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Cost–benefit comparisons of investments in improved water supply and cholera vaccination programs

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ABSTRACT

This paper presents the first cost–benefit comparison of improved water supply investments and cholera vaccination programs. Specifically, we compare two water supply interventions – deep wells with public hand pumps and biosand filters (an in-house, point-of-use water treatment technology) – with two types of cholera immunization programs with new-generation vaccines – general community-based and targeted and school-based programs. In addition to these four stand-alone investments, we also analyze five combinations of water and vaccine interventions: (1) borehole + hand pump and community-based cholera vaccination, (2) borehole + hand pump and school-based cholera vaccination, (3) biosand filter and community-based cholera vaccination, (4) biosand filter and school-based cholera vaccination, and (5) biosand filter and borehole + hand pump. Using recent data applicable to developing country locations for parameters such as disease incidence, the effectiveness of vaccine and water supply interventions against diarrheal diseases, and the value of a statistical life, we construct cost–benefit models for evaluating these interventions. We then employ probabilistic sensitivity analysis to estimate a frequency distribution of benefit–cost ratios for all four interventions, given a wide variety of possible parameter combinations. Our results demonstrate that there are many plausible conditions in developing countries under which these interventions will be attractive, but that the two improved water supply interventions and the targeted cholera vaccination program are much more likely to yield attractive cost–benefit outcomes than a community-based vaccination program. We show that implementing community-based cholera vaccination programs after borehole + hand pump or biosand filters have already been installed will rarely be justified. This is especially true when the biosand filters are already in place, because these achieve substantial cholera risk reductions on their own. On the other hand, implementing school-based cholera vaccination programs after the installation of boreholes with hand pump is more likely to be economically attractive. Also, if policymakers were to first invest in cholera vaccinations, then subsequently investing in water interventions is still likely to yield positive economic outcomes. This is because point-of-use water treatment delivers health benefits other than reduced cholera, and deep boreholes + hand pumps often yield non-health benefits such as time savings.

However, cholera vaccination programs are much cheaper than the water supply interventions on a household basis. Donors and governments with limited budgets may thus determine that cholera vaccination programs are more equitable than water supply interventions because more people can receive benefits with a given budget. Practical considerations may also favor cholera vaccination programs in the densely crowded slums of South Asian and African cities where there may be insufficient space in housing units for some point-of-use technologies, and where non-networked water supply options are limited.

1. Introduction

In recent years international donors have advocated expanded vaccination programs to combat diseases such as cholera and typhoid [1]. Cost-effectiveness analysis is typically used by donors and international agencies to make the policy argument in favor of such expanded vaccination programs [2–4]. Vaccination programs are judged to be economically justified if their cost-effectiveness ratio is better than some predetermined benchmark, which usually corresponds to some fraction of average national GDP per capita. But such cost-effectiveness arguments have often failed to convince health policymakers in developing countries of the economic attractiveness of expanded vaccination campaigns. Policymakers typically want to understand how expanded vaccination programs compare to the outcomes resulting from public expenditures in other sectors, particularly water and sanitation investments [5].

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Comparisons of cost-effectiveness ratios for different health interventions, such as those of the recent Disease Control Priorities Project [6], only go part of the way toward addressing policymakers' concerns; cost–benefit analysis is still needed to compare (1) health interventions with projects in other sectors and (2) interventions with both health and non-health-related outcomes, such as improved water supply [7].

The use of cost–benefit analysis to evaluate water supply projects is much more common than for vaccination programs. The major international development banks have all published cost–benefit guidelines for appraising water supply projects and the methods for assigning monetary values to project outcomes are better developed than for vaccination programs [8–10]. Recently Hutton et al. [11] and Haller et al. [12] have published studies that present global assessments of the costs and benefits of water supply projects, using the latest findings on the effectiveness of different types of water supply and treatment interventions from Fewtrell et al. [13] and Clasen et al. [14]. Both studies report high benefit–cost ratios for such investments. However, these estimates are based on country or WHO regional averages for all key input parameters, and thus provide little insight into the relative attractiveness of investments for specific communities or circumstances.

This paper presents the first cost–benefit comparison of improved water supply investments and cholera vaccination programs. Specifically, we compare two improved water supply interventions – deep boreholes (wells) with public hand pumps and biosand filters (an in-household water treatment technology) – with two types of cholera vaccination programs using new-generation vaccines. Utilizing recent data on such parameters as disease incidence, intervention effectiveness against various diarrheal diseases, and the value of a statistical life, we build cost–benefit models that rely on probabilistic sensitivity analysis (or Monte Carlo analysis[1]) to generate a frequency distribution of benefit–cost ratios for all four interventions under a wide variety of parameter combinations [15,16]. We also consider the benefits and costs of five combinations of these four interventions: (1) borehole + hand pump and community-based cholera vaccination, (2) borehole + hand pump and school-based cholera vaccination, (3) biosand filter and community-based cholera vaccination, (4) biosand filter and school-based cholera vaccination, and (5) biosand filter and borehole + hand pump. Here we also estimate the net benefits of adding the second intervention if the first is already in place.

The next, Section 2 of the paper provides brief descriptions of the two improved water supply interventions and the two vaccination programs. Section 3 summarizes the methods and data used to estimate the costs and benefits of the four interventions and the probabilistic sensitivity analyses. In Section 4 we present the results, and in Section 5 we discuss their importance.

2. Background: description of the improved water supply interventions and cholera vaccination programs

2.1. Deep borehole with public hand pump

A deep borehole with a public hand pump is commonly recommended for improving water supply in many poor rural communities in Africa and South Asia. Many donors and national governments would consider this an appropriate technology when households are too poor to afford individual household connections and when deep groundwater is the best available water source [17]. The implementation of this technology often requires the use of drilling rigs in potentially remote rural locations. It will typically be necessary to transport drilling rigs on unpaved roads, and dry holes are not infrequent. Public hand pumps need to be built to withstand heavy daily use, and appropriate systems need to be put in place to assure long-term operation, such as creation of community water committees and/or availability of spare parts for routine repairs [18].

2.2. Biosand filters for "Point-of-use" household water treatment

Biosand filters are one of several possible technologies that households can use in their homes to remove a wide variety of contaminants, including bacteria and viruses, from their drinking and cooking water [19]. We selected the biosand filter for illustrative purposes; we do not argue that it is the "best" of the available POU technologies. Nonetheless, we do believe the biosand filter has important advantages over other POU technologies, especially in terms of convenience. Globally, boiling is the most prevalent and accepted means of treating water in the household. It is highly effective at removing pathogens if done for a sufficient length of time (15–20 min). However, it is today infrequently promoted because it can be expensive in terms of fuel use, is often inconvenient, and is in many places environmentally harmful in terms of indoor air pollution and as a contributor to deforestation. Boiled water is also prone to recontamination. Chlorination, though inexpensive, is also inconvenient and results in water that many individuals consider has a poor taste, as is shown by the difficulty of maintaining high usage and/or compliance rates among households even in field trials of relatively short duration [20].

The biosand filter has been demonstrated in the field to be safe and effective under a wide variety of conditions, and close to 100,000 biosand filters are now being used by households in numerous developing countries [13,14,21–23]. The biosand filter uses commonly available materials, is inexpensive to install, and is convenient and simple to use. Essentially all that is required is a concrete or plastic chamber, and sand, gravel and a small section of PVC pipe. Household members pour water into the top of the filter and allow time for the water to seep through the sand. Pathogens are removed by physical filtration and a biologically active slime layer ("Schmutzdecke") that forms at the top of the sand column.

2.3. Cholera vaccines

Cholera is caused by exposure to the bacterium *Vibrio cholerae 01 or 0139*, resulting in acute dehydration and sometimes death [24]. Cholera occurs in two types of situations. First, in some locations cholera will only be a problem in the aftermath of catastrophes or natural disasters when water and sanitation systems fail. Second, there are also large parts of South Asia and sub-Saharan Africa (such as Kolkata and the cholera belt in Mozambique) where cholera is endemic and outbreaks occur with some regularity. Although improvements in water and sanitation infrastructure and food hygiene could reduce the disease burden, another strategy to reduce cholera cases in the near term is vaccination with new-generation vaccines.

There are two internationally licensed oral cholera vaccines: the two-dose killed whole cell, recombinant B-subunit (WC/rBS) vaccine (Dukoral™), produced by the Dutch company, Crucell; and the single-dose live attenuated CVD 103Hgr (Orochol™), originally manufactured by Berna Biotech of Switzerland but no longer available. Field trials of Dukoral in Bangladesh and Peru indicated

[1] Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling from specified distributions of the random parameters in a model to compute outcomes. When using Monte Carlo analysis to do probabilistic sensitivity analysis, the basic steps of this approach are as follows: (1) specify probability distributions for all the important uncertain quantitative assumptions; (2) execute a trial by taking a random draw from the distribution of each parameter to arrive at a set of specific values for computing outcome values; (3) repeat the trial many times to produce a large number of realizations of the outcome values [16].

85–90% protection for 6 months followed by declining effectiveness with time and a cumulative 50% protection for 3 years [25–27]. In Mozambique, a case–control study following a Dukoral demonstration project found 78–84% vaccine effectiveness over 6 months of surveillance [28]. This vaccine, however, is expensive (at least US$4 per dose not including the delivery cost), and its cost effectiveness has been questioned [6].

A much cheaper modified version of the vaccine (containing only killed whole cells without the B subunit) is now produced in Vietnam and used in high-cholera risk areas in the Mekong delta and during floods and other emergency situations. This vaccine has been modified to comply with WHO standards and is being evaluated in a large Phase III clinical trial in Kolkata, India. Its protection is thought to be similar to that conferred by Dukoral [29,30]. It is anticipated that this vaccine will soon be manufactured by producers in India and other developing countries and will be available at a low price for public health programs in cholera-endemic countries. In addition, there is new epidemiological evidence that cholera vaccines provide increasing herd protection to non-vaccinated individuals as cholera vaccine coverage rises among the target population [31,32]. As a result of indirect protection and its lower cost, the cost effectiveness of the modified vaccine is much improved over that previously found for the Dukoral vaccine [33].

The cheap, Vietnamese-type vaccine could be offered to a community through a mass vaccination program targeting all age groups, or a vaccination program designed to reach specific age cohorts with high disease incidence. Cholera incidence tends to be higher among children than adults [34]. It is conceivable, therefore, that policymakers would choose to design cholera vaccination programs to target children rather than the entire population. In this analysis we assume that the target population has an average disease incidence so our results will be applicable for either a mass vaccination program of a population with this average incidence or for a smaller, school-based vaccination program in which the vaccinated children have this average cholera incidence and the rest of the population has a lower incidence rate. In practice, it may be difficult to vaccinate the most vulnerable children who are younger than school-age, but we assume that such children could be reached through a well-designed program.

The indirect protection achieved through targeted cholera vaccination programs would be lower than that achieved through larger, community-based programs. In our analysis we include the effect of coverage-dependent direct and indirect protection to show the influence of vaccination coverage on cost–benefit outcomes. Though the nature of the herd protection effect might well vary with differences in targeting, we assumed it would only vary with coverage due to lack of empirical evidence on the effect of targeting.

3. Methods and data

The unit of analysis for the cost–benefit calculations is the individual household; we compare the monthly costs of providing each of the four interventions (as well as combinations of them) to a typical household in a given community with the economic benefits that it would receive. For each of the interventions, we construct a simple benefit–cost model in which the monthly costs and benefits to a household are a function of approximately 25 different parameters. Many of the parameters are common across the four interventions. These cost–benefit calculations require that: (1) the initial capital costs of interventions be annualized (using a capital recovery factor) and added to the annual operation and maintenance costs; (2) total annual costs be presented on a monthly basis; (3) different types of benefits be calculated on a monthly basis and added together; (4) the total monthly benefits be divided by the total monthly costs to determine a benefit–cost ratio; (5) the total incremental net benefits be calculated when one of the four interventions is added to the second. We utilize these benefit–cost ratios and incremental net benefit indicators to judge the overall economic attractiveness of the various interventions.

Both the four stand-alone interventions and their five combinations span different periods of time, so one assumption of our comparison is that the shorter interventions (for example the vaccination efforts) would be repeated over the planning horizon of the longer life intervention. Another important assumption is that the investment funds come from sources with the same opportunity cost. For the five combinations of interventions, we calculate both the cost–benefit outcome of the total investment, as well as the incremental net benefits of the second interventions sequenced after (i.e., added to) the first intervention.

For each parameter in the cost–benefit models, we make three types of assumptions. First, we specify a range of plausible values based on professional judgment and our reading of the literature. Second, we assume parameter probability distributions that determine the likelihood that a particular value within the specified ranges will occur; specifically, we assume that the parameter values are uniformly distributed over the specified ranges. The use of uniform probability functions for all parameters is unusual in probabilistic sensitivity analysis. We chose uniform probability functions for the parameters in the cost–benefit models because our goal is to provide a global perspective on the economic comparison of water supply and cholera vaccination interventions, not to choose among interventions for a typical or representative location. Many of the parameters in our cost–benefit models, e.g., the disease incidence, case fatality rate, value of time savings, etc., will vary across locations. We do not know the global distribution of each of these parameters. This is actually not critical for our purposes because we are not trying to estimate the proportion of times globally that one of our interventions will be preferred to the other. Instead we try to identify the combinations of parameter values that would lead one to choose one intervention over the other—not the relative frequency of this occurrence globally.

Third, we specify whether there is a correlation between the given parameter and other parameters in the cost–benefit model. For example, the cost of drilling a borehole is likely to be higher in remote locations, which are also likely to be placed where case fatality rates (CFRs) for diarrhea would be higher due to longer distances to health clinics.[2]

We next conduct a probabilistic sensitivity analysis (using Monte Carlo simulation) in which the benefit–cost ratio is calculated for each of the four stand-alone interventions and five combinations of interventions for all of 10,000 different realizations of values for the parameters in the cost–benefit models. This yields a distribution of benefit–cost ratios for each of the interventions. We emphasize that this distribution of benefit–cost ratios for an intervention does not correspond to the distribution of actual situations in developing countries. Rather this resulting distribution of benefit–cost ratios is associated with the ranges of parameter values we believe to exist in developing countries. Since we have used our best professional judgment to select the ranges for these parameters, we do expect to find site-specific circumstances in developing countries with a similar range of benefit–cost ratios. We do not know, however, the precise frequency with which any specific combination of parameter values – or benefit–cost ratios – would arise.

[2] Using the Crystal Ball software add-in (Oracle Corporation), such correlations are easy to build into the Monte Carlo simulation routines in Excel. This software allows specification of both distribution assumptions for the uncertain parameters and cross parameter correlations.

Table 1
Parameters used in cost–benefit analysis models[a].

Symbol	Parameter description	Lower limit	Upper limit	Interventions[b]	Correlated parameters
C_c	Capital cost of borehole + hand pump ($)	$5,000	$8,000	B	C_p (0.5), w (−0.5)
	Cost of biosand filter + training + program ($)[c]	$60	$90	F	d (0.5)
	Cost per dose of cholera vaccine ($)[d]	$0.7	$3.3	C	w (−0.5)
C_p	Program (software) cost–capacity building and management ($/borehole)	$2,000	$5,000	B	w (−0.5)
C_o	O&M expenditures, repairs ($/year)	$50	$150	B	C_C (0.5)
C_m	Management costs (non-pecuniary)—village + program ($/year)	$200	$800	B	
C_s	Transportation of filters ($)[c]	$15	$35	F	CFR_d (0.5), I (0.5), w (−0.5)
T_t	Training time (hr/household)[c]	4	12	F	
T_o	Operator's maintenance time (hr/(household-yr))[c]	1	3	F	
T_m	Maintenance time for filters (min/wash)[c]	10	20	F	
m	Number of washes per year[c]	2	10	F	
B	Days before *Schmutzdecke* regrowth[c]	3	7	F	
T_v	Time to acquire vaccines (hr/dose)[e]	0.25	1.25	C	Cov (0.5)
D	Borehole duration (years)	10	20	B	C_p (0.5)
	Filter lifespan (years)[c]	6	10	F	
	Vaccine duration (years)[d]	2	4	C	
r	Real (net of inflation) discount rate (%)	3%	6%	B, F, C	
N	# Households served	30	90	B, F	T_1 (0.5)
S	Household size	4	6	B, F, C	
T_0	Status quo collection time (hr/20 L)—traditional source	0.1	1.9	B	
T_1	Collection time per liter (hr/20 L)—improved	0.1	0.5	B	n (0.5)
w	Market wage for unskilled labor ($/day)	$0.50	$2.00	B, F, C	
v_t	Value of time savings/market wage for unskilled labor[e]	10%	50%	B, F, C	
a	Ratio of aesthetic and lifestyle benefits to time savings benefits	0%	50%	B	
I_d	Diarrheal incidence (cases/(person-yr))[f]	0.4	1.4	B, F	C_C (0.5), C_p (0.5), C_s (0.5)
I_c	Cholera incidence–all (cases/(1000 person-yr))[d]	0.1	4	B, F, C	C_C (0.5), w (−0.5), I_{C2} (0.7)
$I_{c,child}$	Cholera incidence–children only (cases/(1000 person-yr))[d]	0.1	9	C2	C_C (0.5), w (−0.5), I_{C1} (0.7)
E	% Reduction in diarrhea due to borehole project[g]	10%	40%	B	
	% Reduction in diarrhea due to filter project[g]	20%	60%	F	
	% Reduction in cholera due to cholera vaccination[d]	Function of Cov		C	
COI_d	Cost of illness of diarrhea ($/case)	$2	$10	B, F	w (0.5)
COI_c	Cost of illness of cholera ($/case)[d]	$15	$85	C	w (0.5)
CFR_d	Diarrhea case fatality rate (%)[f]	0.04%	0.12%	B, F	C_C (0.5), C_p (0.5)
CFR_c	Cholera case fatality rate (%)[h]	0.5%	3.0%	C	CFR_d (0.7)
VSL	Value of a statistical life ($)[i]	$10,000	$50,000	B, F, C	w (0.7)
H	Percentage of aesthetic benefits that are actually health-related	0%	50%	B	
δ	Rate of disuse (% of filters per year)[c]	1%	5%	F	T_o (−0.5), T_t (−0.5)
Cov	Coverage achieved through community-based vaccination (%)	50%	80%	C1	
	Coverage achieved through school-based vaccination (%)	10%	20%	C2	
γ	Extent of herd protection from cholera vaccination (% of Matlab effect)	60%	100%	C1, C2	

[a] Our uncertainty analysis does not purport to use the real probability distributions associated with these parameters, but instead is aimed at assessing the range of possible situations in poor developing countries; therefore we use uniform distributions of parameters.
[b] B, borehole + hand pump; F, biosand filter; C, both cholera programs; C1, community-based cholera program; C2, school-based cholera program.
[c] Cost of filter obtained from Samaritan's Purse [personnal communication], Stauber et al. [21,40] and Kaiser et al. [23].
[d] From Jeuland et al. [33]; Poulos et al. [44].
[e] From Jeuland et al. [43].
[f] WHO [35]. Revised Global Burden of Disease (GBD) 2002 Estimates. Available at: http://www.who.int/healthinfo/bodgbd2002revised/en/index.html. Diarrhea incidence in developing country sub-regions ranges from 0.6 to 1.29 case per capita per year (mean ∼0.9), CFR ranges from 0.02 to 0.09, and is ∼0.08% in Africa.
[g] From Fewtrell et al. [13] and Clasen et al. [14].
[h] From WHO [24].
[i] From Maskery et al. [36].

We believe there are three reasons this methodological approach is conceptually appealing. First, we specify ranges for all parameters in the cost–benefit model, not just a few selected parameters, and can identify which parameters have the largest effect on the benefit–cost ratio. Second, probabilistic sensitivity analysis allows us to incorporate associations between selected parameters, and thus reduce the occurrence of improbable combinations of parameter values. Third, we believe that probability distributions of benefit–cost ratios for the interventions are more useful than point estimates because they allow us to focus on (1) the range of cost–benefit outcomes that seem plausible and (2) the proportion of parameter combinations that result in benefit–cost ratios in which one intervention is preferred to others.

In the remainder of this section of the paper we briefly describe the cost–benefit calculations and parameter assumptions (summarized in Table 1) for the four stand-alone interventions: (1) deep borehole with public hand pump, (2) biosand filter and (3) community-based and (4) school-based cholera vaccination programs.[3]

3.1. Deep borehole plus public hand pump

3.1.1. Costs

The economic costs of the borehole and hand pump intervention are composed of the initial capital cost of installation and its routine, ongoing costs. The latter includes both operation and main-

[3] A more detailed presentation of the equations used to calculate these household costs and benefits is included in the online Appendix.

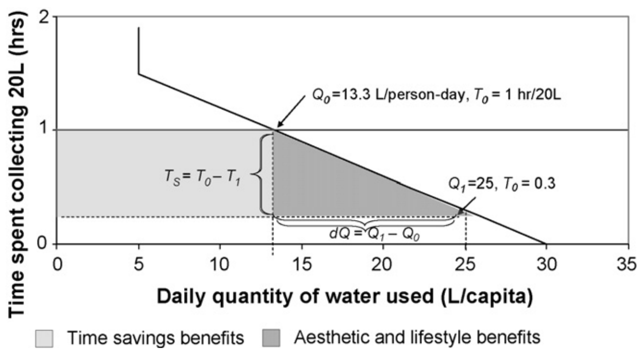

Fig. 1. Demand curve for water as a function of collection time, showing different types of non-health benefits from the borehole + hand pump intervention.

tenance costs and the economic costs (in time and/or salaries) of the community management system. The initial investment costs include capital and installation costs, and the overhead associated with implementing a rural water supply program [17].

Over the past decade, increasing numbers of Chinese contractors have become active in many countries in Africa. The majority of their work has been in road and other construction projects, but increasingly they also bid for drilling contracts from national rural water supply agencies. Chinese contractors typically bring Chinese-made drilling rigs and their own drilling teams. As a result of the increased competition for drilling contracts, often from these Chinese firms, prices of borehole drilling and hand pump installation have fallen dramatically in Africa. The price per borehole has dropped 50% in countries where small to medium sized drilling contracts are regularly awarded—from about US$12,000 a decade ago to about US$6000 today. This large drop in the real prices of boreholes has changed the economic landscape of rural water programs in Africa, and we assume that these cost savings will soon be available in a wide set of developing countries [17].

We thus use a capital cost range for a deep borehole plus hand pump of US$5000–8000. Program overhead which includes capacity building and "software" costs for a large national rural water supply program are estimated to range from US$2000 to 5000, for a total of US$7000–13,000. We determine the capital recovery factor based on a real (i.e., net of inflation) interest rate (range 3–6%) and the life of the capital (range 10–20 years). Recurrent expenditures of spare parts and minor repairs are assumed to fall between US$50 and 150 per year. We also assume for our calculations that the real resource costs of village labor and management range from US$200 to 800 per year. To determine the cost per household, we assume that 30–90 households share the borehole, and that the average household size is 4–6 people. It is thus possible for anywhere from 120 to 540 people to share one borehole.

3.1.2. Benefits

The economic benefits of this improved water supply intervention have three main components (Fig. 1): (1) the value of any time savings that result from the installation of the new water source; (2) the monetary value of the health benefits (avoided all-cause diarrhea and cholera disease); (3) the value of lifestyle, aesthetic benefits from increased use of higher quality and increased quantity of water obtained from the new source [17].

The economic value of time savings to households will vary greatly depending on local labor market conditions and economic opportunities. We calculate the time savings benefits by multiplying (1) an estimate of the time savings associated with the initial quantity of water consumed; (2) an estimate of the market wage for unskilled labor (ranging from $0.5 to $2/day); (3) a parameter less than one to denote the ratio of the value of time spent collecting water to the market wage (ranging from 0.1 to 0.5). Our estimates of the time savings assume that the time required to collect water from the traditional source varies from 0.1 to 1.9 h/20 L water, and the collection time from the improved source varies from 0.1 to 0.5 h/20 L water. Thus, it is possible in the model for there to be positive time costs to households using the new source instead of time savings (if collection time from the improved source exceeds that from the traditional source). Such a situation might arise in places where alternative water sources are plentiful and convenient to use.

We disaggregate the health benefits for this intervention into four components: (1) the economic benefits of reduced morbidity due to reduction in cholera risk; (2) the economic benefits of reduced morbidity due to reduction in other (non-cholera) diarrhea risk; (3) the economic benefits of reduced mortality due to reduction in cholera risk; (4) the economic benefits of reduced mortality due to reduction in other (non-cholera) diarrhea risk. We estimate each component separately. This allows us to directly compare (a) the cholera reduction benefits of the vaccination programs and the two water interventions and (b) the health benefits due to cholera reduction and to other non-cholera diarrhea reduction.

We assume that the reduction in risk of cholera and all-cause diarrhea infection due to the improved water source is similar (ranging from 10 to 40%) [13]. We then calculate the avoided cases of all-cause diarrhea and cholera, and value these according to their different costs of illness and mortality risks. In general, Cholera has higher cost-of-illness (COI) and higher case fatality rates (CFRs) but lower incidence than all-cause diarrhea. The ranges of cholera cost-of-illness, cholera CFRs, and cholera incidence rates are described in more detail in our discussion of the benefits of cholera vaccination programs (Section 3.3).

For all-cause diarrhea, we assume the baseline incidence is 0.4–1.4 cases per person per year [35]. To obtain an estimate of the diarrhea mortality risk reduction, we then multiply this by the diarrhea CFR (ranging from 0.04 to 0.12%) [35]. We value this mortality risk reduction by multiplying it by an estimate of the value of a statistical life (or VSL, ranging from US$10,000 to 50,000) [36]. The COI for an episode of diarrhea includes productivity losses for both patients and caretakers and diagnostic and treatment costs borne by both private households and public sector health care providers (ranging from US$2 to 10). To determine the morbidity benefits, we multiply the COI for an episode of diarrhea by the disease risk reduction.

The final component of the benefits from the water supply intervention is the consumer surplus on the increased water use that occurs because of the fall in the effective price of water due to the more convenient, new water source. We think of these as the lifestyle and aesthetic benefits the household obtains from increased water use, although there will probably be health benefits from this increased water use as well. We estimate these lifestyle and aesthetic benefits as a proportion (which we vary from 0 to 50%) of the time savings benefits [10]. Since a portion of these aesthetic and lifestyle benefits may actually be health-related, we also apply a downward correction (expressed as an uncertain parameter) – assuming that a portion (also ranging from 0 to 50%) of the aesthetic and lifestyle benefits is actually health benefits – to avoid this possibility of double-counting.[4]

[4] An alternative approach to estimating the economic benefits of an improved water supply (or a vaccination program) would be to use stated preference techniques to measure households' willingness to pay for the intervention [37–39]. There are two main reasons we decided not to base our estimates of economic benefits on evidence from stated preference surveys. First, our objective was to show the range of possible economic outcomes, and how these changed with different location-specific parameters. There has not yet been a meta-analysis of the contingent valuation studies of either improved water supplies or private demand for cholera vaccines in developing countries, so we did not have access to an agreed-

3.2. Biosand filter

3.2.1. Costs

This intervention requires inclusion of three types of costs: (a) implementation costs, composed of filter production and transportation cost and program software costs; (b) the cost of the community maintenance program, which we count as the value of the community manager's time; (c) the value of time spent by households participating in the program, in training and filter cleaning time [17]. We use a range of US$60–90 per biosand filter for the manufacturing and software costs, and US$15–35 for transportation and delivery costs of the filter and sand. We assume the time spent in training and health promotion activities can vary from 4 to 12 hr. The time required for filter cleaning is 10–20 min; this is done 2–10 times per year. The frequency depends on the quality of the surface water source. The community manager is estimated to spend 1–3 hr per year on each filter. We assume that the average filter lasts 6–10 years. The value of the household's opportunity costs of time is the time spent times the value per hour, which we value in a similar manner to the time savings from the borehole plus public hand pump intervention.

3.2.2. Benefits

Our estimates of the economic benefits of the biosand filter are based solely on the improved health outcomes from the intervention. Unlike the rural water supply, the biosand filter intervention provides no time savings benefits to the household, and it therefore will not likely lead to increased consumption of water (with associated aesthetic and lifestyle benefits) [17]. We assume a 20–60% reduction in diarrhea (and cholera) incidence from the biosand filter intervention [13,14,21]. We calculate the mortality and morbidity reductions due to the intervention, and assign monetary values in the same manner as used for the rural water supply, with two additional adjustments.

The first adjustment is the inclusion of a parameter that accounts for the annual rate of disuse of filters. We estimate that filter usage declines at a constant 1–5% rate each year. Preliminary findings from a field trial in the Dominican Republic show that 85–90% of filters remain in use after 8 years in the field [40]. The second adjustment reflects the lost health benefits just after the necessary routine cleaning of the filters, before there is regrowth of the *Schmutzdecke* and resumption of biological degradation of contaminants. We consider that there are no health benefits for the 3–7 days required for regrowth of the *Schmutzdecke* following cleaning.

3.3. Cholera vaccination

3.3.1. Costs

The economic costs of cholera vaccination with the inexpensive Vietnamese vaccine include the cost of its production and delivery, and the private time costs associated with vaccination, i.e., the value of the time households spend acquiring the two required doses of the vaccine. We assume that the production and delivery cost per vaccinated individual for each dose is $0.7–3.3, and that individuals being vaccinated spend 0.25–1.25 hr travelling and queuing for each dose, based on evidence from several recent cholera vaccination trials [33,41–43]. Since two doses are required, we assume that the production and delivery cost per vaccinated individual is $1.4–6.6, and that individuals being vaccinated spend 0.5–2.5 hr travelling and queuing for both doses.

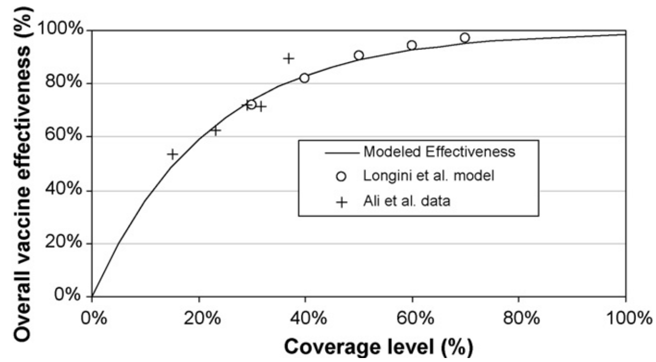

Fig. 2. Model of overall cholera vaccine effectiveness as a function of vaccination coverage rate and comparison with results from epidemiological studies [31,32], adopted from [33].

3.3.2. Benefits

As with the biosand filters, the economic benefits from cholera vaccination programs result solely from reduced morbidity and mortality, and are calculated similarly to those described for the rural water intervention, except that they only apply to the burden of disease from cholera infection (and thus do not include all-cause diarrhea). We include the effect of indirect herd protection (i.e., protection of unvaccinated individuals) and increased total protection (i.e., enhanced protection of vaccinated individuals) measured in recent epidemiological studies, as shown in Fig. 2 [31–33].[5]

Field studies of cholera incidence in endemic areas have shown that disease rates among children are higher than in the population as a whole [34,41,44]. This has led policymakers to separately consider community and school-based vaccination programs. We use the results from these studies to establish the parameter range for cholera incidence among children (0.1–10 cases per 1000 children per year) and adults (0.1–4 cases per 1000 people per year), and assume that the CFR for cholera is 0.5–3.0%, based on evidence from the WHO [24]. We also use field data to establish the range for cholera COI (US$15–85) [45]. The range of coverage rates in the overall population that might be achieved in the two vaccination programs are assumed to be 10–20% and 50–80% for school-based and community-based programs, respectively. The duration of the effectiveness of the vaccine is assumed to fall within the range of 2–4 years.

4. Results

4.1. The four stand-alone interventions

Table 2 presents a summary of the cost–benefit calculations, and Fig. 3 presents the frequency distribution of benefit–cost ratios for the four interventions from the probabilistic sensitivity analysis (i.e., the results of the Monte Carlo simulations). The ranges shown in Table 2 correspond to the 90% confidence intervals from the simulations, which we believe to be plausible outcomes in developing country locations. There is clearly a wide range of benefit–cost ratio outcomes for each of the interventions. Nonetheless, it is clear from these simulations that the majority of realizations for the borehole + hand pump (84%), biosand filters (90%), and school-based

upon valuation function based on data from contingent valuation studies that we could use to estimate economic benefits in a wide variety of locations in developing countries. Second, many economists are skeptical about the answers people give to hypothetical questions in contingent valuation surveys. Our own view is that carefully designed surveys can often yield "pretty good results," and that estimates of economic benefits from contingent valuation surveys are useful for policy analysis if the surveys are done well. However, this debate about the reliability and accuracy of stated preference surveys was not our focus in this paper.

[5] The functional relationship used to model the effect of indirect protection is described in more detail in the Appendix.

Table 2
Comparison of the costs and benefits for the four separate and five combined interventions[a] (US$/(household-month)).

Cost/benefit category	Single intervention							
	Borehole + hand pump		Biosand filters		Community-based cholera vaccination		School-based cholera vaccination	
	Low	High	Low	High	Low	High	Low	High
Benefits								
Time savings	−1.00	5.72	0	0	0	0	0	0
Quantity/aesthetic	0.00	3.29	0	0	0	0	0	0
Morbidity	0.15	1.27	0.23	1.60	0.00	0.07	0.00	0.04
Mortality	0.51	5.99	0.74	7.54	0.04	0.75	0.03	0.50
Total benefits	1.54	12.53	1.07	8.86	0.04	0.80	0.04	0.53
Costs								
Capital and program costs	0.76	2.63	0.94	1.76	0.15	0.85	0.03	0.20
Maintenance costs	0.40	1.71	0.02	0.10	0	0	0	0
Household time costs	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00
Total costs	1.32	4.43	1.00	1.82	0.15	0.86	0.03	0.20
Net benefits	−1.53	10.10	−0.28	7.50	−0.61	0.44	−0.08	0.43
BC ratio	0.53	6.44	0.81	6.61	0.11	2.79	0.40	7.67
Net benefits at average parameter values	4.63		2.57		−0.04		0.15	
BC ratio at average parameter values	3.17		2.93		0.90		2.64	
Simulations BCR ≤1 (%)	16%		10%		69%		23%	
Simulations BCR 1–3 (%)	49%		53%		27%		46%	
Simulations BCR >3 (%)	35%		37%		4%		31%	

	Combined interventions				
	Borehole + community vaccination	Borehole + school vaccination	Biosand filter + community vaccination	Biosand filter + school vaccination	Borehole + biosand filter
Simulations BCR ≤1 (%)	16%	13%	15%	10%	8%
Simulations BCR 1–3 (%)	57%	52%	61%	56%	56%
Simulations BCR >3 (%)	28%	35%	24%	34%	35%

[a] Ranges shown correspond to the 90% confidence intervals of calculations given parameter assumptions.

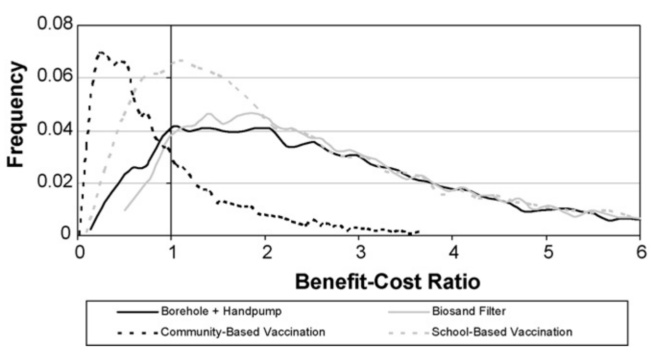

Fig. 3. Frequency distributions of benefit–cost ratios for the four compared interventions.

vaccination programs (77%) yield favorable benefit–cost ratios (>1). Of these, the biosand filter has the fewest economically unattractive outcomes (Fig. 3). The community-based vaccination program does not fare as well; only 31% of simulations yield a benefit–cost ratio greater than 1 for this intervention (Table 2). The proportion of simulation outcomes that look very attractive (i.e., ratio >3) is much lower for community vaccination (4%), compared to borehole + hand pump (35%), biosand filters (37%), and school-based vaccination (31%).[6]

[6] A benefit–cost ratio of 3 has no special significance. We use this admittedly arbitrary numerical value of the benefit–cost ratio simply as a convenient marker to separate very attractive outcomes from the simulation from somewhat less attractive outcomes.

Turning to the composition of the costs and benefits in the four stand-alone interventions, we note that a substantial portion of the benefits from the borehole + hand pump intervention do not arise from improvements in health; indeed, in many simulations the non-health benefits (time savings and aesthetic benefits) are greater than the health benefits. In communities with very poor access to water, these non-health benefits will be especially high.

In contrast, the other three interventions deliver only health benefits. For the biosand filter and the two cholera vaccination programs, the majority of these health benefits stem from reduced mortality. The biosand filter, which reduces all-cause diarrhea (including cholera), achieves the highest health benefits because it is more effective in reducing disease than the borehole intervention, and is not focused on a single disease, like the cholera vaccination programs. If the borehole + hand pump and biosand filter interventions are assumed to have no effect on cholera incidence, which seems implausible, the benefit–cost ratios are only slightly reduced (by 2 and 4%, respectively).

The borehole + hand pump is the most costly of the four interventions, requiring an investment of US$1.3–4.4 per household per month, compared with US$1.0–1.8 per household per month for the biosand filter, US$0.15–0.9 per household per month for community-based cholera vaccination, and US$0.03–0.2 per household per month for the school-based vaccination. The time costs associated with training and management of these programs are all very low compared with the capital and program costs, and only the borehole + hand pump intervention requires significant expenditures for maintenance. Ensuring sustained community-based or external support for that intervention is thus important to its success. However, because the duration of cholera vaccine protection is estimated to be 2–4 years, these would also require institutional

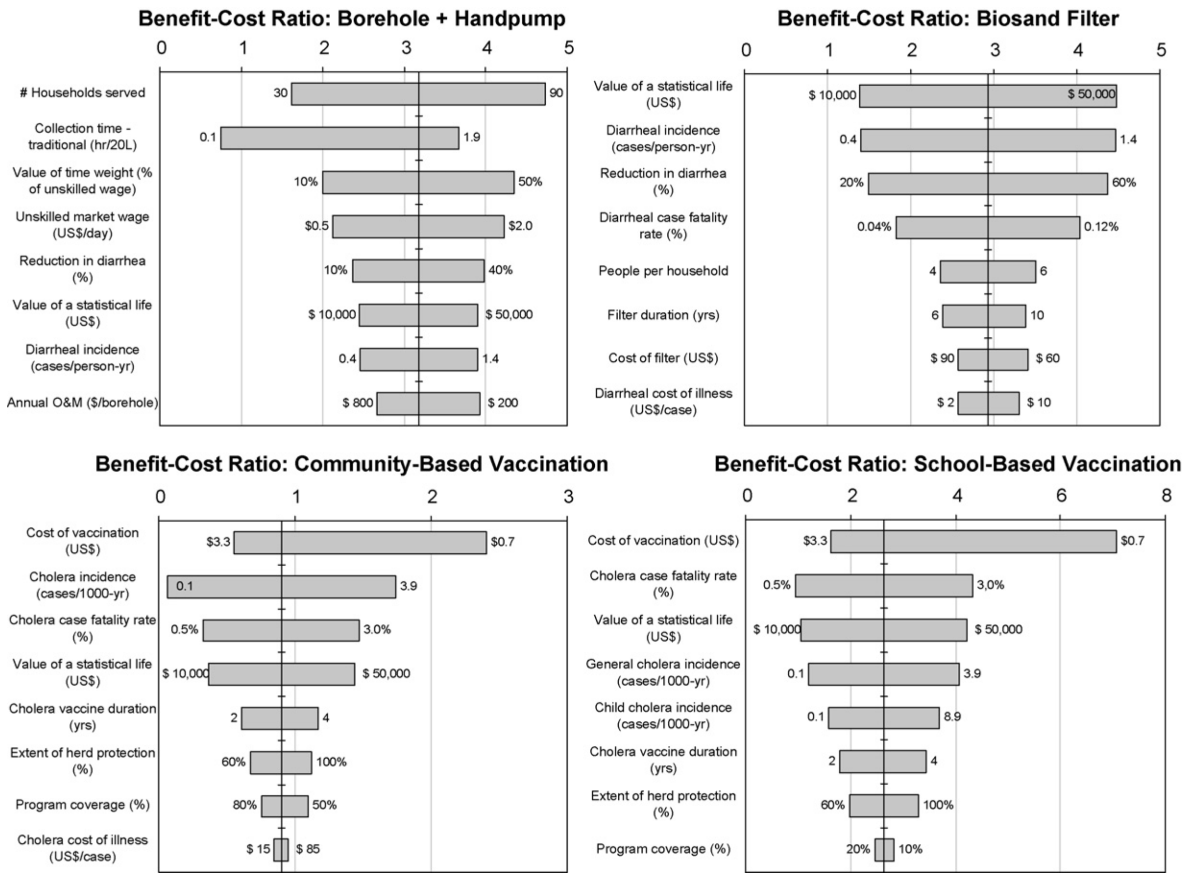

Fig. 4. Tornado diagrams showing sensitivity of benefit–cost ratios to model parameters, for the four stand-alone interventions.

support if individuals are to be re-vaccinated as vaccine efficacy expires.

The difference between the distributions of benefit–cost ratios for the two cholera vaccination programs stems from two factors: the incidence of the targeted age group(s), and the nature of the herd protection effect. With community-based vaccination, substantial resources are devoted to protecting some people who are at relatively low risk of being infected with cholera. Because children typically have a higher incidence of cholera than the general population, targeted school-based programs are more effective in reaching the high-incidence population. Also, herd protection increases very quickly with coverage at low coverage rates (Fig. 2); thus small, targeted programs lead to large benefits (in both the vaccinated and unvaccinated population) at relatively low cost. As coverage increases, the marginal benefit of added herd protection decreases [41].

Fig. 4 presents four "tornado" diagrams that show which parameters have the largest effect on the benefit–cost ratios for each of the four stand-alone interventions (a one-way sensitivity analysis). For the borehole + hand pump, three of the top five parameters are related to the value of time savings (i.e., the time spent collecting water from the traditional source, the ratio of the value of time savings to the market wage, and the market wage for unskilled labor), reflecting the importance of time savings component of the economic benefits. Also important are the number of households served by the borehole (since reaching more households leads to higher benefits) and the percentage reduction in diarrhea incidence.

For the biosand filter, two of the most important parameters are directly related to the mortality reduction benefit [the "value of statistical life (VSL) and the case fatality rate (CFR) for diarrhea], and two others are related to the health risk reduction (the effectiveness of the filter and diarrheal incidence). These four parameters have much more influence on the benefit–cost outcome for this intervention than the others shown in Fig. 4. The initial costs associated with both the biosand filter and borehole + hand pump interventions play a less important role in the cost–benefit outcomes because these interventions have a long duration.

For both vaccination programs, the most important parameters are the cost of vaccination, the cholera incidence rate, the VSL, and the cholera CFR. The latter two have a large effect on the benefit–cost ratio of these programs because mortality reduction constitutes a much larger proportion of the total benefits than morbidity reduction. Less important parameters for cost–benefit outcomes of vaccination programs are the vaccine duration and the extent of herd protection.

4.2. The five combinations of interventions

Table 2 also presents cost–benefit results for the five combinations of interventions. Many of these have benefit–cost ratios greater than one. However, because these investments can be made sequentially (i.e., not simultaneously), one needs to examine the marginal effect of adding one investment (intervention) assuming the other has already been made. Fig. 5a–c presents the distribution of incremental (marginal) net benefit outcomes for the five combined interventions. This incremental net benefit is calculated by estimating the benefits obtained from the second intervention minus its costs assuming the first intervention has been carried out.

As Fig. 5a (top panel) shows, implementing community-based cholera vaccination programs after a borehole + hand pump or biosand filters have already been installed will rarely be justified.

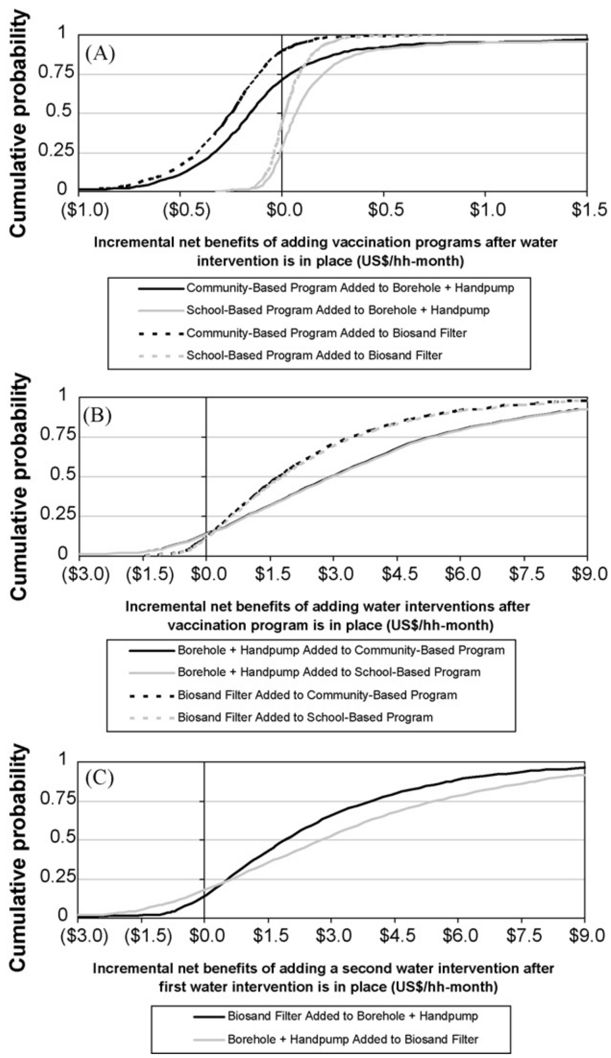

Fig. 5. Cumulative frequency distributions of the incremental net benefits of adding (A) cholera vaccination programs to the two water supply interventions, (B) water interventions to the cholera vaccination programs, and (C) one water intervention to a second water intervention. All realizations to the left of the *y*-axis indicate that the added interventions would not pass a benefit–cost test.

This is especially true when community-based vaccination is added to biosand filters, which achieve substantial cholera risk reductions on their own (about 90% of model realizations result in incremental net benefits <0). On the other hand, implementing school-based cholera vaccination programs after the installation of boreholes with hand pumps is much more likely to be attractive economically (70% of our model realizations result in incremental net benefits >0). Adding the school-based cholera vaccination program to the biosand filters is less attractive, resulting in positive economic incremental net benefits for just over half of the simulations.

In contrast, Fig. 5b (middle panel) shows that if policymakers were first to make a unilateral decision to invest in one of the cholera vaccination programs, then subsequently investing in either boreholes + hand pumps or biosand filters is likely to yield positive economic outcomes (in about 85% of our model realizations incremental net benefits were positive). For the borehole + hand pump, this is because substantial time savings and aesthetic benefits can still be gained from the investment. In addition, for both the biosand filter and the borehole + hand pump interventions, the majority of health benefits actually result from the reduced risk of all-cause (not cholera-specific) diarrhea morbidity and mortality.

Finally, Fig. 5c (lower panel) shows that the incremental net benefits of a second water intervention added to a first water intervention will often be positive. In about 80% of the model simulations, it is economically attractive to add the borehole + hand pump intervention after biosand filters have already been installed. Adding biosand filters on top of the borehole + hand pump intervention is attractive in 85% of the simulations. The synergies between water interventions stem from the fact that both of them only partly reduce diarrheal disease, and the borehole + hand pump delivers additional, time savings and aesthetic benefits.

The results of our probabilistic sensitivity analyses confirm that the sequencing of water supply and cholera vaccination interventions needs to be considered carefully. The vaccination options have fewer parameter combinations that provide positive incremental net benefits if an investment in either of the water interventions has already been made. To illustrate this point more fully, Fig. 6a–d displays the simulation outcomes for the biosand filter and the two cholera interventions. For parameter combinations that depict plausible conditions in different developing country locations (communities), the four scatter diagrams show:

(1) the benefit–cost ratio from investing in the biosand filters or community-based cholera vaccination intervention separately (Fig. 6a);
(2) the benefit–cost ratio from investing in the biosand filters or school-based cholera vaccination intervention separately (Fig. 6b);
(3) the incremental net benefit from investing in community-based cholera vaccination after biosand filters are installed, versus the benefit–cost ratio of the biosand sand filter as a stand-alone intervention (Fig. 6c);
(4) the incremental net benefit from investing in school-based cholera vaccination after biosand filters are installed, versus the benefit–cost ratio of the biosand sand filter as a stand-alone intervention (Fig. 6d).

The scatter plots in Fig. 6a–d display the simulation outcomes in four quadrants. In Fig. 6a and b, the top right quadrant shows the outcomes for which both interventions had benefit–cost ratios greater than one. In Fig. 6c and d, the top right quadrant shows outcomes for which the benefit–cost ratio of the biosand filter is positive when this intervention is done first, and the incremental net benefit of the vaccination program is positive when it is added to the biosand filter. Similarly, in Fig. 6a and b, the bottom left quadrant shows the outcomes for which both interventions had benefit–cost ratios less than one; in Fig. 6c and d the bottom left quadrant shows the outcomes for which the benefit–cost ratio of the biosand filter is negative and the incremental net benefit of the vaccination program is negative when it is added to the biosand filter.

As shown in Fig. 6a and b, there are very few parameters combinations in which either cholera vaccination program has a benefit–cost ratio greater than 1, and the benefit–cost ratio for the biosand filter is less than 1 (only 2% of the parameter combinations for community vaccination programs and 6% for school-based vaccination programs). There are many more parameter combinations for which the biosand filter is attractive, and the cholera vaccination programs are not (61% for community vaccination programs and 19% for school-based vaccination programs).

Fig. 6b also shows that there are many parameter combinations for which both the school-based cholera vaccination and the biosand filter interventions would have benefit–cost ratios greater than 1 if either was implemented as a stand-alone investment (71%). In some of these cases the school-based vaccination programs have a higher benefit–cost ratio than the biosand filter intervention. In other cases the biosand filter has a higher benefit–cost ratio than the school-based vaccination program.

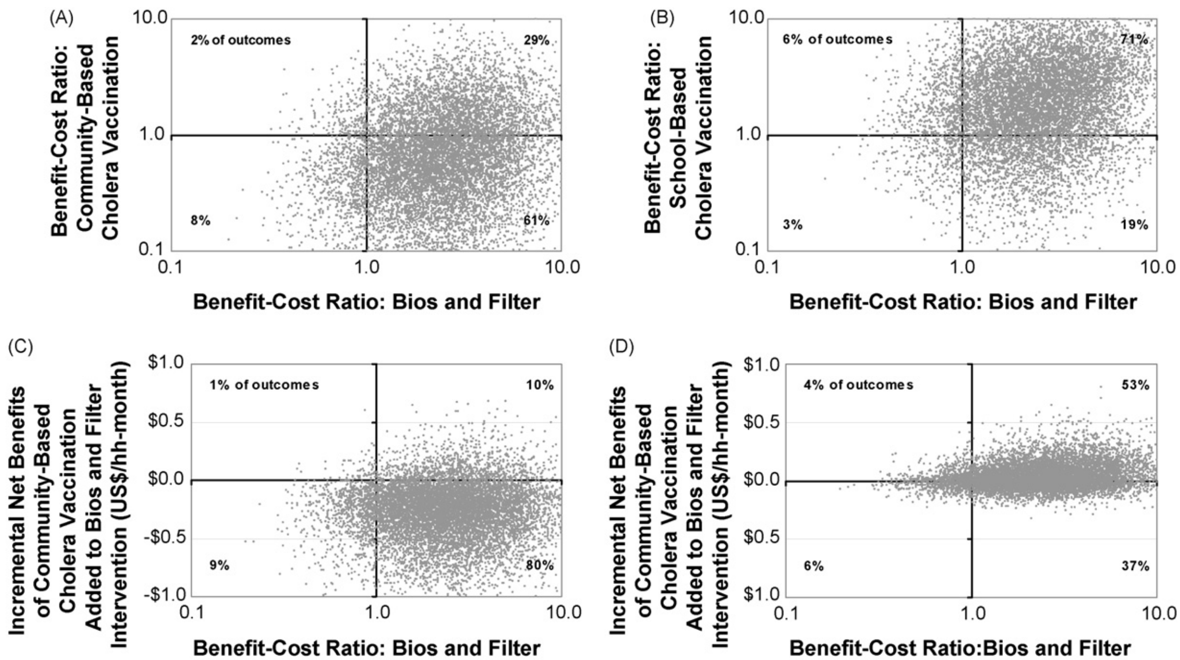

Fig. 6. Scatter diagrams comparing cholera vaccination and biosand filter programs: Simulation outcomes for (A) interventions considered separately (community-based vaccination), (B) interventions considered separately (school-based vaccination), (C) the incremental net benefits of a community-based cholera vaccination program added to a biosand filter intervention, and (D) the incremental net benefits of a school-based cholera vaccination program added to a biosand filter intervention.

Fig. 6c shows that the incremental net benefit of adding a community vaccination programs after biosand filters have been installed is rarely positive (in only 10% of the simulations). In contrast, Fig. 6d illustrates that there are many parameter combinations for which the incremental net benefit of adding a school-based vaccination program after biosand filters have been installed is positive (57%). However, the total percentage of parameter combinations with economically attractive outcomes for school-based vaccination programs drops from 77% when these are carried out as a stand-alone intervention (top two quadrants of Fig. 6b) to 57% when they are added to the biosand filters (top two quadrants of Fig. 6d).

5. Discussion

The findings presented in this paper lend support to the preference DeRoeck et al. [5] found among health policymakers in developing countries for improved water supply investments over vaccination programs. There are several reasons that the improved water supply interventions are generally more attractive than cholera vaccination programs. First, deep boreholes with public hand pumps provide time savings and aesthetic benefits in addition to health benefits. Second, both deep boreholes and biosand filters provide benefits for a longer time than cholera vaccination. Third, both water supply interventions protect household members against infection by multiple pathogens, not just *V. cholerae 01 or 0139*. Fourth, the apparent attractiveness of targeted vaccination programs is complicated in practice by the fact that vulnerable populations (high-incidence groups) may not be easy to identify, and studies to estimate the burden of disease are expensive.

Our cost–benefit calculations for deep boreholes with hand pumps and the biosand filter assume that these improved water supply interventions reduce cholera incidence just as they reduce all-cause diarrhea incidence. Biosand filters may reduce the risk of cholera infection even more effectively than they do all-cause diarrhea because high exposures to the pathogen are necessary for transmission. However, even if these water supply interventions do not protect individuals against cholera, our cost–benefit results for the stand-alone interventions do not change substantially.

For cholera vaccination programs to be more economically attractive than the water supply interventions, at least two critical conditions must be satisfied. First, cholera incidence has to be high (which explains the better performance of programs targeted to high-incidence population subgroups). Second, the cost per vaccinated individual has to be low. This economic calculus of vaccination programs is easy to understand. Because the costs per vaccinated person are multiplied by the number of people vaccinated in the target population, the total costs of a one-time vaccination program do not depend on disease incidence. On the benefit side of the ledger, increased incidence acts as a multiplier on the benefit–cost ratio: as incidence increases, the number of cases avoided increases without a corresponding increase in costs. Because disease incidence is expressed as a ratio, an increase in annual incidence from, for example 1-in-1000 to 20-in-a-1000 increases the benefit–cost ratio of a vaccination program 20 times. Because of the multiplier effect of incidence on the benefit–cost ratio, small programs targeted to particular subgroups of the population who are at high risk of contracting cholera will cost roughly the same per vaccinated individual as larger ones that target the entire population (among which incidence may be lower), while resulting in larger benefits per vaccinated individual.[7]

The existence of indirect protection due to cholera vaccination contributes additional complexity to the argument in favor of targeted vaccination programs. As shown in Fig. 2, the marginal increase in indirect protection decreases as coverage increases. Adding a given number of vaccinees to a large vaccination program thus provides relatively less benefit than adding the same number of vaccinees to a small program. In economic terms, the

[7] This argument will not hold if there are important economies of scale in vaccination campaigns. However, there is little evidence for such an effect; for a recent review see Lauria et al. [46].

benefit–cost ratios of targeted programs will thus look even better than those of large, community-based programs, except in the case where disease eradication (and hence a very long stream of future benefits) is a possibility. Disease eradication is unlikely with cholera.

Finally, because of the high cost of high-quality burden of disease studies, there are few known locations in the world where cholera incidence exceeds 2–3 cases per 1000 people; a few of these locations are already being considered as potential vaccination sites [33]. Given the high cost of conducting the epidemiological studies needed to provide data for calculating vaccination benefits, it seems unlikely that policymakers can be confident that cholera vaccination is a wise economic investment in many locations in developing countries. However, this point applies to the measurement of the health benefits of water supply interventions as well. To measure the health benefits of both vaccination programs and water supply interventions requires baseline epidemiological data, and these data are expensive to collect whichever intervention is chosen.

The main advantages of cholera vaccination programs are related to considerations that are not strictly economic (i.e., not based on cost–benefit calculations). First, on a per-household basis, cholera vaccination programs are much cheaper than the water supply interventions. Thus, in situations with severe financial constraints, donors and governments may have the financial resources to implement vaccination programs, but not water supply interventions of sufficient size to capture economies of scale. Vaccination programs allow donors and government with a limited budget to reach more households. Even if water supply interventions are more attractive economically, vaccination programs have the potential to be more equitable.

Second, practical considerations may also have an influence on the choice of programs. In the densely crowded slums of South Asian and African cities, cholera vaccination may be appropriate when there is insufficient space in housing units for the installation of a biosand filter. Nor will deep boreholes with public hand pumps be a realistic or favorable water supply option in such locations because of (1) the risks of groundwater contamination and excessive withdrawal demands on the aquifer and (2) the lack of time savings in situations where people are able to obtain water from neighbors, vendors, or other alternative sources. In such circumstances cholera vaccination programs may prove attractive before the installation of modern water and sanitation piped networks.

Furthermore, in circumstances where an improved water supply yields few time savings, many households may continue to use contaminated sources. In this case the health benefits from the improved water source will be low. This behavioral component influencing the economics of water and sanitation programs is only captured in our cost–benefit calculations through the parameter that describes the percentage reduction in diarrheal incidence. In situations where households are likely to continue to use contaminated sources of water and cholera incidence is not well known, biosand filters will prove to be the most suitable technology for delivering health benefits to people.

Development economists are increasingly utilizing randomized controlled trials (RCTs) to obtain improved estimates of the effectiveness of program interventions such as improved water supplies [47]. The results of such RCTs provide site-specific estimates of program effectiveness that can be combined with the numerous other parameters and assumptions needed for cost–benefit analysis. This movement in development economics toward more rigorous program evaluation is to be applauded; data from RCTs have been the gold standard for the evaluation of the effectiveness of health interventions for decades. Indeed, without evidence from RCTs, health policymakers simply will not deploy new-generation vaccines.

Health policymakers thus have long familiarity with the strengths and limitations of data from RCTs, and the use of data from RCTs in economic evaluations of policy interventions. In the vaccine field, health policymakers often want RCTs of vaccine effectiveness and safety conducted in their own country populations. An example illustrates why they are often reluctant to generalize results from one location to another. The live oral cholera vaccine, CVD 103-HgR, was highly protective in experimental studies in which volunteers in Baltimore, MD were immunized and then challenged with virulent cholera “cocktails” [48]. But when the vaccine was tested with RCTs in North Jakarta, Indonesia, for its efficacy against naturally occurring cholera, it failed to confer protection [49,50].

Not only can transferring the experimental evidence from one site to other sites be problematic, but also the results on program effectiveness may not be the most important parameter affecting the cost–benefit results. For example, for the biosand filter, the baseline diarrheal incidence and the assumed value of a statistical life are more important parameters in the cost–benefit calculations than the percentage reduction in diarrheal disease from the intervention. For the borehole + hand pump, the number of households served, the collection time from the traditional source, the market wage rate, and the value of time spent collecting water as a percentage of the market wage rate, are all more important parameters than the percentage reduction in diarrheal incidence from the intervention. Similarly for the vaccination interventions, the value of a statistical life, baseline disease incidence, the case fatality rate, and the marginal cost of vaccination are all more important parameters for the cost–benefit calculations than the parameters describing the effectiveness of the vaccine (duration, herd protection, and efficacy).

Finally, a more general observation emerges from these analyses. The point estimates of the net benefits of sector-level interventions that are typically presented in the literature are seriously misleading. In every sector there are some projects that are economically attractive, and others that are not. It is not helpful for sector specialists to argue that projects in “their sector” are better than projects in another sector based on cost–benefit analyses that use global or average values. The challenge in every sector is to find the good projects and avoid the poor ones.

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We wish to thank Christine Stauber and Mark Sobsey for their assistance in interpreting the literature on the use and performance of biosand filters in developing countries, and Claudia Sadoff and W. Michael Hanemann for their collaboration during the development of the cost–benefit models for the water supply interventions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.vaccine.2009.02.104.

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