parliamentary meetings were suspended, members of Parliament approved unprecedented centralized authority to the Metropolitan Board of Works over >90 different local authorities [3]. In the ensuing 15 years Chief Engineer Joseph Bazalgette oversaw an enormous civil works effort that constructed 37 acres of embankments along the Thames, 4 major steam engine powered pumping stations and over 100 miles of underground interceptor sewers that connected with over 13,000 miles of smaller local sewers some dating from the 15th century [4,5]. The resulting system diverted 180 million gallons of sewage each day to a stretch of the river east of the city past the tidal segment so that the waste would flow into the ocean [4]. The cleaner Thames, combined with a requirement that municipal water be filtered before being piped to city residents [2], markedly improved water quality and reduced fecal exposure to the residents of London. Since this definitive big pipe infrastructure was implemented, cholera outbreaks have not recurred in London.

More than a century later, the 1991 cholera outbreak in Santiago, Chile prompted government officials to construct wastewater treatment plants that interrupted sewage contamination of crops grown in agricultural fields surrounding Santiago [6]. Ultimately, only 142 cholera cases and 3 deaths were identified in the 1991 outbreak in Chile, but the investment in infrastructure also eliminated typhoid as a public health problem and markedly reduce the incidence of hepatitis A for the city [7,8].

The objective of this paper within this supplemental issue of *Vaccine* focused on cholera vaccine, is to reflect on the importance of complementary strategies to reduce the burden of cholera and other infectious water borne diseases, and to consider how such efforts can be simultaneously advanced to work towards decreasing the burden of disease. When deployed in settings where cholera is endemic, the current vaccine reduces incidence of severe cholera by 37–65% over the ensuing 2–3 years [9,10]. Even in settings where cholera is a public health problem, cholera represents a small proportion of the burden of disease transmitted by the fecal oral pathway [11]. Thus, while the other articles in this issue address appropriate settings and strategies for deployment of vaccine as a focused tool, we aim to provide some consideration on

* Corresponding author at: Stanford University, Y2E2, MC 4205, 473 Via Ortega, Stanford, CA 94305, United States.

E-mail address: sluby@stanford.edu (S.P. Luby).

https://doi.org/10.1016/j.vaccine.2019.07.084
0264-410X/© 2019 Published by Elsevier Ltd.

broader strategies to reduce fecal-oral transmission in high-risk communities.

London's 19th century big pipes approach–that is, delivering piped clean drinking water to households, collecting human feces and urine, diluting it with water, pumping this waste stream over long distances and discharging it away from population centers–has been replicated in high-income cities globally. Treatment of wastewater prior to discharge to the environment was added 25 years later in London [4] and not until the middle of the 20th century in most cities in the United States [12]. Although networked sewers have been implemented in wealthier cities and wealthier neighborhoods in less wealthy cities, this solution has not been extended to the lowest income communities throughout Asia where the risk of cholera is highest.

Arguably the largest barrier to implementing city-wide, networked water and sewer infrastructure throughout Asia is high cost relative to the wealth of the population. These large civil works are expensive to construct, expensive to operate and expensive to maintain. Across Asia two-thirds of wastewater is discharged back into the environment without any form of treatment [13].

Comprehensive citywide water and sanitation systems also require a municipal government that is able to operate, maintain, repair and collect sufficient revenue to support these complex systems. Most low-income country municipal governments, however, have limited administrative, revenue-generating and technical capacity. Although most low-income country governments claim they are responsible for providing essential services, government actors often have incentives to provide such poor service that households pay additional fees to secure some basic form of service [14,15]. In the water sector, these fees might pay for an illegal connection or for a tanker truck, whose exclusive contract to operate includes a kickback to ruling politicians [16–19].

The critical shortage of available water in many Asian cities also prevents a 19th century London style big pipe solution. Transporting wastes from one person through a conventional waterborne sewer system requires an average of 15,000 L of water per year [20]. Even at the current level of service, which leaves many residents without a reliable convenient water supply or a sewer connection. Many large Asian cities including Chennai, Delhi, Lahore and Dhaka are drawing substantially more groundwater from aquifers than is being replenished [21–24]. These unsustainable withdrawals means that in the future there will be a marked reduction in available water and no cushion for drought emergencies. Since 2000, the population in Asian cities has increased by >850,000 persons per week [25]. The combination of population growth and reduction in available water supply means that the water supply per capita is progressively decreasing [26].

Climate change is likely to affect monsoon timing and magnitude [27]. With long-term constraints on physical water shortage, political leaders are pursuing engineered water storage and diversion infrastructure [28,29]. Upstream human activities will affect the quantity, quality, and timing of surface-water resources. For example, the construction of the Farakka Barrage by India diverted the flow of the Ganges River to increase water supply to Kolkata beginning in the early 1970s. This dam reduced the flow into Bangladesh by 73% during the dry season, with calamitous effects including increasing soil salinity and decreasing available freshwater [30]. The cascading effects of reduced transboundary flow is likely to reduce access to freshwater downstream and thus increase risk to cholera.

With rapid population growth and dwindling freshwater supplies, municipal water managers across Asia ration water. Households receive only intermittent supply when water is provided to their branch of the distribution network, perhaps a few hours per day or less [31]. Indeed, no major city in India provides piped drinking water 24 h per day 7 days a week to all residents [32]. All piped water systems leak [19]. When water is flowing in a fully pressurized system, clean water moves through the leaks into the environment. By contrast, when water is turned off contaminants from the environment can be drawn back into the pipes [33]. This ingress is particularly dangerous when water pipes course through sewage contaminated soils that are heavily enriched with pathogens such as *Vibrio cholerae*. When water services resume, these contaminants circulate throughout the system. An intermittent water supply is a contaminated water supply [34,35]. When the municipally supplied water was collected and cultured from households where a resident was hospitalized for cholera in Dhaka, Bangladesh, 33% grew *V. cholerae* [36].

Low-income residents of urban slums are serviced by the worst water and sanitary infrastructure in cities and are at particularly high risk for cholera [32,37]. They are often exposed not only to the fecal waste generated by their own community, but also to waste generated from other areas of the city that flows through their communities in open drains [38]. Although the proportion of Asian residents living in slums decreased between 1990 and 2012, the absolute number of urban slum residents increased by 100 million [25]. Without adequate piped water supply, the urban poor are often dependent upon more expensive water delivered by tanker trucks to their community.

The other low-income group at high risk of mortality from cholera are the rural poor who live far from available services. A person exposed to *V. cholerae* can progress from feeling well to sudden onset of voluminous diarrhea to death in a matter of hours [39]. During the rainy season in rural areas of Bangladesh when seasonal flooding makes transportation more difficult, living far away from a healthcare center increases the risk of death from severe diarrhea [40].

2. Household level interventions

Because of the many barriers to and slow pace of implementing robust municipal level systems to provide safe water and remove waste in low-income country cities, many public health advocates have promoted household level efforts to improve drinking water quality, construct latrines and encourage handwashing. When assiduously implemented, these household level strategies can reduce transmission of enteric pathogens including cholera; however, these are not the same approaches that controlled cholera in London, Tokyo or Singapore. At best, household strategies represent a partial, interim approach with a quite limited track record of success.

2.1. Household water treatment

A systematic review of the impact of water, sanitation and hygiene interventions on cholera [41] identified three trials that evaluated the effectiveness of point of use water treatment on cholera incidence; each reported a significant reduction [42–44]. These results are consistent with the observed impact of household water treatment on all causes of diarrhea. In settings where diarrhea is a leading cause of death and a community's drinking water is contaminated with feces, people who treat their drinking water with an approach that reduces microbiological contamination reduce their risk of developing diarrhea [45]. Encouraging household water treatment with sodium hypochlorite (bleach) can save lives and would be appropriate during an emergency response, especially if the disinfectant were distributed at no cost. If people are charged for household disinfectants, then the most impoverished households, that is those are who are at greatest risk of death from cholera, will be systematically excluded from this life saving intervention [46].

Moreover, despite its efficacy, household water treatment has not made a substantial contribution to reducing cholera burden because of low uptake among those households at highest risk. Household water treatment costs money and requires an ongoing commitment of time and effort for correct and consistent use. Even in the setting of cholera outbreaks where point-of-use water treatment supplies are provided at no cost, use of these interventions has characteristically been low, including 12% in Kenya, 19% in Nepal and 24% in Haiti (10.9% using a filter and 12.7% using chlorine) [47,48]. The low uptake of point-of-use water treatment in emergency outbreak response is consistent with low uptake observed more generally in impoverished households whose drinking water is chronically contaminated with human feces [49,50]. This experience suggests that expecting the poorest people in the world to assume the responsibility of disinfecting their drinking water, when these households are the most financially tenuous and the least educated, is an unsound strategy.

In settings where the local government utility fails to provide potable water, most middle-class and wealthier households in Asia understand that their drinking water is often contaminated with enteropathogens. They have sufficient knowledge and wealth to implement household water treatment [46]. When local governments fail to provide potable water to them, the private sector fills the gap with an array of home water treatment products. Impoverished residents of the same cities are serviced neither by the government nor by the market. This is the group at highest risk for cholera mortality. Thus, during cholera outbreaks, free provision of household water treatment with heavy promotion encouraging regular water treatment may avert some illness.

Although research on point-of-use water treatment continues, there is little evidence that any of these technologies has made substantial progress against the hard problem of low uptake amongst the highest risk populations. If an intervention could be developed that was so inexpensive and easy to use that it resulted in >80% uptake of effective treatment in large scale implementations among households in the lowest income decile, it could protect vulnerable populations from cholera in their drinking water at levels approaching an appropriately operating municipal system. Such an intervention, however, would require a technology that was so low cost that it presented no meaningful barrier to uptake among households who live on <1US$ per person per day, that required very little time, effort, training or behavioral promotion, and that so improved the drinking water experience that target households were motivated to use it. None of the current interventions are close to these performance criteria. They are either small programs that rely on external funding and reach less than 0.01% of the population in need or they sell products primarily to wealthier households who are not those at the highest risk of death from cholera.

2.2. Sanitation

The Millennium Development Goals targeted halving the proportion of the population without access to improved sanitation over the period 1990–2015 [51]. In response many government and aid organizations built or encouraged the construction of latrines, that is a toilet with a pit for containment of fecal and urinary waste [52]. The push for improved access also included events to raise awareness such as the designation of November 19 as World Toilet Day. A toilet, however, is not a sanitation system. Engineers in London did not control cholera in the 19th century by building toilets. Building a toilet is only the first step, containment. In urban settings where the volume of feces generated by the human population far exceeds the capacity of the environment to assimilate these wastes, a sanitation system requires safely collecting and transporting this excreta out of the immediate community, treating it, and then either reusing or safely disposing the resulting material. In settings where cholera occurs in Asia, many people have toilets, but the fecal sludge that collects in these toilets is usually dumped back into the environment untreated. For example, in Dhaka, Bangladesh, 99% of the population have access to a toilet, but 98% of the fecally contaminated wastewater is discharged back into the environment untreated from leaking or damaged toilets, deliberately by vacuum truck operators or through open drains or drainage pipes that discharge into local surface water bodies [53]. In dense urban areas, providing toilets to people without an effective system for managing the waste will not control cholera.

In rural areas, population densities are lower and so the environment can more readily absorb and break down the lower volume and concentration of locally generated human feces. Although the evidence is equivocal, a latrine that contains feces would be expected to reduce population exposure to fecally shed organisms including cholera. Few studies have rigorously evaluated the public health benefit from latrine construction in rural areas [41,54]. Whether or not a simple latrine is sufficient or whether a more hygienic latrine that consistently separates feces from flies and the environment is more useful is an open question. Of course, intervention programs that build toilets that are not used do not contribute to cholera control [55]. Many rural sanitation programs in India have focused on building toilets with little attention to understanding the interests and perspectives of potential users and so have resulted in quite low uptake [56].

In urban areas, the key policy consideration is moving beyond toilets with on-site containment and instead improving the entire sanitation system (discussed below). In rural areas, policies that support quality latrine construction and use are likely to reduce the risk of cholera and other enteric disease. Research priorities in rural areas include developing more effective strategies to promote habitual use of latrines, developing effective strategies for containment of child feces, and better evaluations of health impact to provide ongoing guidance to policy and intervention.

2.3. Handwashing

Risk factor studies during cholera outbreaks consistently identify handwashing with soap as protective [57]. In a public health crisis, fear of illness coupled with aggressive promotion can markedly increase handwashing behavior [58,59]. Although evaluations of handwashing promotion during cholera outbreaks have notable methodological limitations, each of four intervention assessments identified in a recent systematic review concluded that the interventions were effective [41].

Most people know that washing hands with soap is a good idea, though this behavior is not habitually practiced [60]. A primary barrier to adopting a handwashing habit is the paucity of environments that support the regular practice of handwashing with soap. For example, in Bangladesh 36% of government hospitals do not have running water within the hospital [61]. In a structured observation of 4676 potential handwashing opportunities observed within a nationally representative sample of hospitals in Bangladesh, healthcare workers only washed their hands 2% of time [61]. Similarly, only 21% of schools across Bangladesh have a location for students to wash hands with both soap and water present [62].

The primary policy steps to improve handwashing in settings where cholera is a public health risk is for institutions to develop and maintain the infrastructure and provide the consumable supplies to support handwashing. Hospitals, schools and food markets should have water supplies that are not contaminated by human feces, as well as easily accessible locations to wash hands with soap. Because contaminated water often contaminates food [63],

Please cite this article as: S. P. Luby, J. Davis, R. R. Brown et al., Broad approaches to cholera control in Asia: Water, sanitation and handwashing, Vaccine, https://doi.org/10.1016/j.vaccine.2019.07.084

food markets are particularly important loci to interrupt transmission. If low-income communities do not have sufficient running water to wash hands, then handwashing promotion efforts to these communities will be ineffective.

A productive area for handwashing research is developing scalable strategies to improve handwashing practices in high-risk resource-constrained environments. Both the cost of soap and the time required to wash hands are important barriers to handwashing. Using soapy water made from low cost detergent [64] or developing other inexpensive approaches can help address these barriers. Approaches other than soap and water may extend the reach of hand hygiene especially in water scarce contexts, but these approaches need to be remarkably low cost to reach people at highest risk.

3. Definitive solutions

Cholera has been successfully controlled by infrastructure improvements that reliably separate the community's excreta from its water and food supplies. This approach was effective in London in the 19th century and in Singapore in the 20th century [65]. It is the one proven approach with a sound historical track record. Implementing such definitive approaches offers the most robust protection against cholera and other enteropathogen transmission.

By contrast, beginning in the 1960s, to reduce the risk of diarrhea, residents of rural Bangladesh were encouraged to switch from surface water that was commonly contaminated with human and animal feces, to instead exploit shallow groundwater by installing tubewells. Contemporary studies found no impact on the incidence of cholera or diarrhea in this move from surface water to groundwater [66–69]. Subsequently, much of the shallow groundwater in Bangladesh was found to be heavily contaminated with arsenic, and so the switch to shallow groundwater as a source for drinking water has generated an ongoing public health catastrophe [70].

Despite 150 years of evidence from high income settings, we lack robust strategies for removing fecal contamination and the attendant risk of exposure to *Vibrio cholerae* and other pathogens from drinking water and from the food supply in low-income communities of low-income countries. Professionals working in this space should own the failure of these efforts. Neither a few marginal technical tweaks nor impassioned exhortations on the human right to water and the responsibilities of governments are likely to solve this longstanding hard problem.

Nevertheless, well delivered focused interventions can interrupt enteropathogen transmission. The WASH Benefits trial in Bangladesh specifically evaluated the impact of 3 focused individual interventions on (1) drinking water quality, (2) handwashing promotion and (3) hygienic sanitation when delivered separately and when combined on reported diarrhea and on objective measures of enteropathogen prevalence in children stool. Giardia [71] and hookworm [72] transmission as well as reported diarrhea [73] were reduced in some, but not all, of the single intervention arms. This is consistent with the notion that enteropathogen transmission varies by place and time. For example, contaminated water was the primary transmission pathway for *V. cholerae* transmission in Freetown, Sierra Leone in 2012 [74], while contaminated raw vegetables were the primary transmission pathway in Lusaka, Zambia in 2003–2004 [75]. Although comprehensive strategies provide the most robust protection, reducing transmission one pathway at a time can progressively improve community health.

3.1. Improving drinking water supply

Well-functioning centralized water distribution systems require capital for construction and funds for ongoing maintenance and repair, but municipal water suppliers in weak states commonly lack the incentives and capacity to regularly collect customer payments [16,76]. People living in poor communities are willing to pay for water. Indeed, the poor in Asia pay 10 to 20 times more per liter for water that they purchase from small-scale providers or vendors, as compared to wealthier households who receive water from piped networks that benefit from both economies of scale and government subsidies [19,77]. Expanding high quality service to poor neighborhoods is impeded by a variety of perverse incentives within municipal water institutions which encourage overstaffing, prioritizing service improvements to politically connected customers, and failing to set service prices to cover operating costs [78]. Water, like food, should be priced at a level that is sufficient to cover the costs of ensuring ongoing supply. Setting prices that are artificially low means that providers have insufficient resources to reach populations in need [78].

One potential low-cost strategy to better align the incentives of water municipalities and communities would be requiring water service providers to complement the current standard practice of testing microbiological quality of drinking water as it exits the pumping station/treatment plant with evaluating water samples collected from randomly selected points throughout the municipal distribution system. The goal of a municipal water supply system is to supply sufficient safe water to residents. Collecting water samples throughout the distribution network would assess whether or not the municipally supplied drinking water met World Health Organization criteria for potability. New technologies permitting pathogen detection in municipal water supplies [79] could further motivate attention to these often neglected systems. Sharing such results could help stimulate broader discussion and, ultimately, longer term strategies to address widespread drinking water contamination. If government authorities are reluctant to generate such data, non-government organizations could partner with credible laboratories to conduct such analyses to initiate these conversations.

Some municipalities, often at the insistence of donors, have engaged private industry in the hope that private sector skills and incentives could manage water utilities more efficiently, provide better service, collect bills more regularly and be less likely to have service undermined by political interference. Experience with this approach has varied. In Argentina, cities that privatized their water services in the 1990s expanded water service so effectively into poor communities that child mortality fell 26% in the poorest communities of cities adopting water privatization compared with cities that maintained government water service provision [80]. Similarly water privatization in La Paz and El Alto, Bolivia also improved access to the lowest income communities [81]. However, under public pressure politicians in both Argentina and Bolivia revoked these arrangements. Formal private sector firms provide only 5% of water services globally [82]. Indeed, there is little evidence that providing water to poor communities is a sufficiently profitable business to attract private international finance and multinational firms to fill this role. We do not have robust models of efficient cost-effective water service delivery reaching populations who are at highest risk of cholera.

A more limited role for the private sector may help improve the availability of potable water in these environments. In several settings private entrepreneurs have established water kiosks that provide water for purchase that is often of substantially improved microbiological quality [83–85]. Water treatments of this privately vended water range from none at all to reverse osmosis. The cost per liter is generally higher than the stated government price for municipal water, but the perceived quality and convenience is of sufficient value to water constrained communities to support a sustainable business model in at least some locations. Although private water kiosks are unlikely to provide abundant safe water

Please cite this article as: S. P. Luby, J. Davis, R. R. Brown et al., Broad approaches to cholera control in Asia: Water, sanitation and handwashing, Vaccine, https://doi.org/10.1016/j.vaccine.2019.07.084

to the poorest households, they may provide an essential service to some communities. By providing a separate treatment and distribution system for water intended for drinking and cooking, this method of delivery inserts some efficiency by prioritizing the highest investment in water quality for water that will be ingested.

The private sector can also play a role in reducing leaks in municipal water supplies by performance-based contracting [86]. With this approach, a public utility enters a performance-based contract with a private company to reduce non-revenue water across the municipal area. Payment is linked to the reduction in lost water. This saves the utility money, because they can expand service without expanding supply. It also leverages the creative flexibility of the private sector. Although eliminating illegal connections that contribute to non-revenue water risks reducing water access to the poor, physical losses in water systems and underpayment by big users are much larger components of non-revenue water than are connections to low income communities [76]. Low income communities would generally benefit from a more efficient and transparent system, since they use less water per person and are currently paying so much more per liter than are wealthier consumers [19,77].

Another potential role for the private sector would be collecting wastewater, either graywater and/or blackwater (contains feces), treating it and returning it to consumers or municipalities. In water short areas, water is a scarce resource. Private companies might be better placed to maximize efficiency in water reclamation. Municipalities, may find it more feasible and less expensive to purchase reclaimed water, rather than attempting to exploit new sources, or invest in and manage their own facilities.

Expected economic growth across Asia will generate more wealth and so more revenue is likely to be available from these communities to improve municipal water utilities. Rising incomes, on their own, however, are unlikely to eliminate the risk of cholera, because the health of rapidly growing cities will be constrained by dwindling supplies of available water.

Contemporary thinking in integrated urban water cycle management can help service growing urban populations in the setting of reduced supply [87]. Since a minority of the water supplied to cities is ingested, fit-for-purpose water quality production and treatment can provide water from a greater diversity of water sources including water recycling to meet urban demand [88]. An integrated water cycle approach can also improve sanitation by collecting water from the effluent stream and reduce environmental contamination. A fit-for-purpose water treatment framework also focuses behavior and expenditure on that component of water that truly needs to be potable.

The current approach adopted by most municipalities in low-income countries of extending piped water service to wealthy new neighborhoods while dramatically underserving impoverished neighborhoods will not provide a sustainable defense against cholera. Only by providing safe drinking water to the poorest, least politically empowered residents, will the whole city be protected. Advocacy for water as a human right [89] may motivate improved availability in some circumstances, but framing access to water as a right risks implying that poor water availability is solely an issue of political will. We assert that insufficient safe water for low income communities is a complex problem that results from population growth, progressive reduction in available surface and groundwater, poverty, climate change, limited government capacity, perverse incentives and technologies that are not fit for purpose in these highly constrained environments. Addressing the complex problem requires that we accept its complexity, which means recognizing that urging a handful of key political leaders to enact a specific policy is insufficient. We assert that the failure to resolve this problem reflects how difficult of a problem it is to solve and so requires investment in additional research to design, iterate and evaluate interventions. These are not only technology interventions on how to better purify and distribute water, but also political, administrative and informational interventions that might improve municipal water management.

Informed by the long history of failure of municipal systems in low income countries to provide safe water to low income neighborhoods, new approaches are called for. One technological development is lower cost water meters [90]. The improved transparency offered by applying information technology to track water connections, water consumption, water billing, repairs and services provides an opportunity to combat the corrupt private deals that undermine service and water utility revenue. Developing new technology for identifying leaks could improve efficiency of municipal systems and reduce the need for increasing environmental withdrawals.

Because the long history of failure of adapting large expensive centralized systems that require more water, more funding and more government capacity than is available, new approaches are needed for collecting, disinfecting and distributing water that are specifically designed to function in the water-, capital- and governance-constrained contexts where risk of cholera and other waterborne diseases is greatest. Such approaches are likely to operate on a smaller scale than traditional municipal networks [91,92]; rigorous evaluation of these decentralized approaches can provide valuable sector guidance. In addition, developing and testing approaches to prevent or mitigate the effects of intermittent water supply service could reduce risk. Importantly, researchers and change agents should appreciate that a safe and sufficient water supply is not solely a technical challenge, but also a difficult political issue [16,93]. Research should explicitly develop and evaluate strategies to break the dysfunctional political economy equilibrium that incentivizes poor service provision. This requires broadening the community of researchers and practitioners addressing these issues to ensure an adequate range of disciplinary expertise to assess dimensions of the problem that transcend civil engineering.

3.2. Upgrading sanitation systems

Around the world and throughout history, communities have prioritized meeting their water supply needs before addressing their sanitation needs; similarly, containment and isolation of waste is prioritized over waste treatment [12]. Since large sewered sanitation systems cost considerably more than water distribution systems, improvement in sanitation systems generally require more time and wealth accumulation than improvements in water systems [12]. High-income countries currently treat approximately 70% of their wastewater, while low-income countries treat only 8% [13]. The immense volume of untreated wastewater generated by rapidly growing cities that is dumped back into the immediate environment worsens health in the affected communities, adversely impacts the broader ecology and worsens water quality for downstream communities.

The big pipe approach implemented to serve London's 3 million residents in the 1860s is not a fit-for-purpose approach for sanitation in water scarce cities of Asia in the 21st century. High capital and operating costs means sanitary system infrastructure will be slow to arrive in poor cities and particularly slow to arrive in informal settlements at the highest risk for cholera.

Efforts to improve these conditions should focus less on constructing toilets and latrines and more on developing systems for the collection, transport, treatment, and reuse or discharge of fecal sludge. Because infrastructure investments are designed to last for several decades, technical recommendations by lending bodies

Please cite this article as: S. P. Luby, J. Davis, R. R. Brown et al., Broad approaches to cholera control in Asia: Water, sanitation and handwashing, Vaccine, https://doi.org/10.1016/j.vaccine.2019.07.084

tend to reflect conservative old technology approaches [12,93,94], but the populations at highest risk for devastating high mortality cholera outbreaks are the least likely to be served by these traditional high capital approaches. Lenders and policymakers should create a more flexible policy environment that permits innovation and experimentation.

Improving sanitation systems in water scarce low-income cities in Asia will require new approaches and new research. Green urban design and technologies that are being increasingly implemented in high-income countries to improve water security, sustainability and resilience could be adapted to enable low-income communities to implement decentralized approaches that recycle wastewater, harvest rainwater and storm water, and protect themselves against flooding and pollution [95]. Applied at different scales (households, neighborhoods, and whole precincts), this approach supports outcomes beyond simply providing clean water and sanitation services. Such approaches close the water cycle loop to make local waterways healthier and water supplies more secure. They reduce flood vulnerability, create landscapes for growing high-value crops and deliver a viable receiving environment for effluent from wetlands constructed for wastewater treatment. The adaptation of these approaches to low income country municipal environments is only beginning [96]. The primary wastewater of concern in low income country cities is blackwater, that is water contaminated with feces and urine. There are well established wetland systems for wastewater treatment [97]. However, they need to be re-configured for dense urban settings. Recent success in urban storm water wetlands embedded in dense urban settings provide templates for the required modification [98].

Other potential decentralized technical approaches include urine diverting toilets with dry sanitation [20], container based sanitation approaches that collect and process excreta into compost or solid fuel briquettes [99] and low energy decentralized electrolysis to remove pathogens from wastewater [100]. Advances in resource recovery from wastewater, including recovering the water, can offset at least some of the system costs [101]. All engineered civil works require ongoing operation and maintenance which, in turn, requires funding, trained personnel and local government capacity. Designing new approaches that require less technical sophistication, less active management and less ongoing funding to maintain are more likely to overcome the shortcomings of historical approaches in reaching the highest risk communities. Research that focuses on solutions that are fit-for-purpose for communities at highest risk for cholera are particularly important because of the failure of the traditional model to address these highest risk groups. Although none of the systems are yet sufficiently robust and low cost enough to be effective at managing the excreta of entire communities living in dense urban settlements of over 10,000 people per square kilometer, the approaches are sufficiently promising to justify further investment in research to advance their development. Unless we develop a technical and institutional approach to either remove or decontaminate the fecal effluent from these communities, then fecal oral transmission will continue, including outbreaks of cholera.

Handwashing should be viewed as an important complementary behavior that can reduce fecal oral transmission, but is not the primary definitive strategy. An environment that is supportive of handwashing is a necessary condition for optimal handwashing practices [102]. In a water scarce setting, especially when families have to devote considerable time to collecting water, handwashing with water will not be a priority. Alternative approaches to hand hygiene are attractive but it is hard to imagine even a product as inexpensive as alcohol gel being affordable to the households at highest risk of cholera mortality. Integrating handwashing stations into public facilities including public toilets might be an efficient strategy to reduce community transmission of enteric pathogens.

4. Conclusion

The mixture of community fecal effluent with drinking water and food presents an ongoing risk of cholera and other enteric diseases including enteric fever, Hepatitis E, Hepatitis A, Norovirus, *Shigella*, and *Campylobacter* to populations across Asia. Since the available cholera vaccine leaves at least 35% of vaccinated individuals unprotected from severe cholera and no immunization program reaches its entire target population, approaches that provide clean water, uncontaminated food and safe management of human excreta provide additional protection to the population against cholera and other enteropathogens. Like vaccinations, water supply, sanitation and hygiene interventions are not one-off investments, but require substantial ongoing operational commitments to maintain a skilled workforce and consistent service delivery. During an acute cholera outbreak, efforts to improve drinking water quality by encouraging household disinfection and promoting handwashing with soap can marginally reduce the transmission and burden of cholera. The approaches used to eliminate cholera as a public health problem in high-income countries require too much money, too much water and too much energy to address rapidly growing low income communities in Asian cities. New approaches that are specifically designed to provide potable water and management of wastewater are essential to further reduce risks. These approaches will require both policy flexibility and investment in research and evaluation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Tien JH, Poinar HN, Fisman DN, Earn DJD. Herald waves of cholera in nineteenth century London. J Roy Soc Interface 2010.
[2] Luckin W. The final catastrophe—cholera in London, 1866. Med Hist 1977;21:32–42.
[3] Halliday S. The Great Stink of London. Gloucestershire: Sutton Publishing Limited; 1999.
[4] Sochan G. Making the city inhabitable: London's sewer system. Humanit Technol Rev 2007;26:27–48.
[5] Thornbury W. The Victoria Embankment Old and New London. London: Cassell, Petter & Galpin; 1878. p. 322–9.
[6] Ferreccio C. Santiago, Chile: avoiding an epidemic. In: Serageldin I, Cohen MA, Sivaramakrishan KC, editors. The human face of the urban environment. Washington DC: The World Bank; 1995. p. 160–2.
[7] Bartone CR. From fear of cholera to full wastewater treatment in two decades in Santiago, Chile. Environmental Engineering Consultant World Bank Water Days, Agricultural Water Management Session, Washington DC, USA; 2011.
[8] Alcayaga S, Alcayaga J, Gassibe P. Cambios del perfil de morbilidad en algunas patologías de transmisión entérica con posterioridad a un brote de cólera. Servicio de salud metropolitano sur. Chile. Rev Chilena Infectol 1993;1:5–10.
[9] Qadri F, Ali M, Chowdhury F, Khan AI, Saha A, Khan IA, et al. Feasibility and effectiveness of oral cholera vaccine in an urban endemic setting in Bangladesh: a cluster randomised open-label trial. Lancet 2015;386:1362–71.
[10] Sur D, Ochiai RL, Bhattacharya SK, Ganguly NK, Ali M, Manna B, et al. A cluster-randomized effectiveness trial of Vi typhoid vaccine in India. New Engl J Med 2009;361:335–44.
[11] Najnin N, Leder K, Qadri F, Forbes A, Unicomb L, Winch PJ, et al. Impact of adding hand-washing and water disinfection promotion to oral cholera vaccination on diarrhoea-associated hospitalization in Dhaka, Bangladesh: evidence from a cluster randomized control trial. Int J Epidemiol 2017;46:2056–66.
[12] Melosi MV. The Sanitary city. Baltimore: The Johns Hopkins University Press; 2000.
[13] Sato T, Qadir M, Yamamoto S, Endo T, Zahoor A. Global, regional, and country level need for data on wastewater generation, treatment, and use. Agric Water Manag 2013;130:1–13.
[14] Wade R. The market for public office: why the Indian state is not better at development. World Dev 1985;13:467–97.
[15] Killingsworth JR, Hossain N, Hedrick-Wong Y, Thomas SD, Rahman A, Begum T. Unofficial fees in Bangladesh: price, equity and institutional issues. Health Policy Plan 1999;14:152–63.

[16] Davis J. Corruption in public service delivery: experience from South Asia's water and sanitation sector. World Dev 2004;32:53–71.
[17] Hackenbroch K, Hossain S. "The organised encroachment of the powerful"—everyday practices of public space and water supply in Dhaka, Bangladesh. Plan Theory Pract 2012;13:397–420.
[18] Hossain S. The informal practice of appropriation and social control–experience from a bosti in Dhaka. Environ Urbaniz 2013;25:209–24.
[19] McIntosh AC. Asian water supplies reaching the urban poor. London; 2003.
[20] Winblad U. Towards an ecological approach to sanitation. Stockholm: Swedish International Development Cooperation Agency (Sida); 1997.
[21] Rodell M, Velicogna I, Famiglietti JS. Satellite-based estimates of groundwater depletion in India. Nature 2009;460:999–1002.
[22] Srinivasan V, Seto KC, Emerson R, Gorelick SM. The impact of urbanization on water vulnerability: a coupled human–environment system approach for Chennai, India. Glob Environ Change 2013;23:229–39.
[23] Briscoe J, Qamar U. Pakistan's water economy: running dry. Karachi: Oxford University Press World Bank document; 2006.
[24] Hoque MA, Hoque MM, Ahmed KM. Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: causes and quantification. Hydrogeol J 2007;15:1523–34.
[25] Habitat UN. State of the world's cities 2012/2013: Prosperity of cities. London: Routledge; 2013.
[26] World Economic Forum Water Initiative. Water security: the water-food-energy-climate nexus. Washington DC: Island Press; 2012.
[27] Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, et al. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change: IPCC; 2014.
[28] Gleick PH. China dams. The World's Water. Springer; 2012. p. 127–42.
[29] Zhang Q. The south-to-north water transfer project of China: environmental implications and monitoring strategy. JAWRA J Am Water Resou Assoc 2009;45:1238–47.
[30] Rahman MM, Hassan MQ, Islam MS, Shamsad S. Environmental impact assessment on water quality deterioration caused by the decreased Ganges outflow and saline water intrusion in south-western Bangladesh. Environ Geol 2000;40:31–40.
[31] Lee EJ, Schwab KJ. Deficiencies in drinking water distribution systems in developing countries. J Water Health 2005;3:109–27.
[32] McKenzie D, Ray I. Urban water supply in India: status, reform options and possible lessons. Water Policy 2009;11:442–60.
[33] Kumpel E, Nelson KLCh. Mechanisms affecting water quality in an intermittent piped water supply. Environ Sci Technol 2014;48:2766–75.
[34] Kumpel E, Nelson KL. Comparing microbial water quality in an intermittent and continuous piped water supply. Water Res 2013;47:5176–88.
[35] Jeandron A, Saidi JM, Kapama A, Burhole M, Birembano F, Vandevelde T, et al. Water supply interruptions and suspected cholera incidence: a time-series regression in the Democratic Republic of the Congo. PLoS Med 2015;12:e1001893.
[36] George CM, Monira S, Sack DA, Rashid MU, Saif-Ur-Rahman KM, Mahmud T, et al. Randomized controlled trial of hospital-based hygiene and water treatment intervention (CHoBI7) to reduce cholera. Emerg Infect Dis 2016;22:233–41.
[37] Rebaudet S, Sudre B, Faucher B, Piarroux R. Environmental determinants of cholera outbreaks in inland Africa: a systematic review of main transmission foci and propagation routes. J Infect Dis 2013;208(Suppl 1):S46–54.
[38] Jena M. Pollution in the Mahanadi: urban sewage, industrial effluents and biomedical waste. Econ Polit Weekly 2008:88–93.
[39] McCrickard LS, Massay AE, Narra R, Mghamba J, Mohamed AA, Kishimba RS, et al. Cholera mortality during urban epidemic, Dar es Salaam, Tanzania, August 16, 2015-January 16, 2016(1). Emerg Infect Dis 2017;23.
[40] Paul RC, Faruque AS, Alam M, Iqbal A, Zaman K, Islam N, et al. Incidence of severe diarrhoea due to Vibrio cholerae in the catchment area of six surveillance hospitals in Bangladesh. Epidemiol Infect 2016;144:927–39.
[41] Taylor DL, Kahawita TM, Cairncross S, Ensink JH. The impact of water, sanitation and hygiene interventions to control cholera: a systematic review. PLoS ONE 2015;10:e0135676.
[42] Deb BC, Sircar BK, Sengupta PG, De SP, Mondal SK, Gupta DN, et al. Studies on interventions to prevent eltor cholera transmission in urban slums. Bull World Health Organ 1986;64:127–31.
[43] Conroy RM, Meegan ME, Joyce T, McGuigan K, Barnes J. Solar disinfection of drinking water protects against cholera in children under 6 years of age. Arch Dis Child 2001;85:293–5.
[44] Colwell RR, Huq A, Islam MS, Aziz KM, Yunus M, Khan NH, et al. Reduction of cholera in Bangladeshi villages by simple filtration. Proc Natl Acad Sci USA 2003;100:1051–5.
[45] Clasen TF, Alexander KT, Sinclair D, Boisson S, Peletz R, Chang HH, et al. Interventions to improve water quality for preventing diarrhoea. Cochrane Database Syst Rev (Online) 2015:CD004794.
[46] Rosa G, Clasen T. Estimating the scope of household water treatment in low- and medium-income countries. Am J Trop Med Hygiene 2010;82:289.
[47] Lantagne DS, Clasen TF. Use of household water treatment and safe storage methods in acute emergency response: case study results from Nepal, Indonesia, Kenya, and Haiti. Environ Sci Technol 2012;46:11352–60.
[48] Patrick M, Berendes D, Murphy J, Bertrand F, Husain F, Handzel T. Access to safe water in rural Artibonite, Haiti 16 months after the onset of the cholera epidemic. Am J Trop Med Hygiene 2013;89:647–53.
[49] Stockman LJ, Fischer TK, Deming M, Ngwira B, Bowie C, Cunliffe N, et al. Point-of-use water treatment and use among mothers in Malawi. Emerg Infect Dis 2007;13:1077–80.
[50] Luby SP, Mendoza C, Keswick BH, Chiller TM, Hoekstra RM. Difficulties in bringing point-of-use water treatment to scale in rural Guatemala. Am J Trop Med Hygiene 2008;78:382–7.
[51] WHO/UNICEF., Programme. JWSSM. Progress on drinking water and sanitation: 2014 Update: World Health Organization; 2014.
[52] Kar K, Chambers R. Handbook on community-led total sanitation. Brighton: Plan UK; 2008.
[53] Peal A, Evans B, Blackett I, Hawkins P, Heymans C. Fecal sludge management: a comparative analysis of 12 cities. J Water Sanitation Hygiene Develop 2014;4:563–75.
[54] Wolf J, Pruss-Ustun A, Cumming O, Bartram J, Bonjour S, Cairncross S, et al. Assessing the impact of drinking water and sanitation on diarrhoeal disease in low- and middle-income settings: systematic review and meta-regression. Trop Med Int Health 2014;19:928–42.
[55] Clasen T, Boisson S, Routray P, Torondel B, Bell M, Cumming O, et al. Effectiveness of a rural sanitation programme on diarrhoea, soil-transmitted helminth infection, and child malnutrition in Odisha, India: a cluster-randomised trial. Lancet Glob Health 2014;2:e645–53.
[56] Hueso A, Bell BP. An untold story of policy failure: the Total Sanitation Campaign in India. Water Policy 2013;15:1001–17.
[57] Wolfe M, Kaur M, Yates T, Woodin M, Lantagne D. A Systematic review and meta-analysis of the association between water, sanitation, and hygiene exposures and cholera in case-control studies. Am J Trop Med Hygiene 2018;99:534–45.
[58] Lau JT, Yang X, Tsui H, Kim JH. Monitoring community responses to the SARS epidemic in Hong Kong: from day 10 to day 62. J Epidemiol Community Health 2003;57:864–70.
[59] Rubin GJ, Amlot R, Page L, Wessely S. Public perceptions, anxiety, and behaviour change in relation to the swine flu outbreak: cross sectional telephone survey. BMJ (Clinical research ed.) 2009;339:b2651.
[60] Curtis VA, Danquah LO, Aunger RV. Planned, motivated and habitual hygiene behaviour: an eleven country review. Health Educ Res 2009;24:655–73.
[61] Horng LM, Unicomb L, Alam MU, Halder AK, Shoab AK, Ghosh PK, et al. Healthcare worker and family caregiver hand hygiene in Bangladeshi healthcare facilities: results from the Bangladesh National Hygiene Baseline Survey. J Hospital Infect 2016;94:286–94.
[62] icddr b. Bangladesh National Hygiene Baseline Survey. Dhaka: WaterAid Bangladesh; 2014.
[63] Lanata CF. Studies of food hygiene and diarrhoeal disease. Int J Environ Health Res 2003;13(Suppl 1):S175–83.
[64] Hulland KR, Leontsini E, Dreibelbis R, Unicomb L, Afroz A, Dutta NC, et al. Designing a handwashing station for infrastructure-restricted communities in Bangladesh using the integrated behavioural model for water, sanitation and hygiene interventions (IBM-WASH). BMC Public Health 2013;13:877.
[65] Otaki Y, Otaki M, Sakura O. Water systems and urban sanitation: a historical comparison of Tokyo and Singapore. J Water Health 2007;5:259–65.
[66] Sommer A, Woodward WE. The influence of protected water supplies on the spread of classical-Inaba and El Tor-Ogawa cholera in rural East Bengal. Lancet 1972;2:985–7.
[67] Levine RJ, Khan MR, D'Souza S, Nalin DR. Failure of sanitary wells to protect against cholera and other diarrhoeas in Bangladesh. Lancet 1976;2:86–9.
[68] Briscoe J. The role of water supply in improving health in poor countries (with special reference to Bangla Desh). Am J Clin Nutr 1978;31:2100–13.
[69] Khan MU, Mosley WH, Chakraborty J, Sarder AM, Khan MR. The relationship of cholera to water source and use in Rural Bangladesh. Int J Epidemiol 1981;10:23–6.
[70] Smith AH, Lingas EO, Rahman M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bull World Health Organ 2000;78:1093–103.
[71] Lin A, Ercumen A, Benjamin-Chung J, Arnold BF, Das S, Haque R, et al. Effects of water, sanitation, handwashing, and nutritional interventions on child enteric protozoan infections in rural Bangladesh: a cluster-randomized controlled trial. Clin Infect Dis 2018.
[72] Ercumen A, Benjamin-Chung J, Arnold BF, Lin A, Hubbard AE, Stewart C, et al. Effects of water, sanitation, handwashing and nutritional interventions on soil-transmitted helminth infections in young children: A cluster-randomized controlled trial in rural Bangladesh. PLoS NeglTrop Dis 2019;13:e0007323.
[73] Luby SP, Rahman M, Arnold BF, Unicomb L, Ashraf S, Winch PJ, et al. Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial. Lancet Global Health 2018;6:e302–15.
[74] Nguyen VD, Sreenivasan N, Lam E, Ayers T, Kargbo D, Dafae F, et al. Cholera epidemic associated with consumption of unsafe drinking water and street-vended water–Eastern Freetown, Sierra Leone, 2012. Am J Trop Med Hygiene 2014;90:518–23.
[75] Centers for Disease C, Prevention. Cholera epidemic associated with raw vegetables–Lusaka, Zambia, 2003–2004. MMWR 2004;53:783–6.

Please cite this article as: S. P. Luby, J. Davis, R. R. Brown et al., Broad approaches to cholera control in Asia: Water, sanitation and handwashing, Vaccine, https://doi.org/10.1016/j.vaccine.2019.07.084

[76] Frauendorfer R, Liemberger R. The issues and challenges of reducing non-revenue water. Asian Development Bank; 2010.
[77] Segerfeldt F. Water for sale: How business and the market can resolve the world's water crisis. Washington: Cato Institute; 2005.
[78] Baietti A, van Ginneken M. Characteristics of well-performing public water utilities. Water Supply and Sanitation Working Notes: World Bank; 2006.
[79] Karkey A, Jombart T, Walker AW, Thompson CN, Torres A, Dongol S, et al. The ecological dynamics of fecal contamination and Salmonella Typhi and Salmonella Paratyphi A in Municipal Kathmandu Drinking Water. PLoS NeglTrop Dis 2016;10:e0004346.
[80] Galiani S, Gertler P, Schargrodsky E. Water for life: the impact of the privatization of water services on child mortality. J Polit Econ 2005;113:83–120.
[81] Hailu D, Osorio RG, Tsukada R. Privatization and renationalization: what went wrong in Bolivia's water sector? World Dev 2012;40:2564–77.
[82] Budds J, McGranahan G. Are the debates on water privatization missing the point? Experiences from Africa, Asia and Latin America. Environ Urbaniz 2003;15:87–114.
[83] Sima LC, Kelner-Levine E, Eckelman MJ, McCarty KM, Elimelech M. Water flows, energy demand, and market analysis of the informal water sector in Kisumu, Kenya. Ecol Econ J Int Soc Ecol Econ 2013;87:137–44.
[84] Patrick M, Steenland M, Dismer A, Pierre-Louis J, Murphy JL, Kahler A, et al. Assessment of drinking water sold from private sector kiosks in post-earthquake Port-au-Prince, Haiti. Am J Trop Med Hygiene 2017;97:84–91.
[85] Huttinger A, Brunson L, Moe CL, Roha K, Ngirimpuhwe P, Mfura L, et al. Small water enterprise in rural Rwanda: business development and year-one performance evaluation of nine water kiosks at health care facilities. Int J Environ Res Public Health 2017;14.
[86] Kingdom B, Liemberger R, Marin P. The challenge of reducing non-revenue water in developing countries–how the private sector can help: a look at performance-based service contracting. Washington, DC: The World Bank; 2006.
[87] Asian Development Bank. Asian water development outlook 2016: strengthening water security in Asia and the Pacific. Mandaluyong City, Philippines: Asian Development Bank; 2016.
[88] Grant SB, Saphores JD, Feldman DL, Hamilton AJ, Fletcher TD, Cook PL, et al. Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability. Science 2012;337:681–6.
[89] United Nations General Assembly. The human right to water and sanitation (A/RES/64/292). United Nations (28 July); 2010.
[90] Mutikanga HE, Sharma SK, Vairavamoorthy K. Assessment of apparent losses in urban water systems. Water Environ J 2011;25:327–35.
[91] Wang A, Hardy C, Rajasingham A, Martinsen A, Templin L, Kamwaga S, et al. Notes from the field: chlorination strategies for drinking water during a cholera epidemic—Tanzania, 2016. MMWR Morb Mortal Wkly Rep 2016;65:2.
[92] Lijadu K. A Kenyan nonprofit's innovative aerial water system just won it the world's largest humanitarian prize. Quartz Africa. New York: Atlantic Media; 2018.
[93] Brown R, Ashley R, Farrelly M. Political and professional agency entrapment: an agenda for urban water research. Water Resour Manage 2011;25:4037–50.
[94] Brown RR. Local institutional development and organizational change for advancing sustainable urban water futures. Environ Manage 2008;41:221–33.
[95] Wong THF, Brown RR. The water sensitive city: principles for practice. Water Sci Technol 2009;60:673–82.
[96] Mguni P, Herslund L, Jensen MB. Green infrastructure for flood-risk management in Dar es Salaam and Copenhagen: exploring the potential for transitions towards sustainable urban water management. Water Policy 2014;17:126–42.
[97] Verhoeven J, Meuleman A. Wetlands for wastewater treatment: opportunities and limitations. Ecol Eng 1999;12:5–12.
[98] Wong THF. Water sensitive urban design-the journey thus far. Austral J Water Resour 2006;10:213–22.
[99] World Bank. Evaluating the potential of container-based sanitation. Washington DC: World Bank; 2019.
[100] Huang X, Qu Y, Cid CA, Finke C, Hoffmann MR, Lim K, et al. Electrochemical disinfection of toilet wastewater using wastewater electrolysis cell. Water Res 2016;92:164–72.
[101] Tilmans S, Diaz-Hernandez A, Nyman E, Davis J. The potential for financing small-scale wastewater treatment through resource recovery: experience from Bocas del Toro, Panama. J Water Sanitation Hygiene Develop 2014;4:449–59.
[102] Dreibelbis R, Winch PJ, Leontsini E, Hulland KR, Ram PK, Unicomb L, et al. The integrated behavioural model for water, sanitation, and hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings. BMC Public Health 2013;13:1015.

Please cite this article as: S. P. Luby, J. Davis, R. R. Brown et al., Broad approaches to cholera control in Asia: Water, sanitation and handwashing, Vaccine, https://doi.org/10.1016/j.vaccine.2019.07.084