assessment paper

WATER AND SANITATION

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COPENHAGEN CONSENSUS on Human Challenges

Water and Sanitation

Economic Losses from Poor Water and Sanitation: Past, Present, and Future

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Introduction

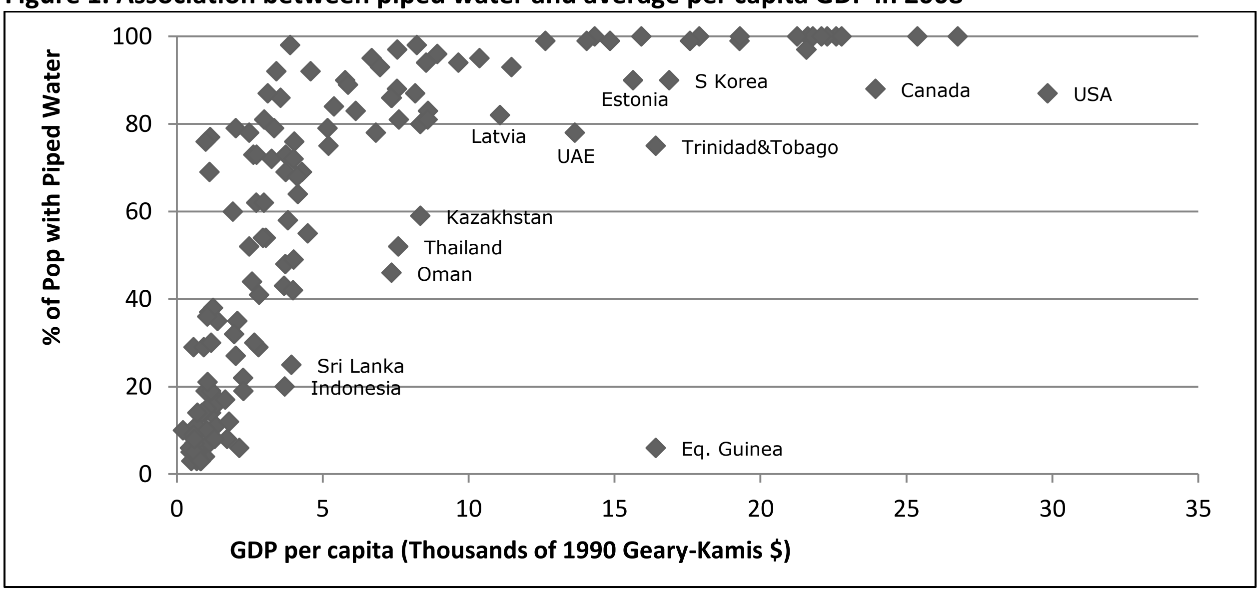
Diseases associated with poor water, sanitation and hygiene comprise on average 6-7% of the annual mortality in developing countries (WHO 2004; Prüss-Üstün et al. 2008). A growing body of research suggests that a variety of different types of water, sanitation, and hygiene (WASH) interventions are effective and capable of delivering large health benefits to target populations (Hutton and Haller 2004; Fewtrell et al. 2005; Luby et al. 2005; Clasen et al. 2007; Hutton et al. 2007). Many of these interventions – the provision of improved community water supplies, point-of-use water treatment, hygiene education, on-site sanitation – can be delivered at very low cost, but their adoption remains surprisingly low (Jeuland et al. 2010). Piped water and sewerage services, the gold standard for water and sanitation in the developed world, do not seem to be necessary to achieve many of the health benefits from improving existing water and sanitation conditions. Household demand for these network services, however, is much higher than for low cost interventions, perhaps because they bring other types of improvements that households value, such as time savings and greater convenience (Whittington et al. 2009).

In this paper we present a global analysis of the "economic losses" associated with inadequate water and sanitation from 1900 to 2050. These estimates provide an entry point for thinking about the challenges of ameliorating water and sanitation services in poor countries. Using a simple simulation model, we calculate the economic losses from the morbidity and mortality associated with inadequate water and sanitation services, and from the time spent collecting water from outside the home, in developing countries during the period 1950 to 2008. We then use projections of GDP and population growth to forecast economic losses from 2008 to 2050. We compare total economic losses with non-monetary measures of disease burden, such as deaths due to WASH-related diseases.

We are forced to make many assumptions in our attempt to describe the associations that exist between socio-economic conditions, coverage with improved water and sanitation services, and reduced burden of disease. We confront problems related to both data availability and the difficulty of drawing causal inferences between improved health, the provision of improved water and sanitation services, and economic growth. We are forced to rely primarily on country-level data for which only short time series and/or cross-sectional measurements exist. These data obscure important sub-national differences in income, coverage, and mortality. We use data on mortality due to water, sanitation and hygiene (WASH) related diseases, coverage with water and sanitation services such as piped water / sewerage and "improved" access as defined by the World Health Organization (WHO), and various other socio-economic indicators such as per capita GDP and urbanization rates. Unfortunately, estimates of coverage with improved water and sanitation do not exist prior to 1990, and the data for many of our key socio-economic indicators are spotty for much of the estimation period.

Importantly, our analyses should not be interpreted as implying a causal link between coverage with improved water and sanitation services and decreases in morbidity and mortality. However, empirical evidence from many countries shows that there is a strong association between these factors. For example, Komives et al. (2003) show that coverage with conventional piped water and sewerage infrastructures initially increases very rapidly up to household income of about US$4000-5000 per year, after which coverage grows more slowly. These associations also apply at the national level (Figure 1**Error! Reference source not found.**).[1] In a recent paper, Günther and Fink (2011) use household survey data to relate coverage with various levels of improved water and sanitation to child mortality and find a strong negative association.

Figure 1. Association between piped water and average per capita GDP in 2008



These associations do not necessarily imply that expanding piped water and sewerage itself causes the changes in mortality, though some evidence from the literature suggests that it is likely to play a significant role (Van Poppel and Van Der Heijden 1997; Galiani et al. 2005). Many coincident changes – in infrastructure, the quality of health systems, diet and nutrition, etc. – occur simultaneously in countries undergoing rapid development, and it is difficult to isolate the causal impact of any single

[1] In this paper, all economic estimates are presented in 1990 International Geary-Khamis dollars.

factor (such as coverage with piped water and sewerage) on mortality rates. Our backward projections and future forecasts of economic losses over much of the historical period for which data are unavailable are sensitive to assumptions about the strength of association between GDP, coverage with improved services, and mortality rates.

In the next section, we discuss findings from the literature that are critical for a nuanced understanding of the problems inherent in the estimation of country-level economic losses associated with unimproved water and sanitation. Many of these findings are puzzling, and their implications are not fully recognized by the global community. We then discuss a key issue regarding the interpretation of our simulated results in Section 3: whether inadequate water and sanitation should actually be conceptualized as creating "economic losses" in poor countries. In section 4 we present the structural model that underpins our economic simulations. Section 5 describes the data and parameters for our simulation model and describes our simulation procedure and sensitivity analyses. Section 6 presents the simulation results, and Section 7 summarizes our findings.

Recent findings from the literature on improvements in water and sanitation

This second section of the paper summarizes some recently published findings from the literature on water and sanitation interventions in developing countries that we believe are relevant for understanding the challenge and potential benefits of expanding access to such services.

Finding 1 – Household demand for nonpiped water and sanitation interventions is low, while many households in developing countries appear to want piped services but cannot afford to pay for their full cost.

It is surprisingly difficult to obtain high-quality information on the demand for improved, nonpiped water and sanitation services, such as community taps or handpumps, point-of-use household treatment, on-site sanitation, and hygiene education for stimulating hand-washing. During the pilot phase of program development, most WASH interventions are provided to beneficiary households in target communities for free or at highly subsidized rates (Jeuland et al. 2010). Then, scaled-up programs (such as the large, recent campaigns to stop open defecation in South Asia) rarely charge users the full cost of new services, or collect the type of information needed to understand the relationship between user fees and uptake rates (WSP 2005)[2]. A few recent studies provide limited information on this issue. In one recent intervention in ten panchayats in Kerala, India, for example, capital subsidies were very high (75%), but the increase in latrine ownership varied considerably (by 26-62% depending on the site) (Cairncross et al. 2005). Tremolet et al. (2010) summarize results from six countries that provided capital subsidies for sanitation facilities ranging from 12-82%; uptake rates varied from 15 to 70% in these programs. Pattanayak et al. (2009) provide the most specific information on the effect of prices on adoption of improved sanitation, for latrines in Orissa. Uptake among households living below the poverty line and who were eligible for subsidized prices of 7.5 USD increased by 31% during a recent promotion campaign, whereas uptake among households living above the poverty line and paying the full cost (about 50 USD) was 19% (Pattanayak et al. 2009).

Field evidence on the demand for point-of-use water treatment and community water systems (spring protection, community standposts, or pumps) is even harder to obtain. Point-of-use technologies such as household filters or bottles of chlorine are almost always provided free of charge during intervention studies, and usage estimates are difficult to maintain once these interventions and associated subsidies come to an end (Olembo et al. 2004; Arnold and Colford 2007). A recent study found that very few households in rural Kenya were willing to pay anything for chlorine for point-of-use water treatment, which is cheap, effective, and readily available in numerous developing countries (Ahuja et al. 2010).

Finally, household demand for piped water supply appears to be much greater, but there are significant economic and financial hurdles to providing these services to the majority of a population (Whittington et al. 2009). Deveto et al. (2009) conducted a randomized experiment to investigate the effect of home water connections on self-reported health and other outcomes among households in urban Morocco. Households randomly selected into the treatment group received an offer of credit toward a new connection, as well as administrative assistance in applying for the credit. Uptake for the treatment group was 69% (compared with 10% in the control group). Despite the widespread perception that stated preference methods lead to inflated willingness-to-pay estimates, the evidence on demand for community water improvements from contingent valuation studies is consistent with this picture of low and heterogeneous household demand (Whittington et al. 2009; Pattanayak et al. 2010).

[2] Capital subsidies in large-scale sanitation campaigns supported by the Water and Sanitation Program of the World Bank, in India and Bangladesh, vary from 40-100%, depending on the program location, technology, and income of recipients.

Finding 2 - Many interventions to improve water and sanitation reduce baseline diarrhea incidence by 10-50%, but multiple interventions do not seem to increase health benefits more than this.

A large number of evaluations, some of which are randomized controlled trials while others use quasi-experimental designs, suggest that a variety of interventions to improve water, sanitation and hygiene lead to reduced incidence of self-reported diarrheal disease. Point-of-use treatment interventions (chlorination, filtration, etc.) seem to reduce morbidity by 20-60% (Fewtrell et al. 2005; Arnold and Colford 2007; Clasen et al. 2007), though the effects are lower in urban and peri-urban environments (Fewtrell et al. 2005). Hand-washing interventions also appear to generate large reductions of 25-65% in self-reported incidence of diarrhea (Curtis and Cairncross 2003; Luby et al. 2005; Ejemot et al. 2009). Fewtrell et al. (2005) find effects of similar magnitude for sanitation campaigns.

The effects of water supply and source improvements on diarrheal disease incidence are less clear. Fewtrell et al.'s (2005) meta-analysis suggests a relative risk of 0.90 for households obtaining new in-house connections, and 0.94 for those using new standpipe connections; the relative risk associated with source water quality improvements is similar (0.89).[3] The absence of sizeable health gains from water supply interventions may be due to the fact that water can easily become contaminated during transport to the home (in containers or via poorly designed and maintained pipe systems) or because of unhygienic water handling within the household. The random experiment conducted by Deveto et al. (2009) revealed that the incidence of self-reported diarrheal disease among households with new water connections in urban areas in Morocco was no different than that in a control group with much lower access to piped water. This may be due to the fact that the water quality from alternative sources – communal taps with chlorinated water – is generally good. Households with private connections did increase their water use substantially, however, suggesting that they experienced other benefits.

Fewtrell et al. (2005) review evidence from five studies that assess the joint introduction of water, sanitation and hygiene/health education measures and find that risk reductions are also about 25-60%. Given that point-of-use, hygiene and sanitation interventions address different routes of contamination, the lack of additional gains from interventions that combine more than one of these components is puzzling, but several other studies have obtained similar results (Esrey et al. 1991). Fewtrell et al. (2005) offer several possible explanations for these findings: a) "piecemeal implementation" of programs; b) an

[3] Relative risk is the risk of a developing a disease relative to exposure (in this case to improved water supply), and is the ratio of the probability of illness in the exposed group versus the non-exposed, control group.

overall lack of focus or lack of sufficient attention to sanitation and hygiene education components; and c) the lack of assurance of water quality at the point of consumption.

Finding 3 - Access to reliable piped water supply is highly correlated with decreases in mortality in countries experiencing rapid economic development, but not in low-income countries or among the poor.

Jalan and Ravallion (2003) used propensity-score matching methods to estimate the causal effects of piped water (a tap inside the house or a public tap) on diarrhea prevalence and duration in children under 5 in India.[4] Children living in households with piped water had significantly lower prevalence and duration of diarrhea than the comparison group. However, the health gains were not significant for the poorest 40% in terms of income, and were lower for children in households with less educated women. Two hypotheses have been advanced for why health gains from increased piped water access among the poor are elusive: a) there may be a mortality penalty associated with living in cramped urban environments in poor countries due to poor sanitation, which could be made worse by increasing households' supply of water (Miller and Cutler 2005; Bennett 2008); or b) poor areas may experience low reliability of piped water supply due to cost recovery problems and/or mismanagement, which undermines the quality of water delivered (Hunter et al. 2009).

Gamper-Rabindran et al. (2010) investigated the impact of piped water on the infant mortality rate in Brazil. They used quantile regression models with panel data to examine whether the provision of piped water reduces infant mortality, controlling for potential time invariant confounders. They found a highly nonlinear relationship between coverage, income, and mortality rates. The provision of piped water services had a small effect on mortality in the poorest counties, but rose rapidly as counties experienced economic development. However, once a certain level of economic development was achieved, decreases in mortality slowed, and the most developed counties experienced limited health gains from extension of piped water services. Surprisingly, they also found that piped sewerage did not have any significant effect on infant mortality. Their results lend support to the threshold-saturation hypothesis, i.e., that the relationship between water supply and mortality rates varies with changing socioeconomic levels (Shuval et al. 1981). They conclude that studies that fail to find associations between mortality reductions and the expansion of coverage with piped water services must therefore be interpreted with caution.

[4] Propensity score matching is a statistical technique that aims to limit bias in the measurement of an intervention's effects by matching treated units with control units that are similar on observed pre-treatment attributes that influence selection into the treatment group (Rosenbaum and Rubin, 1983).

Finding 4 - Increasing knowledge about the health benefits of preventative health interventions, such as water and sanitation infrastructure, does not always increase household demand.

There are many examples from the literature that lend support to the idea that social marketing or information related to the benefits of WASH services can be effective in increasing uptake of improved technologies (Waterkeyn and Cairncross 2005; Pattanayak et al. 2009). In one recent study, Jalan and Somanathan (2008) found that providing information about an individual household's water quality did modestly affect the behavior of households in a relatively affluent suburb of Delhi, India. A random sample of households was given a water quality test, and half of these households were informed of their result. A follow-up visit 8 weeks later revealed that households who were told that their drinking water might be contaminated (following a positive test for fecal contamination), were 11% more likely to change water purification, storage and handling practices (incurring average out-of-pocket expenses of US$7.24 more for these changes) than those who were not informed of their test result. The effect was strongest among the wealthiest households. Hamoudi et al. (2011) recently found that providing households in rural Andhra Pradesh, India with information about the quality of their drinking water increased the purchase of water from advanced community treatment facilities by about 50% in communities with average baseline uptake of about 10%, and that these effects occurred among both low and higher income households—a much larger information effect than reported by Jalan and Somanathan.

However, two other recent studies suggest that some caution is warranted regarding the effect of social marketing and information. In a randomized evaluation of a deworming program in rural Kenya, Miguel and Kremer (2004) found that school health education did not increase household demand for the deworming treatment, in spite of the fact that deworming is highly effective at reducing infection. A social mobilization campaign also failed to increase demand, and a modest cost recovery program reduced uptake by 80%. The researchers even found that uptake was lower among households with more knowledge about the health benefits of deworming. Also, Kremer et al. (2009) find that almost no households were willing to purchase a water treatment product called *WaterGuard* after 6 months experience using it, even though diarrhea rates among users had decreased by 35-40%. Moreover, they found only modest positive effects of social networks on uptake (i.e., households were only slightly more likely to use WaterGuard when they saw their neighbors using it). The researchers concluded, "We find no evidence that valuation of the product is higher among households who stand to benefit most from it." The limitations of social marketing have been highlighted in studies of other health prevention technologies as well (Snow et al. 1999).

What are the implications of these findings for our analysis?

These facts suggest a set of dynamic, complicated causal relationships between investments in water and sanitation infrastructure, public health, the demographic transition, and economic development. We suspect that these relationships are unstable and nonstationary, and are mediated by household income, education, and awareness of disease pathways. Today's industrialized countries escaped from the constraints of the Malthusian economy so long ago that most people have forgotten its cruel logic. In a Malthusian economy, high morbidity and mortality reduce the labor supply and drive up real average wages (Clark 2007). Conversely, interventions that reduce mortality and morbidity, with a simultaneous increase in economic opportunities, drive down average wages. Water, sanitation and hygiene interventions that focus solely on improved health may thus have the direct effect of improving the well-being of households who do not become ill, but also the indirect effect of driving down average household income in the community, which then leads to lower health. In a Malthusian economy, increasing investment in preventative health is not a way out of a poverty trap.

As a result, one should be cautious about claims that improvements in water, sanitation and hygiene will automatically translate into better health and economic outcomes. Given the complexity and uncertainty in these relationships, we do not claim that our simulation model unravels the conflicting causal claims in the literature. Rather we rely on relatively robust associations between key variables that enable us to simulate future developments with modest confidence. We prefer to think of the results of these simulations as "plausible scenarios." We do not claim that improved water and sanitation services are the fundamental cause of the reduced mortality rates we project. But before we describe the simulation model and present these forecasts, we turn to the question of how best to frame the problem of "economic losses" from unimproved water and sanitation infrastructure.

Problem framing: What precisely are we trying to measure?

Before the 20th century people living in countries that are now industrialized suffered greatly from poor water and sanitation conditions in both urban and rural areas. Today, in industrialized countries, almost all of this acute suffering from poor water and sanitation conditions has been alleviated due to the installation of piped water and sewer infrastructure, good housing, food safety, and modern health care systems. Diseases such as cholera and typhoid are no longer a concern for citizens of countries like the

United States, Britain, or Japan. This is not true for the nearly six billion people in developing countries, where the status quo today is similar in important respects to conditions in the 19th and early 20th centuries in industrialized countries that have now largely solved their water- and sanitation-related health problems.

By definition economic losses and gains are measured as a change from some reference point. "Economic value" is defined as the change in human well-being that results from a move from one state of the world to another. For people in industrialized countries today the reference point--or status quo state of the world-- is improved water supply and sanitation infrastructure. If they had to live in conditions that exist in many parts of the developing world (where they would be at risk of contracting diseases such as cholera and typhoid), this change would reduce their well-being, and they would experience this change as an "economic loss."

On the other hand, the reference point for many people living in developing countries is poor water and sanitation conditions, and any improvement in water supply or sanitation infrastructure is experienced as an improvement in well-being, i.e. an "economic gain." This difference in perspective (or reference point) between people in industrialized and developing countries is important because psychologists and behavioral economists have demonstrated convincingly that people value losses much more than commensurate gains (Kahneman and Tversky 1979).[5] If economic growth in less-developed countries (LDCs) proceeds and these countries invest in improved water supply and sanitation infrastructure, people living in these countries will experience this change as an economic gain. Trying to empathize with people in LDCs, people living in industrialized countries will likely perceive the same improvement as a reduction in economic loss – and are likely to place higher value on what is actually an improvement over the status quo. It is thus natural for donors to believe that the welfare gains from improved water and sanitation infrastructure are much more important to people in LDCs than people who live in LDCs are likely to feel themselves.[6] As Jack Knetsch (2010) has argued, preferences are reference dependent.

From our perspective, the most appealing, logical way to report the consequences of improved water supply and sanitation infrastructure are as economic gains to the populations affected because we believe this is how people themselves perceive these changes. In other words, the correct measure of

[5] In fact, the feelings associated with gains and losses are different – and are experienced in different parts of the brain.

[6] Similarly, donors appear to believe that the value of mortality risk reductions, perhaps as conceptualized in the value of a statistical life (VSL), is higher than many people who actually live in LDCs, who face a wide array of mortality risks every day.

the welfare gain to poor people in developing countries is their willingness to pay (WTP) for the economic gains that result from infrastructure improvements. This WTP measure could be compared with the cost of installing those infrastructures to determine whether the net benefits of an intervention are likely to be positive.

However, for the purposes of this paper, we call these economic gains "reductions in economic losses" (i.e., the industrialized world's or donors' perspective) so that our estimates are reported in a manner that is consistent with that of the other papers in the Copenhagen Consensus Center project. Moreover, to ensure a standard terminology, we must refer to status quo conditions in LDCs as "economic losses." We caution that this approach of referring to economic gains as reductions in economic losses, and to status quo conditions as "economic losses" can be confusing for several reasons.

The first problem is simply that it re-enforces a donor bias on global challenges (Whittington, 2010). For people in industrialized countries, who empathize with the suffering of people in developing countries, and perceive status quo conditions as "losses," the appropriate measure of economic value will appear to be their willingness to accept (WTA) compensation to move to a state of the world with such poor water and sanitation conditions. This perceived WTA measure will be very high both because citizens of industrialized countries are relatively rich and because they have a different reference point. If people in industrialized countries and donors shift the reference point (to their own state of the world), and measure or conceptualize the potential gains from investments as economic losses to be reduced by investments, then the economic value of the resulting welfare change may be greatly exaggerated. It may also be very difficult for donors to understand poor peoples' behavior.

A second problem occurs when we look back in time and try to characterize the state of the world in a country such as Brazil in, say, 1900. In this paper we attempt to estimate the number of fatalities due to poor water and sanitation infrastructure in Brazil in 1900, and this estimate will show the suffering that occurred in 1900 in this status quo "state of the world." This suffering is expressed in monetary terms as an economic loss compared to a state of the world in which all the citizens in Brazil in 1900 had modern water and sanitation infrastructure and modern health care facilities similar to those that citizens of industrialized countries experience today. Obviously this is a hypothetical reference point that did not happen, nor could it ever have happened.

A third problem arises when one tries to express these "economic losses" as a percentage of a country's GDP at a point of time in the past. For example, the GDP estimates for Brazil in 1900 have embedded in them the actual state of the country's water and sanitation infrastructure existing at that time. If in 1900 Brazil had invested more in modern water supply and sanitation infrastructure, these investments would have reduced investments elsewhere in the Brazilian economy in 1900 (perhaps investments in roads, hospitals, or schools). It is practically impossible to know what the net effect of shifting investments to water and sanitation infrastructure in 1900 would have been on mortality or growth rates in Brazil. When we compare our estimates of "economic losses" due to poor water and sanitation conditions to GDP estimates in 1900, we are thus implicitly forced to assume that someone outside of Brazil "donated" the funds for these investments in water and sanitation infrastructure. In other words, we measure "economic losses" in Brazil in 1900 relative to a state of the world in which someone outside of Brazil gave all the citizens of Brazil modern water and sanitation infrastructure. Such a conception of losses is counterfactual and quite confusing.

Modeling Framework

This section describes the modeling strategy we use to determine historic and future economic welfare "losses" associated with the challenge of water and sanitation. Conceptually, the economic benefits of improvements in water and sanitation to households consist of three main components: a) health, b) time savings, and c) aesthetic and convenience improvements (at the household and business level, including reductions in individuals' psychological stress result from utilization of unimproved infrastructures for water and sanitation) stemming from increased consumption due to the drop in the marginal "price" of acquiring additional water (Whittington et al. 2009). These benefits (gains) are the converse of our desired measure of welfare losses due to inadequate water and sanitation. We thus define the economic cost (measured in monetary terms) of not having improved services ($Loss_i^{WSH}$) as:

$$Loss_i^{WSH} = \sum_j \left[H_{ij} + T_{ij} + A_{ij}\right], \quad (1)$$

where H_{ij}, T_{ij} and A_{ij} are the health, time, and aesthetic gains foregone, respectively, from not having access to improved water and sanitation, summed over all individuals j in location i to yield the overall costs for location i. Note that the reduction in losses related to improved water quality is already included both in health benefits, which increases when water quality is improved, and aesthetic benefits, which may or may not increase depending on individuals' tastes for improved water quality.

The risk of illness from water, sanitation and hygiene-related (or WASH-related) diseases decreases with access to improved water and sanitation services. Health damages consist of morbidity and mortality losses. Each of these two components of health damages is heterogeneous across individuals in a population, and depends on income Y and other socio-economic characteristics X of the affected individuals (including factors related to an individual's water and sanitation situation):

$$H_{ij} = I_{ij}^{WSH}(Y_{ij}, X_{ij}) \cdot \left[morb(Y_{ij}, X_{ij}) + CFR_{ij}^{WSH}(Y_{ij}, X_{ij}) \cdot mort(Y_{ij}, X_{ij})\right], \quad (2)$$

where the first term in the bracketed expression represents the cost of morbidity and the second term corresponds to the cost of mortality. I_{ij}^{WSH} is the incidence (or risk of illness) of WASH-related disease for individual j in location i, CFR_{ij}^{WSH} is the case fatality rate (risk of death given illness), and $morb$ and $mort$ are the economic cost of illness and mortality, respectively, measured in monetary terms.[7] All of these terms depend on income Y_{ij} and the other individual and household characteristics X_{ij}.

The incidence and the case fatality rate are a function of income because richer households are better able to invest ex-ante in preventive health technologies such as water and sanitation, as well as ex-post treatment of illness. As discussed, empirical data support the assertion that coverage with water and sewerage infrastructures increases rapidly as countries move from low GDP per capita to middle-income status (Komives et al. 2003). After this transition, coverage reaches high levels and thereafter grows much more slowly. Interestingly, the kink in the relationship between coverage and average household income (Figure1) occurs around US$4000-5000, which coincides almost exactly with the kink in the "Preston curve" that relates per capita GDP (a proxy for income) and longevity (Preston 1975).[8] The kink in water and sanitation coverage may not be the only factor so closely associated with the Preston curve; others for example have found similar transition points between income and environmental quality, or income and happiness indices (Grossman and Krueger 1995; Dasgupta et al. 2002; Inglehart and Klingemann 2003). Indeed, many coincident improvements occur with rising incomes, including factors such as improved health care systems and better nutrition.

Of course, this stylized description is complicated by the fact that income is endogenous in the production of better health. In fact, the argument that increasing income leads to declines in disease incidence and mortality hinges on the extent to which households acquiring health-improving

[7] To express mortality risks in monetary terms, we rely on the economic concept of the value of a statistical life (VSL), which is obtained by scaling up the willingness to pay for small mortality risk reductions to a single death measured at the population level (see Appendix for details and discussion).

[8] The Preston curve grew out of an empirical study of the relationship between life expectancy and real per capita income. It shows that individuals born in richer countries, on average, can expect to live longer than those born in poor countries, but that the link between income and life expectancy flattens out beyond a certain level of income.

technologies experience health improvements. Figure 2 presents two possible cases (A and B) that depict how mortality rate might change with income. In case A, coverage with improved water services is low and increases slowly with income; the mortality rate also decreases slowly with income. In case B, income growth is associated with rapid increases in coverage and decreases in the mortality rate, perhaps due to a virtuous cycle in which income and health are self-reinforcing.

The economic health cost of WASH-related disease for a representative individual with average income $\bar{Y}_i$ and characteristics $\bar{X}_i$ in location *i* is:

$$H_i = I_i^{WSH}(\bar{Y}_i, \bar{X}_i) \cdot [morb(\bar{Y}_i, \bar{X}_i) + CFR_i^{WSH}(\bar{Y}_i, \bar{X}_i) \cdot mort(\bar{Y}_i, \bar{X}_i)], \quad (3)$$

Differentiating equation 3 with respect to income and dropping the subscripts, yields equation 4 (the signs of each term are shown in parentheses below the equation):

$$\frac{dH}{dY} = \frac{dI}{dY} \cdot [morb + CFR \cdot mort] + I \cdot \left[\frac{dmorb}{dY} + \frac{dCFR}{dY} \cdot mort + CFR \cdot \frac{dmort}{dY}\right] \quad (4)$$

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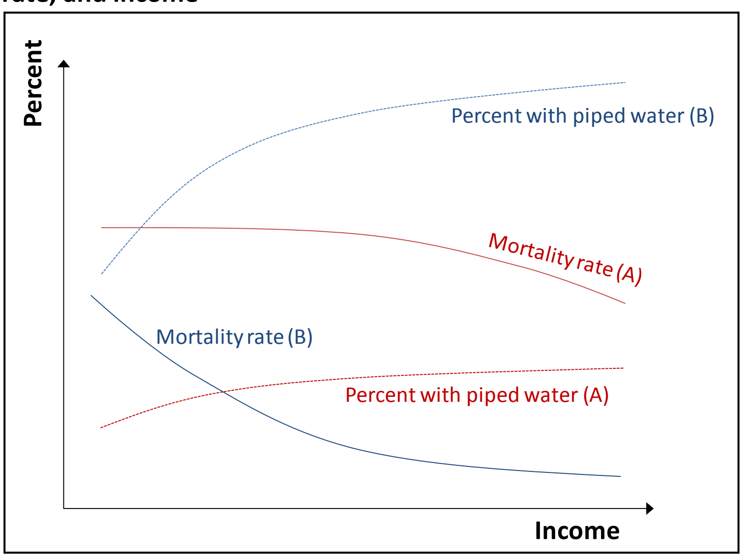
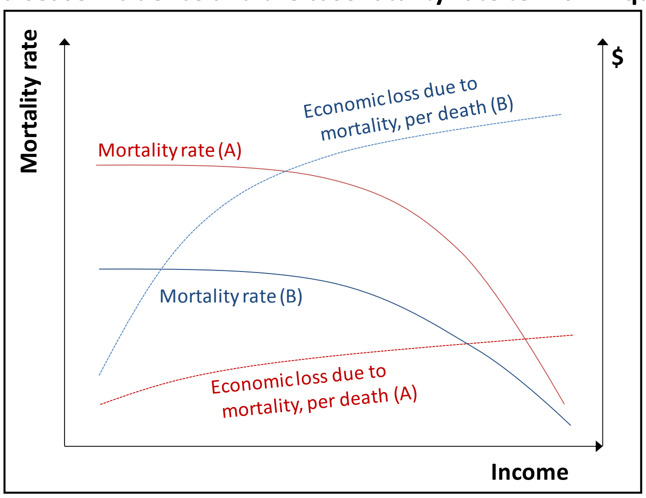
Figure 2. Two scenarios for the relationships between coverage with piped water, WASH-related mortality rate, and income



We expect that incidence (I) of WASH-related diseases and the risk of death among those who fall ill (CFR) both decrease as income increases (Figure 3). As shown in Figure 2, we expect that these changes are strictly monotonic; however they could either be slow (case A) or rapid (case B), depending on the cost of health improvements and the income available to individuals who would make such investments. The terms $morb$ and $mort$ – the “economic losses” in monetary terms due to illness and death per case, respectively – are increasing in income, because richer households are willing to pay more to reduce the negative consequences of poor health (Figure 3). This positive relation between income and the economic value of reduced mortality risks is well documented (Viscusi and Aldy 2003). As development proceeds and income grows, the sign on the change in WASH-related health damages per capita is ambiguous, and depends on the respective rates of change of the terms in equation 4. In case A in Figure 3, "economic losses" decrease overall: mortality rates decrease sharply while "economic losses" per death increase slowly. In case B, however, "economic losses" increase, as decreases in mortality do not keep pace with the increasing "economic losses" of additional deaths. As shown, it is possible that *H* (measured in absolute terms) will increase with income, even as incidence of WASH-related diseases falls, if increases in *mort(Y)* outweigh decreases in $I(Y) \cdot CFR(Y)$. Whether the economic value of health losses and income are positively or negatively related is thus an empirical question.

Figure 3. Illustrations of possible relationships between the mortality rate (which is the product of the disease incidence and the case fatality rate terms in Equation 4), "economic losses" per death, and income

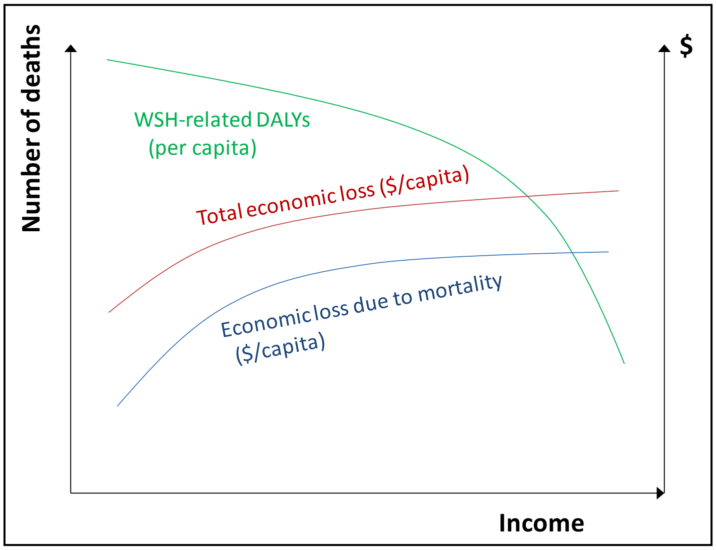


It is useful to contrast equations 2- 4 with a non-economic measure of the burden of disease for an individual *j*, such as the total burden of disease, perhaps as represented by the number of Disability Adjusted Life Years (DALYs):

$$DALY_{ij} = I_{ij}^{WSH} \cdot [w^{WSH} \cdot Dur^{WSH} + CFR_{ij}^{WSH} \cdot LE_{ij}], \quad (5)$$

where the first term is a measure of morbidity, and the second reflects the mortality burden. w^{WSH} is the DALY weight for WASH-related disease (a measure of the relative pain and suffering associated with illness; see Mathers et al. (2005) for details); Dur^{WSH} is the duration of illness; and LE_{ij} is the discounted life expectancy of those who fall ill. All terms in expression 5 are decreasing in income, except perhaps w^{WSH} (which will depend on how the relative proportion of relevant diseases, such as diarrhea, typhoid and cholera, change with income) and LE_{ij}, since longevity increases in income (as shown by the Preston curve). DALYs per person are thus certain to decrease in income for WASH-related diseases given the strong negative relationship between income and the incidence of infectious diseases (i.e. the "environmental risk transition") (Smith and Ezzati 2005).[9] Thus, while measures such as DALYs would likely decrease with rising GDP, "economic losses" per case or death would increase (Figure 4).

Figure 4. Illustrations of possible relationships between DALYs, "economic losses" per capita, and income



Similar to health losses, the time costs and foregone aesthetic benefits foregone due to lack of access to improved water and sanitation services depend on income and other socio-economic characteristics:

$$T_{ij} = t_{ij}^{collection}(Y_{ij}, X_{ij}) \cdot v_{ij}^{t}(Y_{ij}, X_{ij}) \text{ and} \quad (6)$$

$$A_{ij} = q_{ij}^{water}(Y_{ij}, X_{ij}) \cdot v_{ij}^{water}(Y_{ij}, X_{ij}); \quad (7)$$

where $t_{ij}^{collection}$ corresponds to the time required for members of household *j* to collect water or reach sanitation facilities outside the home; v_{ij}^{t} is the shadow value of the time spent by individuals in household *j*; q_{ij}^{water} is the quantity of additional water that would be used if supplies were more conveniently located (i.e. if the shadow price of water were reduced via enhanced access to water and sanitation services) for household *j*; and v_{ij}^{water} is the net economic value of the additional units of consumed water, in location *i*.

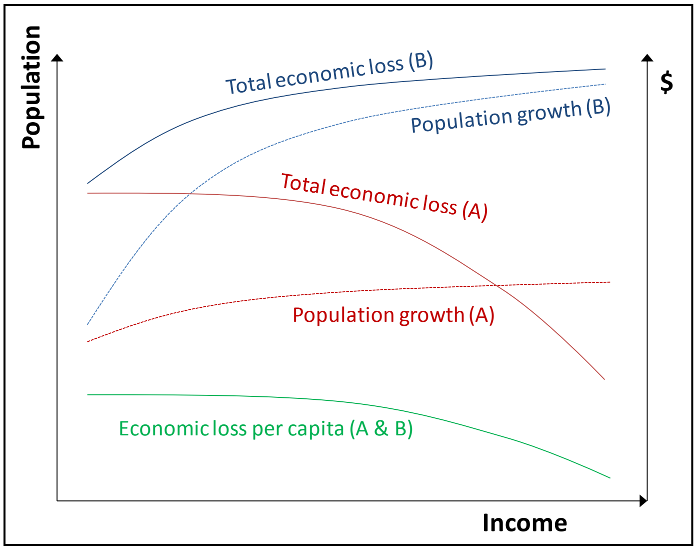
[9] There is actually one odd situation where DALYs per capita could increase even when income is rising and mortality is falling, if increases in life expectancy and thus years of life lost are increasing faster than mortality is dropping.

As with equation 4 for dH/dY, the signs of dT/dY and dA/dY – the rates of change in time savings and aesthetic burden with respect to income – are ambiguous. The term $dt^{collection}/dY$ is negative, since richer households and communities are better able to invest in improved technology to obtain time savings (for example private hand pumps or more convenient connections to piped water networks), but the change in the shadow value of time with respect to income dv_{ij}^{t}/dY is also positive. Similarly, dq^{water}/dY is negative, since richer households are able to purchase technologies or services (for water delivery) that improve convenience and allow them to more easily obtain additional water. However, the change in the net economic value of additional units of consumed water with respect to income dv_{ij}^{t}/dY may (or may not) be positive, depending on the relative magnitude of the income elasticities of the terms in equations 6 and 7.

Finally, many LDCs are in the midst of the demographic transition. It is theoretically possible that per capita losses could decrease while overall "economic losses" at the country-level would increase, due to increase in population (Figure 5). In both cases shown, per capita *Loss* decreases, but case A is characterized by low population growth while case B has high population growth. The consequences for total "economic losses" measured at the country-level would be very different in these two situations, increasing in case B but decreasing in case A.

Our simulations for different countries therefore need to reflect differences in population growth, baseline mortality rates, the costs associated with WASH-related deaths and illnesses, the costs associated with collecting and hauling water over long distances, and the trends of each of these with respect to historical income and future income projections.

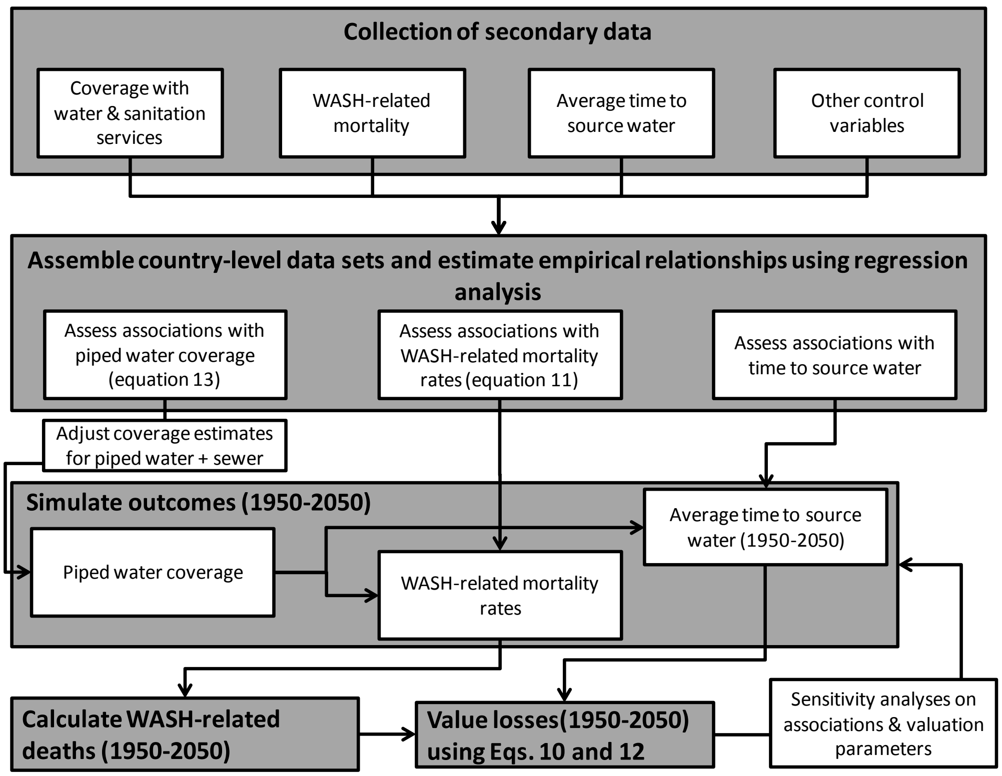
Figure 5. Illustrations of possible relationships between per capita "economic losses," total "economic losses," population growth and income



Data, model parameterization, and analytical approach

This section describes our approach for estimating and parameterizing the relationships described in Section IV. Our unit of analysis for this global analysis is the country rather than the individual household. We consider only the health losses H and time costs T from equation 1, and do not include aesthetic costs, due to the limitations on country-level data availability with respect to the latter. Our analytical approach is summarized in the flow chart shown in Figure 6. We first describe the specification of the key relationships between coverage with improved water and sanitation services, income and WASH-related health burden and time costs, which allow us to value outcomes. Then, we present the regression results that provide the parameter estimates for our modeling of outcomes and losses. Finally, we explain the analytical approach used for our simulations and sensitivity analyses. We utilize country-level data collected from secondary sources for the regressions and simulations whenever possible, and regional data otherwise.

Figure 6. Analytical framework for our calculations of economic losses associated with poor water and sanitation



Data considerations and specification of key components of the model

The literature and existing empirical analyses do not provide much insight on the relationships between WASH-related disease incidence and case fatality rates, income, and access to various levels of improved water and sanitation. Reliable measures of incidence of WASH-related diseases in different countries are nearly impossible to obtain. The mortality attributable to WASH (expressed as the percentage of mortality attributable to all factors), though also uncertain and subject to measurement problems, has at least received some attention.[10] We rely on 2004 country-level data from the World Health Organization's Environmental Burden of Disease project; the methodology used to calculate overall mortality burden is outlined in Fewtrell et al. (2007).[11] The mortality attributable to poor WASH conditions includes: a) infectious diarrhea; b) malnutrition, about 50% of which is estimated to be

[10] In the description that follows, we use the term mortality attributable to WASH as the ratio of the total number of deaths due to WASH to the total number deaths. The terms WASH-related death rate and WASH-related mortality refer to the ratio of the total number of deaths due to WASH to the number of population in a country.
[11] Available at: http://www.who.int/quantifying_ehimpacts/national/countryprofile/intro/en/index.html (Accessed October 2010). The data are only available for 2004.

attributable to inadequate WASH[12], and its consequences, the WASH-related fraction of which is estimated by the authors; and c) intestinal nematode infections, schistosomiasis, trachoma and lymphatic filariasis, 66% of which is attributed to poor WASH (Prüss-Üstün and Corvalán 2006).

We convert country estimates of the mortality attributable to WASH as a percentage of all deaths into a WASH-related death rate by multiplying this percentage by the total number of deaths and dividing by the total population of each country in our dataset for 2004 (132 countries in all):

$$d_{it}^{WSH} = pd_{it}^{WSH} \cdot \frac{Deaths_{it}}{Pop_{it}}, \qquad (8)$$

where d_{it}^{WSH} is the death rate that is attributable to poor water, sanitation and hygiene; pd_{it}^{WSH} is the mortality attributable to WASH; and $Deaths_{it}$ and Pop_{it} are the total number of deaths and population, all for country i in year t. The WASH-related death rate (or WASH-related mortality) is thus equivalent to the combined term $I_i^{WSH} \cdot CFR_i^{WSH}$ from equation 3. In our sample of developing countries for 2004, these death rates range from a low value of 0 in several countries to roughly 5.5 deaths per thousand people per year in Angola, with a mean value of 0.58 deaths per thousand.

To obtain annual country-level health losses H_{it} due to inadequate water and sanitation, we use the economic concept of the value of a statistical life (VSL) to represent the cost of mortality ($mort$) per death, and cost-of-illness (COI) to represent the cost of morbidity ($morb$) per case, and multiply by the population size in each year. We also explicitly separate coverage with improved water and sanitation services $\bar{W}_{it}$ (we use various measures for this variable, which are defined further below) from the other control variables $\bar{X}_{it}$ that determine the health outcomes of interest, and thus rewrite equation 3:

$$H_{it} = Pop_{it} \cdot [I_{it}^{WSH}(\bar{Y}_{it}, \bar{W}_{it}, \bar{X}_{it}) \cdot COI(\bar{Y}_{it}, \bar{X}_{it}) + d_{it}^{WSH}(\bar{Y}_{it}, \bar{W}_{it}, \bar{X}_{it}) \cdot VSL(\bar{Y}_{it}, \bar{X}_{it})]. \qquad (9)$$

Given the paucity of country-level data on incidence rates, it is not possible to specify the first term in equation 9. Instead, our analysis applies estimates of the cost of WASH-morbidity relative to mortality based on the calculations presented in Whittington et al. (2009), which suggest that morbidity makes up roughly 25% of the economic cost of WASH-related disease (we vary this from 10 to 40% in sensitivity analysis). We therefore obtain equation 10, where f_{COI} is this fraction of morbidity burden:

[12] More precisely, the diarrhea rate attributable to WASH was calculated based on access levels to safe water and adequate sanitation service levels, as explained in Fewtrell et al. (2007). For malnutrition, Prüss-Üstün and Corvalán (2006) estimate that 39-61% is attributable to WASH-related factors, based on analysis of expert surveys. Malnutrition rates are highest in South Asia and Sub-Saharan Africa.

$$H_{it} \cong (1 + f_{COI}) \cdot Pop_{it} \cdot d_{it}^{WSH}(\bar{Y}_{it}, \bar{W}_{it}, \bar{X}_{it}) \cdot VSL(\bar{Y}_{it}, \bar{X}_{it})$$
$$= (1 + f_{COI}) \cdot Pop_{it} \cdot d_{it}^{WSH}(\bar{Y}_{it}, \bar{W}_{it}, \bar{X}_{it}) \cdot VSL(\bar{Y}_{it,80}). \quad (10)$$

As shown above, we ultimately specify VSL in our model to be solely dependent on income. The available evidence on VSLs from meta analyses in the literature suggests the need to develop a function that accommodates both low income elasticities for the VSL in rich countries, and higher income elasticities for the VSL in developing countries (Viscusi and Aldy 2003; Hall and Jones 2007; Hammitt and Robinson 2011). We describe our procedure for developing such a function in more detail in Appendix A. The VSL and all economic values in our model are specified in 1990 International Geary-Khamis dollars (1990 IGKD). Also, given the fact that the diarrheal disease burden (and especially mortality from diarrheal disease) is concentrated on the poor in developing countries, we value these deaths using $VSL(\bar{Y}_{it,80})$, which is the VSL calculated from the average income among the bottom 80% of the population, which in part accounts for the amount of inequality in the income distribution in different developing countries. This adjustment is made to address concerns over the relevance of using average per capita GDP when calculating health losses. We evaluate the importance of this adjustment in sensitivity analysis.

We next use regression models to better understand how the WASH-related death rate d_i^{WSH} is associated with income and coverage with improved water and sanitation services:

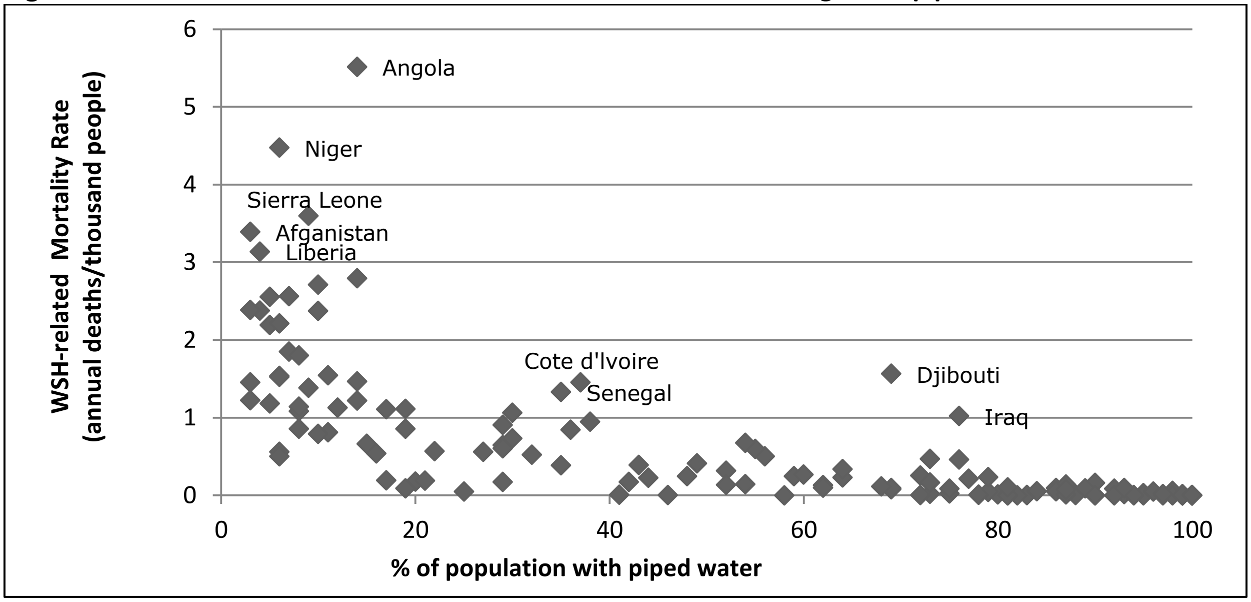
$$d_{it}^{WSH} = \alpha_0 + \alpha_1 \cdot \ln(\bar{Y}_{it}) + \beta \cdot \bar{W}_{ilt} + \gamma \cdot X_{ikt} + \varepsilon_i \,, \quad (11)$$

where $\bar{Y}_{it}$ is per capita GDP (in 1990 IGKD), obtained from Angus Maddison's GGDC database.[13] $\bar{W}_{ilt}$ is the set of l variables that relate to improved water and sanitation, which we take to be the percentage of population with a) access to in-house piped water; b) access to other improved water supply; and c) access to improved sanitation; in country i, obtained from the Joint Monitoring Program (JMP) for Water Supply and Sanitation.[14] We use separate variables for coverage with piped water, coverage with other improved sources, and coverage with improved sanitation, because the empirical data suggest that WASH-related mortality only really drops to zero in countries with high coverage with adequately treated piped water and sewerage (see for example Figure 7 and Figure 8 which show the associations

[13] Available at http://www.ggdc.net/databases/ted.htm.
[14] Available at http://www.wssinfo.org/datamining/tables.html. Improved sources that are not piped water include: plot or yard tap; public tap/standpipe; tubewell/borehole; protected dug well; protected spring; and rainwater collection. Improved sanitation includes: flush or pour-flush to piped sewer system, septic tank or pit latrine; ventilated improved pit latrine; pit latrine with slab; and composting toilet.

with piped versus unimproved water sources, respectively, for 2004). Unfortunately, unlike for piped water, country-level estimates of sewerage are not widely available, so we cannot separately test for associations with improved sanitation versus pipe sewage system.

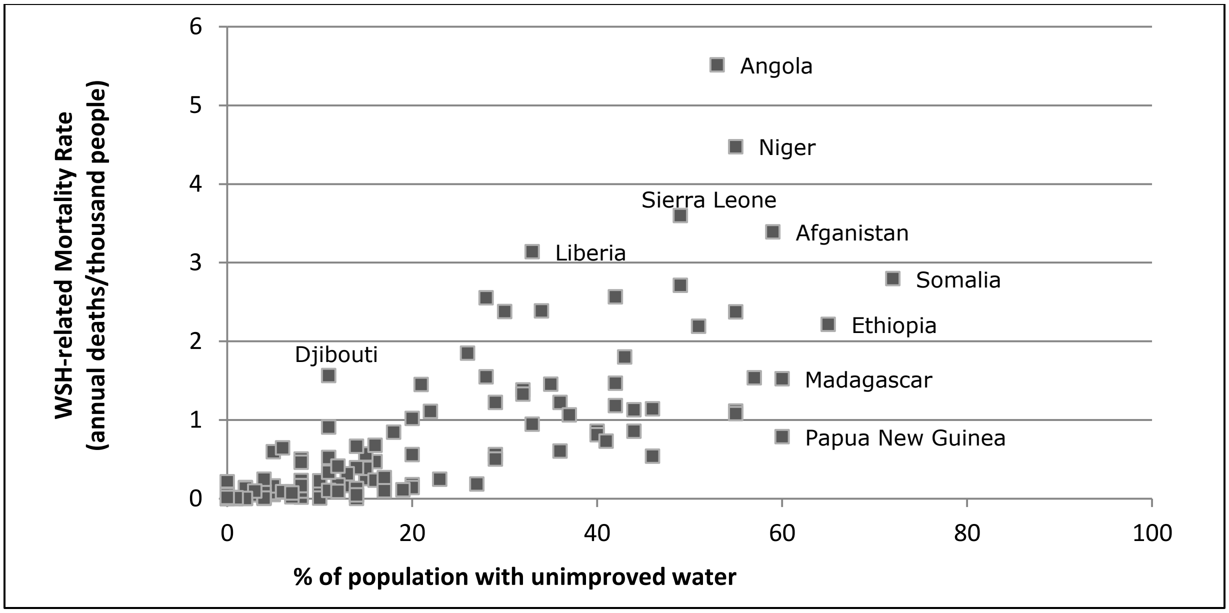
Figure 7. Association between WASH-related death rate and % coverage with piped water in 2004



When estimating equation 11, we use coverage data for piped water from 2005, since these are the data closest to the year for which mortality burden was determined (2004). X_{it} is a vector of other control variables (regional dummy variables, % urban population, income inequality, fertility, literacy, and several governance variables: democracy-autocracy score (polity), regime durability, and an indicator for coup d'états) and ε_i is an error term.[15] The coefficients α_0, α_1, β, and γ are estimated by OLS regression. We expect α_1 and β to be negative since the WASH-related mortality should be negatively related to access with improved services, although we acknowledge that the broad definitions of improved access may lead to less than expected effects.

Figure 8. Association between WASH-related death rate and % coverage with unimproved water in 2004

[15] Appendix B presents additional details on the data sources for the control variables in our regression models; Table C1 in Appendix C presents the regional country groupings.



In similar fashion, we estimate a relationship for the average time to water in minutes, using the limited data available for different countries and years in the Demographic and Health Surveys (DHS), the Multiple Cluster Indicator Surveys (MICS), and the World Health Surveys (WHS) of the WHO.[16] That model is similar to the one shown in Equation 11, except that the dependent variable is replaced by the average time spent to reach water in country *i* and year *t* ($\bar{t}_{it}^{collection}$) among all households, whether connected to piped networks or not, and the control variables other than coverage $\bar{X}_{it}$ do not include literacy and fertility. We then value the time lost due to collection of water at the country level using Equation 12 (adapted from Equation 6 in the previous section):

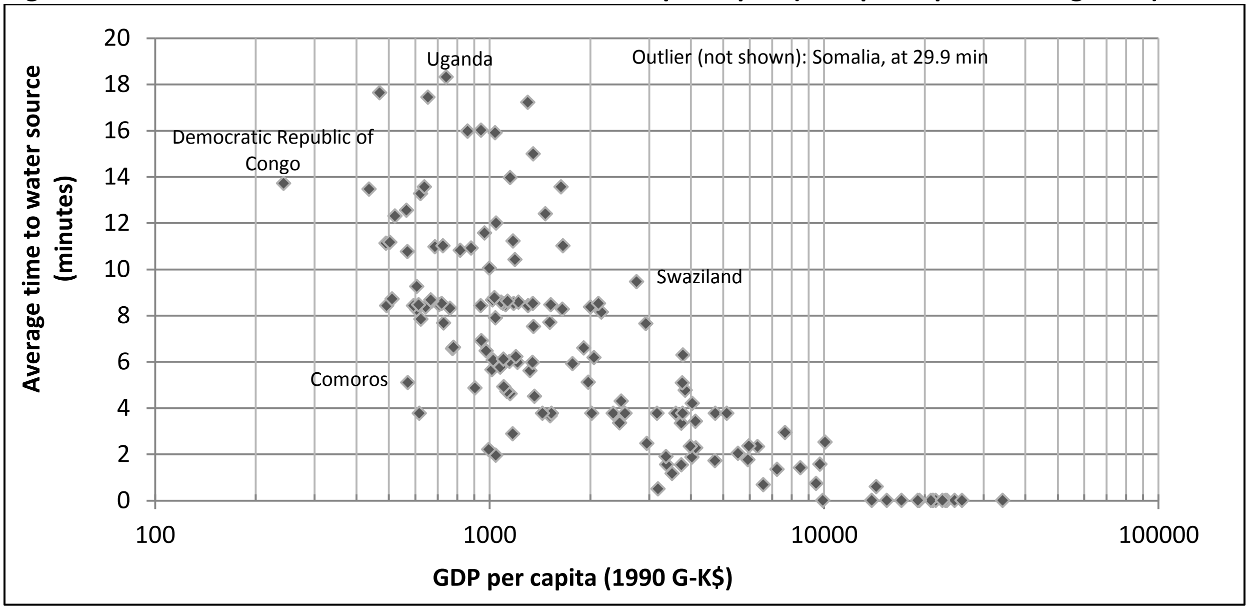
$$T_{it} = (2 \cdot trips \cdot Pop_{it}/hhsize_{it}) \cdot \bar{t}_{it}^{collection}(\bar{Y}_{it}, \bar{W}_{ilt}, \bar{X}_{it}) \cdot v^t(\bar{Y}_{it,80}), \quad (12)$$

where the opportunity cost of time spent gathering water v^t is assumed to be a fraction of the average per capita GDP among the bottom 80% of the income distribution (converted to a per hour value assuming that the GDP is generated from a work week of length L^w). $hhsize_{it}$ is the average household size, and $trips$ is the average number of trips to collect water per household per day. The factor of two

[16] The MICS data can be found at: http://www.unicef.org/statistics/index_24302.html; DHS data are available at: http://www.measuredhs.com/accesssurveys/; and WHS at http://www.who.int/healthinfo/survey/en/. There are quality and consistency problems associated with the time to source data from these sources. In terms of consistency, the DHS summaries by country only report the median time to water, which is not precisely the same as the mean time to water obtained from MICS. Similarly, the WHS data are not ideal because they only collect time-to-water data in categories that range from <5, 5-30, 30-60, 60-90 and >90 minutes per trip. Converting these to mean times by country requires assumptions; we assume that average time to water is zero in countries with 100% of responses in the group for <5 minutes per trip, and otherwise we multiply the percentages in each category by the midpoint of that category.

is to account for the round trip collection time. We expect that time to water sources drops significantly as income and the opportunity cost of time increase, as suggested in Figure 9.

Figure 9. Association between time to water and GDP per capita (GDP per capita on a log scale)



To extrapolate historic and future levels of coverage with piped water and sewerage, which are required to project changes in mortality and time spent collecting water that accompany those changes, we also estimate the relationship between piped water coverage P_i and GDP using regression methods:

$$P_{it} = \kappa_0 + \kappa_1 \cdot \ln(\bar{Y}_{i,t-1}) + \kappa \cdot Z_{ij,t} + \delta_{it} + \nu_i \, , \qquad (13)$$

where $\bar{Y}_{i,t-1}$ is the income from the previous wave of data (period *t – 1*), $Z_{im,t}$ is a vector of m control variables (WHO region dummy variables, linear time trend, year dummy variables, % urban population, income inequality, several governance variables, bilateral aid received for WASH, and a set of time-region interaction variables), measured at time t for country *i*, δ_{it} is a time-varying error term, ν_i is a time-invariant error term, and κ_0, κ_1, and κ are coefficients estimated using regression models. The year and region dummy variables are important to control for differences in technology, access to capital, and other factors that influence uptake of water and sanitation technologies over time and space. In estimating equation 13, we use the Joint Monitoring Programme (JMP) data for all five available years – 1990, 1995, 2000, 2005, and 2008. We estimate both fixed effects and random effects models. We expect $\kappa_1$to be positive since higher income should be associated with higher piped water coverage.

Estimates of associations between WASH-related death rates, income, and coverage with improved WASH services

The results of our OLS regressions for WASH-related death rates (equation 11) are presented in Table 1. Results for piped and improved water access are similar whether or not developed countries are included. Column 1 presents results from a reduced form specification that does not include variables relating to coverage with improved water and sanitation services, and instead relates the mortality rates directly to income. In this specification, a 1-log increase in per capita GDP is associated with a decline of WASH-related death rates of roughly 0.4 per thousand per year (in other words increasing income by a factor of about 2.7 decreases the death rate by 0.4 thousand per year).

Columns 2-4 provide evidence that both piped water and improved water coverage have significant and negative associations with the WASH death rate, and that the magnitude of these associations is similar. The fit for this model is improved over that of the reduced form specification. A 1% increase in piped water coverage or improved water coverage is associated with a decrease of 0.03 deaths per thousand people per year due to WASH-related diseases. Similarly, a 1-log increase in income is associated with a decline in WASH-related deaths by 0.3 per thousand per year; this is the effect of income that excludes its indirect association with coverage with improved services. Given the mortality rates across countries in our sample (ranging from 0 to 5.5 per thousand), these are large declines. Somewhat surprisingly, coverage with improved sanitation is not significantly associated with the WASH-death rate, though this may be due to high correlations (over 0.8) with the water coverage variables. Percent urban population, percent coverage with improved sanitation, inequality, the democracy/autocracy index, and the number of years since a regime change do not have significant associations with the WASH death rate. The association with literacy, however, is negative and significant, as expected, since higher education levels would be correlated with lower death rates. A 1% increase in literacy is associated with a decline of 0.02 deaths per thousand people per year.

Table 1. OLS regression for WASH-related mortality (annual deaths per thousand people)[a]

	All countries, reduced form model		All Countries, base model		Developing countries only, base model		Developing countries only, full model	
	Coef.	**Std. Err.[1]**	**Coef.**	**Std. Err.[1]**	**Coef.**	**Std. Err.[1]**	**Coef.**	**Std. Err.[1]**
% Piped water coverage			-0.031***	0.0086	-0.031***	0.0088	-0.029*	0.015
% Improved non-piped water coverage			-0.030***	0.010	-0.030***	0.010	-0.029*	0.016
% Improved sanitation coverage			0.0048	0.0052	0.0049	0.0053	0.010	0.0067
Ln GDP per capita	-0.43***	0.10	-0.30***	0.089	-0.31**	0.095	-0.27**	0.14
% Urban population	-0.00093	0.0041	0.0049	0.0053	0.0053	0.0059	0.0061	0.0065
Fertility rate							0.00067	0.0030
Literacy							-0.019***	0.0061
% of GDP to lowest 80% of population							0.0071	0.016
Developed countries	-0.34	0.24	-0.24	0.20				
Countries in LAC region	-0.87***	0.19	-0.69***	0.20	-0.69***	0.20	-0.60**	0.27
Countries in MIDEAST region	-0.69***	0.26	-0.39	0.26	-0.40	0.27	-0.55	0.37
Countries in SOUTH ASIA region	-0.96***	0.17	-0.40*	0.23	-0.40*	0.23	-0.44	0.34
Countries in EAST ASIA / PACIFIC region	-0.88***	0.20	-0.69***	0.19	-0.69***	0.19	-0.34	0.28
Countries in EASTERN EUROPE region	-0.79***	0.19	-0.46**	0.20	-0.46**	0.21	-0.13	0.31
Democracy-Autocracy Score	0.0043	0.0092	0.016	0.0096	0.016	0.0099	0.015	0.0099
Years since last regime change	0.00017	0.00083	0.0004	0.00087	0.0007	0.0024	0.0011	0.0025
Constant	4.7***	0.69	5.4***	0.98	5.4***	1.0	5.6***	1.25
Number of observations	148		132		115		104	
Adjusted R^2	0.617		0.693		0.672		0.697	

*Significant at 90%, **Significant at 95%, ***Significant at 99% [1] Robust standard errors

[a] The omitted region in these regressions is Sub-Saharan Africa (SSA)

These results are sensitive to the assumed functional form of the regression relationships. We find some evidence that the associations between coverage variables and death rates may be nonlinear. Additional robustness tests (provided in Appendix C, Table C2) reveal that the coefficient estimates and significance of coverage variables are sensitive to functional form (changing for example with inclusion of higher order squared terms, or with log coverage terms). When higher order terms are included alongside the linear coverage terms in the model, the coefficient for the linear piped water coverage increases by about 65% (to -0.50), and the squared piped water coverage is positive and significant. This suggests that there is a concave relationship between death rates and piped water coverage, whereby declines in WASH-related deaths decrease as coverage increases. Neither non-piped improved water nor improved sanitation remain significantly associated with the WASH-related death rate in this model. With log coverage terms, the strength of association between the decrease in mortality and piped water coverage is roughly two and a half times as strong as that with improved water coverage, and the association with improved sanitation remains insignificant. Taken together, these results suggest that the death rate is more closely associated with piped water coverage than with the other coverage variables. Similar tests on inclusion of different income terms reveal that the log income specification outperforms models with linear or higher order income terms.

Estimates of associations between average water collection time, income, and coverage with improved WASH services

Regression results for the average water collection time (equation 12) are presented in Table 2. For this model, as with the mortality model, we use simple OLS but cluster standard errors by country, since a few countries have more than one observation. Once again, the log of per capita income (lagged) is significant in both the base and more complete model, and negatively related to the average water collection time. An increase in per capita GDP of 1 log is associated with a decrease of roughly 1.2 minutes per trip. Higher urbanization is also associated with lower water collection times; a 10% increase in the percentage of urban population is associated with a decrease in collection time of 0.6 minutes per trip. The constant of 13 or 16 minutes (depending on the model) represents the baseline collection time in a country in Sub-Saharan Africa (the reference group for this regression) with zero values for all other right-hand side variables. Both the MICS and WHS survey dummy variables are significant and positive; these represent the higher "mean collection time" obtained for similar countries in those surveys relative to the DHS surveys, which only reported median collection times. We find no significant associations between coverage with piped water or improved water sources and average water collection times when controlling for GDP, perhaps because of lack of variation and collinearity among these variables. Omitting lagged GDP, the piped water coverage variable becomes significant; specifically a 1% increase in coverage with piped water is associated with a reduction in average time to water of 0.07-0.09

minutes (results not shown). Coverage with improved water however remains insignificant. The governance variables and inequality are also not significant in the model.

We also consider several other model specifications for understanding the associations between average time spent collecting water and these variables. We find that the model with log per capita income performs better than one with linear and squared per capita GDP terms (results available upon request). Also, use of random effects and random effects tobit models (with lower bound censoring at 0 minutes per trip) do not yield results that are qualitatively different, though the coefficients on the income term in such models decreases to 0.9 and 0.7, respectively.

Table 2. OLS regression for average water collection time (in minutes per one-way trip)[a]

	All Countries, base model		All countries, full model	
	Coef.	**Std. Err.[1]**	**Coef.**	**Std. Err.[1]**
% Piped water coverage	-0.039	0.037	-0.0040	0.026
% Improved non-piped water coverage	0.0073	0.061	0.068*	0.038
Ln GDP per capita (lagged)	-1.21*	0.65	-1.16**	0.58
% Urban population	-0.060***	0.023	-0.063***	0.023
% of GDP to lowest 80% of population			-0.051	0.038
Developed countries	2.1	7.0	8.3*	4.8
Countries in LAC region	-1.5	1.0	-0.42	0.82
Countries in MIDEAST region	0.8	1.6	2.1	1.3
Countries in SOUTH ASIA region	-4.7***	1.4	-5.7***	1.1
Countries in EAST ASIA / PACIFIC region	-2.6**	1.0	-2.9***	1.1
Countries in EASTERN EUROPE region	-2.4**	0.99	-2.6**	1.0
Democracy-Autocracy Score			-0.052	0.045
Years since last regime change			-0.0041	0.011
Multiple Indicators Survey	4.9***	1.1	3.7***	0.83
World Health Survey	2.9***	0.59	2.6***	0.55
Constant	16.3***	5.2	15.3***	4.2
Number of observations	184		175	
R^2	0.614		0.682	

*Significant at 90%, **Significant at 95%, ***Significant at 99% [1] Robust standard errors
[a] The omitted region in these regressions is Sub-Saharan Africa (SSA)

Estimates of associations between population coverage with various levels of water and sanitation, income, and other variables

Regression results for equation 13 (fixed effects and random effects models) are reported in Table 3. In both models GDP in the previous period and the percentage of urban population have significant and positive effects on piped water coverage. In the random effects model, a 1-log increase in per capita GDP in the previous period is associated with a 12% increase in piped water coverage in the current period. Percent urban population is also significant and positive – a 0.4% increase in piped coverage for a 1% percentage increase in urban population. The regional dummy variables for all regions except South Asia are significant and positive relative to Sub-Saharan Africa. The governance variable for regime durability is marginally significant and negative, but none of the other governance or inequality variables have significant associations with piped water coverage. Year dummy variables for early years are significant and negative, suggesting higher coverage expansion in later years.

In the fixed effects model, a 1-log increase in per capita GDP in the previous year is associated with roughly a 7% increase in piped water coverage. Percent urban population is significant and positive, and similar to the estimate from the random effects model. Of the governance variables and inequality, only regime durability is marginally significant and unexpectedly negative, but the linear trend is significant and positive, and the early year dummy variables are significant and negative in the basic model, suggesting that access to piped water may have accelerated in these countries in the recent past, relative to the early 1990s.

A Hausman test rejects the hypothesis that the fixed and random effects model estimates are the same, suggesting that the coefficients estimated in the random effects model are biased, probably due to autocorrelation in the error term. We thus use the fixed effects estimates in the simulation, i.e. the more conservative estimates of the association between GDP and piped water coverage. Also, the full model with complete interactions yields estimates of this association that are about 2.5 percentage points lower, i.e. a one log increase in GDP per capita is associated with a 4.5 to 9% increase in piped water coverage, relative to the 7 to 11.5% increase suggested by the simple model. Returning to a comparison of the base and reduced form models for WASH-related mortality presented in Table 1, we would thus calculate the net effect of log income to be -0.3 + (-0.03*4.5) = -0.43 to -0.3 + (-0.03*7) = -0.51 if we use the associations obtained from the fixed effects models for coverage. These seem reasonable given the -0.43 coefficient on log income obtained from the reduced form model. Finally, we also explored whether controlling for aid flows for WASH would affect our estimates. This variable was not significant, and its inclusion did not qualitatively change the results in Table 3, though the limited data for aid flows reduced the sample size to less than 150 observations (results not shown).

Table 3. Estimation of population coverage with piped water (robust standard errors presented in parentheses, clustered at the country level)[a]

	Random Effects [b]				**Fixed Effects**			
	Simple model		**Full model[c]**		**Simple model**		**Full model[c]**	
Lagged ln (GDP per capita)	11.5***	(2.03)	9.25***	(1.87)	7.17***	(2.33)	4.49**	(2.20)
% of GDP to lowest 80% of population	0.070	(0.09)	0.075	(0.09)	0.071	(0.10)	0.072	(0.09)
% Urban population	0.42***	(0.10)	0.45***	(0.08)	0.48***	(0.17)	0.45**	(0.21)
Countries in LAC region	29.2***	(6.06)	33.4***	(5.6)				
Countries in MIDEAST region	31.1***	(6.33)	33.9***	(6.8)				

Countries in SOUTH ASIA region	4.4	(3.53)	5.0	(3.9)				
Countries in EAST ASIA / PACIFIC region	11.5*	(7.04)	14.5**	(7.3)				
Countries in EASTERN EUROPE region	44.1***	(5.61)	35.3***	(4.6)				
Developed countries			40.7***	(7.0)				
Linear time trend	0.14	(0.11)	-0.12	(0.07)	0.21**	(0.10)	-0.022	(0.08)
1995	-1.64**	(0.73)	-0.53	(0.64)	-1.4 **	(0.61)	-0.96*	(0.58)
2000	-0.66*	(0.38)	0.42	(0.31)	-0.66*	(0.36)	-0.03	(0.31)
Democracy-Autocracy Score	-0.065	(0.13)	-0.0027	(0.11)	-0.15	(0.14)	-0.17	(0.13)
Years since last regime change	-0.048	(0.06)	-0.073*	(0.04)	-0.084	(0.05)	-0.12**	(0.05)
Coup	-1.20	(0.89)	-1.06	(0.84)	-0.74	(0.97)	-0.64	(0.82)
Constant	-82.4***	(11.9)	-63.3***	(12.6)	-36.0**	(17.9)	-1.8	(21.6)
Number of observations	361		493		361		493	
Adjusted R^2 (overall)	0.888		0.889		0.730		0.693	
(within)	0.508		0.489		0.523		0.511	
(between)	0.897		0.895		0.739		0.709	
Hausman Test for simple model χ^2 (p-value)	70.0 (0.000)							

*Significant at 90%, **Significant at 95%, ***Significant at 99%.

[a] A random-effects tobit model that allows censoring at 0 and 100% coverage does not yield qualitatively different results.

[b] Includes all countries (including developed and former Soviet republics dropped from the simple model) and full set of year-region interactions (as in the other regressions the omitted region is Sub-Saharan Africa).

We estimated several additional models in order to assess the sensitivity of these results to assumptions about functional form and coverage variables. In terms of functional form, we estimated random and fixed effects models with linear and squared per capita GDP terms, as well as log and squared log per capita GDP terms. The model fit for the models with per capita GDP terms (rather than the log GDP terms) was not as good as the simple log GDP model, and adding squared log GDP terms only provided small improvements in model fit. Furthermore, this squared log GDP term was only statistically significant, and negative, in the fixed effects model that included all countries (rather than developing countries only). We interpret this as evidence that a diminishing rate of expansion of piped services may only apply late in the development path of countries, once they approach full coverage. With regards to the specific coverage variables, we estimated models for coverage with improved water and improved sanitation (see Appendix Table C3). The results for these are generally similar to those for piped water coverage, though urban population is less significant in the models for improved water.

The simulation model for health loss due to inadequate WASH, and sensitivity analyses

The final step of our analytical approach involves use of a spreadsheet simulation model that incorporates the most important associations obtained from the country-level regression models for coverage with improved water and sanitation services, WASH-related mortality, and average time-to-water. Our simulation model, like the regression analyses of the previous section, is a country-level model. We use single-year time steps from

1950 to 2050. The model is calibrated with the historical time series data on a) coverage with piped water from the JMP (1990-2008), b) PPP-adjusted actual per capita GDP from Angus Maddison's GDCC data series (1950-2008), and c) actual population recorded by the United Nations population division (1950-2008). When data for particular years are missing, we conduct simple linear interpolation between the available data points. For simulation of future projections, we use the regional population and two sets of economic growth projections based on historical country averages over the recent past (1990-2008) and over the long term (1950-2008).[17]

Given the results of our empirical analysis, we focus in our calculations of losses from WASH-related mortality and time spent collecting water on how these change with piped water coverage, income, and urbanization. We use the simulation model to make both backward and forward projections of the three left-hand side variables from our regression analysis – coverage with piped services, WSH-related death rates, and average time to water. We assume that:

a) Piped water coverage increases as a function of the log of per capita GDP and the proportion of urban population;
b) WASH-related mortality decreases with piped water coverage and the log of per capita GDP; and
c) Average time to water decreases as a function of the log of per capita GDP and the proportion of urban population.

We backcast and forecast coverage with piped water, WASH-related mortality, and mean time-to-source over the periods of missing data by applying the income and coverage elasticities shown in Table 4, which are obtained from our regression model estimations. For mean time-to-water, we must also impute values for countries that are missing data, which we do using the full model presented in Table 2. We test the sensitivity of our model results using the lower, base case and upper bound estimates of the parameters.

Table 4. Elasticities and ranges used in projections of water and sanitation coverage, WASH-related mortality, and average time spent collecting water

	Low	Base Case	High
A. Elasticities of % coverage with improved water and sanitation services			
For piped water and sewerage			
Ln(Per capita GDP) elasticity	2	7	12
% urban population elasticity	0.3	0.45	0.6
For non-piped improved water only			
Ln(Per capita GDP) elasticity	5	7.5	10

[17] The Copenhagen Consensus Center did provide regional estimates for economic growth for low growth (GDP rising from 1.5% per annum in Europe to 3.5% per annum in Asia, with other regions in between) and high growth (GDP rising from 2.5% in Europe to 4.5% in Asia, respectively) scenarios. We show results using these projections in the Appendix, but prefer in this paper to comment on the more nuanced picture that arises when heterogeneous country trends are used. Historical growth trends in many developing countries have outpaced these regional averages, particularly over the recent 1990-2008 period, the recent economic downturn notwithstanding.

% urban population elasticity	0.1	0.2	0.3
For improved sanitation only			
Ln(Per capita GDP) elasticity	8	11	14
% urban population elasticity	0.2	0.35	0.5
B. Elasticities of the WASH-related death rate (in deaths per thousand)			
Ln(Per capita GDP) elasticity	-0.1	-0.3	-0.5
% piped water coverage elasticity	-0.02	-0.03	-0.04
Sensitivity analysis only: % improved water coverage elasticity	-0.02	-0.03	-0.04
C. Elasticities of average time to collect water (in minutes to source)	-0.5	-2.5	-4.5
Ln(Per capita GDP) elasticity	-0.3	-1.2	-2.1
% urban population elasticity of average time to collect water	-0.025	-0.06	-0.095

The lower and upper bounds for our sensitivity analyses of piped water coverage to income come from the 90% confidence intervals from the base case fixed effects regression model estimates shown in Table 3. We also make one other adjustment to our simulated results because the JMP data do not report sewerage rates, to account for the fact that coverage with sewerage is generally about 10-15% lower than coverage with piped water (Komives et al. 2003). To forecast piped water + sewerage, we therefore reduce the piped water estimates by 12% for all countries in which piped water coverage is greater than 20%; and by a linear factor down to no difference at a coverage level of zero for those in which piped water coverage is less than 20%. Finally, for calculation of the economic benefits of reduced illness and time savings from improved coverage with water and sanitation services, i.e. VSL, COI and the opportunity cost of time savings, we explore the effect of varying simulation model assumptions between the bounds presented in Table 5, which are based on work in Whittington et al. (2009) or on personal judgement.

Table 5. Assumptions for valuation of changes in WASH-related mortality and time spent collecting water

Model parameter (*symbol*)	**Low**	**Base Case**	**High**
Value of a statistical life [$VSL(\bar{Y}_{it,80})$]	See Appendix A		
Cost of illness adjustment, as a fraction of mortality benefits (f_{COI})	10%	25%	40%
Average household size ($hhsize$)	4	5	6
Average trips to collect water per day ($trips$)	1	1.5	2
Assumed work hours per week; for deriving opportunity cost of time from per capita GDP (L^w)	30	40	50
Opportunity cost of time spent collecting water, as a fraction of hourly wage (v^t)	0	0.25	0.5

Other variable assumptions:
- Inclusion of 1) piped water and sewerage only, or 2) all improved water
- GDP growth trajectory: 1) 1950-2008 or 2) 1990-2008
- VSL and opportunity cost of time using average 1) per capita GDP or 2) per capita GDP for bottom 80%
- VSL based on 1) curve fit to empirical data or 2) income elasticity of 1.5, as outlined by Hammitt and Robinson (2011). See Appendix A for details.

Since the Copenhagen Center scenarios assume positive economic growth in all regions, and since we use UN projections for urbanization rates (which also strictly increase over time), the model predict that piped network coverage will increase and WASH-related mortality rates and average time spent collecting water will decrease on a per capita basis. This trajectory does not necessarily hold in absolute terms, however, due to population growth. Similarly, economic losses may increase even as per capita trends improve, since the economic opportunity cost of time and the economic cost of mortality will increase with rising income. We track the following regional and global indicators over time, focusing on the period 1950-2050:

1. Percent coverage with piped water and sewerage (and improved water and improved sanitation only), and population not covered by these services;
2. Regional WASH-related mortality rates (as a percentage of population) and total numbers of deaths; and
3. The value of a statistical life and health-related “economic losses”, and the opportunity cost of time lost collecting water (in dollars and as % of GDP).

We do not extrapolate before 1950 because of insufficient data on the variables required to make those calculations.

Results

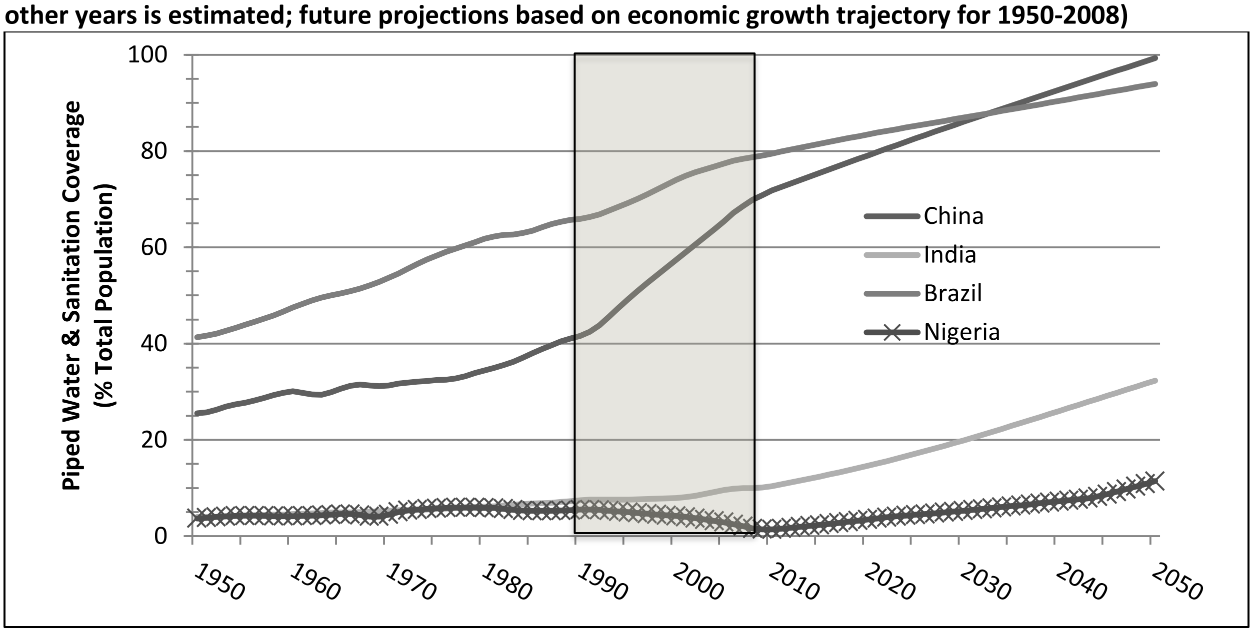
This section of the paper presents our estimates of historical and future coverage, WASH-related mortality, and “economic losses” due to poor water and sanitation services. We first present base case estimates for four large countries (China, India, Brazil and Nigeria) because these results illustrate several interesting features of the global water and sanitation problem, as well as highlight some of the limitations of these projections. Second, we turn to aggregate regional and global estimates of historical, present and future coverage with various levels of improved water and sanitation. Third, we show historical and future projections of the WASH-related mortality risk. Fourth, we present our calculations of regional and global health burden (in deaths) and “economic losses” related to poor water and sanitation from WASH-related illnesses, and time spent collecting water. We also conduct analyses to test the sensitivity of our projections to the model parameters shown in Tables 4 and 5.

The evolution of water and sanitation coverage and WASH-related economic losses in China, India, Brazil, and Nigeria

China, India, Brazil and Nigeria are among the most populous countries in the world, and represented 51% of the total population in the developing world in 2010 (2.9 out of 5.6 billion). They are thus critical to understanding the global picture of water and sanitation in poor countries. Also, the data available suggest that they have very different levels of coverage with water and sanitation services, WASH-related mortality rates, and accessibility to water. As a result, our projections for these four countries illustrate the considerable heterogeneity in the water and sanitation challenge.

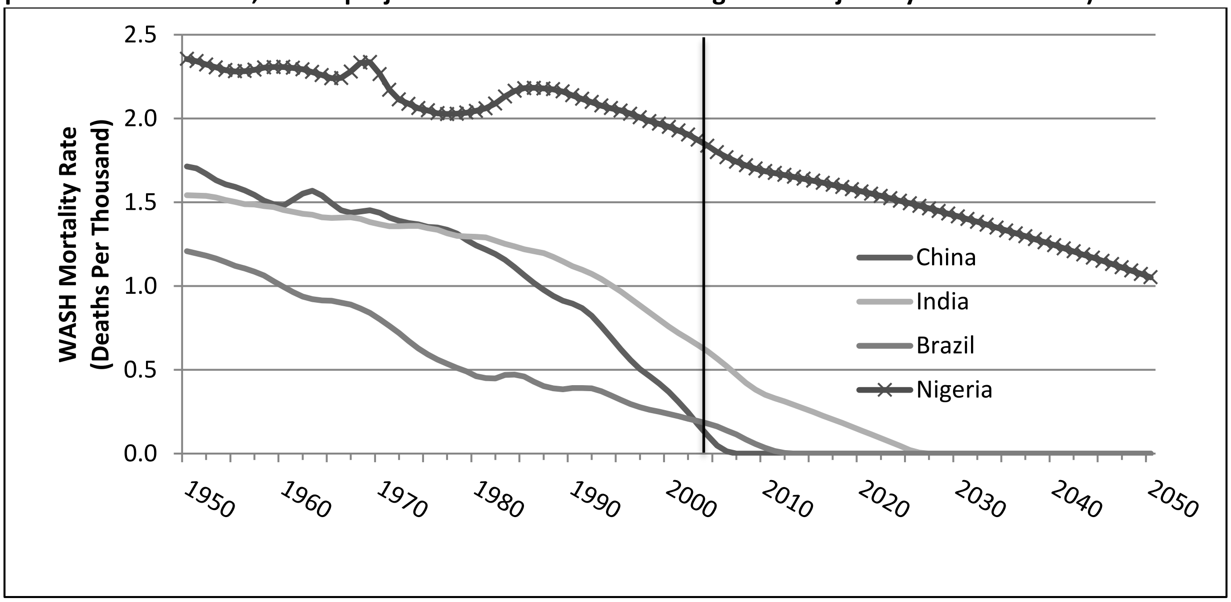
Over the period 1990-2008 China and Brazil increased coverage with piped water and sewer services relatively quickly from moderate levels (40-65%) to 70-80% (Figure 10; the period for which data are available is shown in gray). The extension of these services occurred at a particularly rapid rate in China. In contrast, baseline coverage started from low levels in India and Nigeria (<10%), and increased very slowly in India and actually decreased in Nigeria. These changes took place despite the fact that all four countries were experiencing economic growth during this period (growth in Nigeria and Brazil was slowest, followed by India, and finally China). In Nigeria, the slow expansion of piped water and sanitation services could not keep pace with rapid population growth. Our model projects that coverage will continue to increase most quickly in China, followed by India (as a result of the higher growth projections for these two countries), but that coverage in India will remain relatively low due to its low starting point.

Figure 10. Piped water coverage in four large countries (Shaded area represents years with actual data; coverage in other years is estimated; future projections based on economic growth trajectory for 1950-2008)



Our predicted WASH-related mortality rates mirror these trends (Figure 11). Brazil's and China's mortality rates were lowest in 2004, the year for which we have data (China = 0.04 and Brazil = 0.16 deaths per thousand people). If these data are accurate, China has largely solved the problem of mortality from such diseases, and Brazil is getting close. India, on the other hand, had a WASH mortality rate nearly four times that of Brazil (0.57 deaths per thousand), and Nigeria's was even higher (1.8 deaths per thousand). In the base case, the simulation model suggests that the WASH-mortality rate in India could decline to nearly zero over the next twenty years, but Nigeria, with slowly expanding coverage and a lower growth trajectory, could continue to have high WASH-related mortality through 2050. A key puzzle in the 2004 data is that the WASH-related mortality rate in India appears to be so much lower than that in Nigeria, despite the low piped water coverage in both countries. This could be due to better economic conditions in India, higher general health services, and/or the higher levels of access to more general "improved" water sources (58% in Nigeria vs. 88% in India in 2008).

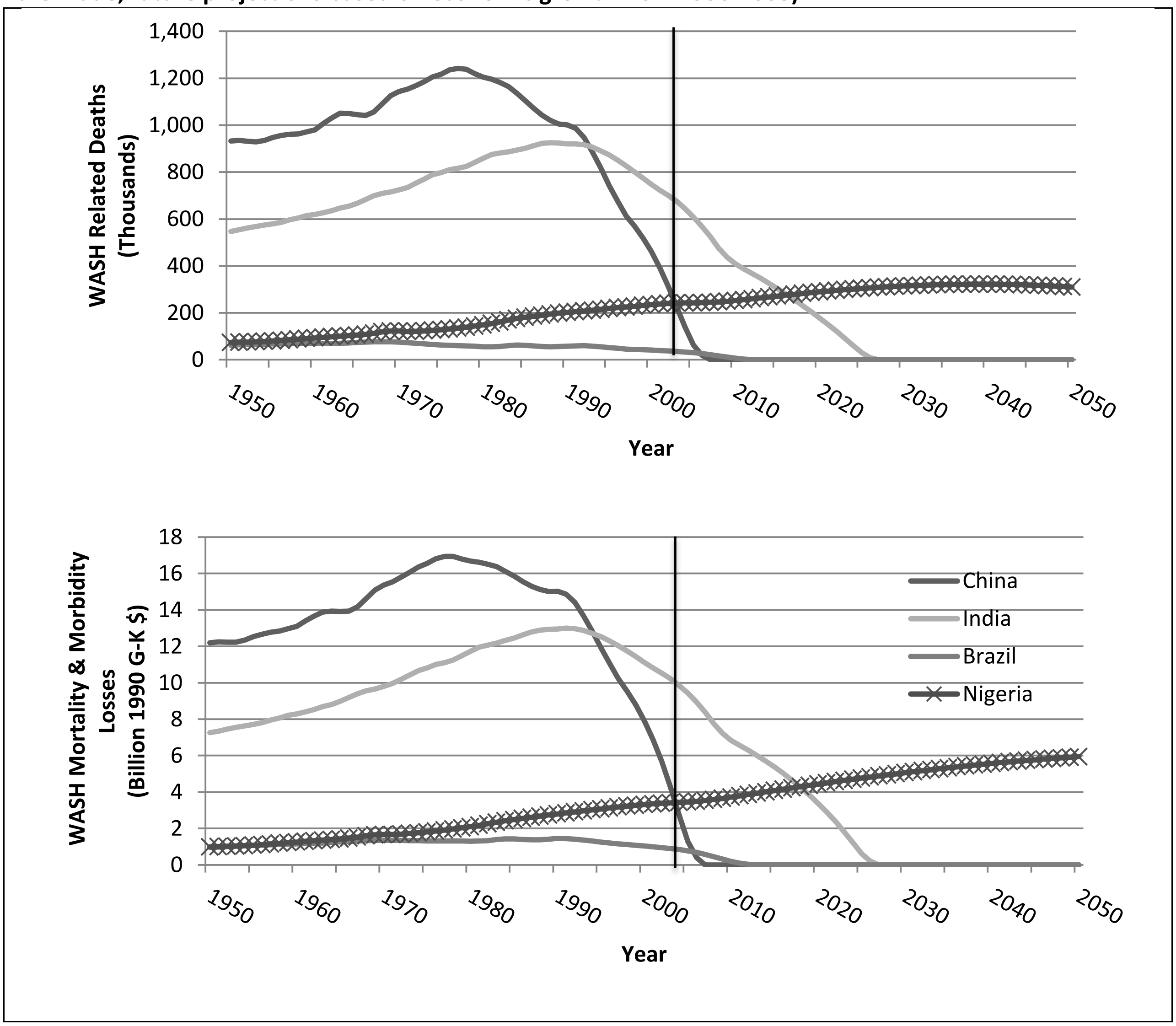
Figure 11. WASH-related mortality in four large countries (Dark line shows the year with mortality data from which predictions are made; future projections based on economic growth trajectory for 1950-2008)



These projections of the mortality rate are used to estimate the number of deaths associated with poor water and sanitation (Figure 12 top panel). Despite mortality rates that are mostly flat or decreasing over the simulation period, the model suggests that the number of deaths in all countries was increasing throughout much of the 20th century, largely because population growth was outpacing projected declines in mortality rates. In China, a dramatic transition occurred in the late 1970s and early '80s, when population growth slowed dramatically even as the mortality rate probably declined at an increasing rate, as shown in Figure 11. These two trends led to rapid declines in the number of WASH-related deaths in China. In Brazil, WASH-related deaths fell slowly, in part because population growth was slower and slightly outpaced by predicted mortality declines. The model suggests that the number of WASH-related deaths in India may have peaked in the early 1990s, but that deaths in Nigeria, where the demographic transition is only beginning and mortality rates remain very high, could continue to increase until the middle of the 21st Century.

Next we turn to the economic losses associated with WASH-related illnesses. Because the economic cost per case or death increases with GDP, the relative position of the peak in health losses depends on the relative rates of decline in mortality rates and of increase in GDP and the VSL (Figure 12 bottom panel). For China, our base case suggests that this peak occurred around 1980, close to when deaths began to decline. Brazil, on the other hand, saw increasing "economic losses" up to a peak around 1990 in spite of decreasing deaths over time. In India, the peak in economic losses from WASH-related illnesses occurred just after the peak in deaths in the early 1990s. The trajectory in India lags that in China by about 15 years. In Nigeria, the economic losses from WASH-related illnesses have been increasing, and continue to do so throughout the simulation period, even though deaths peak around 2040. Nigeria's trajectory represents a case where both incomes and population are increasing quickly and where WASH-related mortality starts from a high level, such that economic losses increase even as death rates are reduced.[18]

Figure 12. Predicted number of WASH-related deaths (top panel) and "economic losses" due to WASH-related health problems (bottom panel) in four large countries (Dark line shows the year with data from which predictions are made; future projections based on economic growth from 1950-2008)

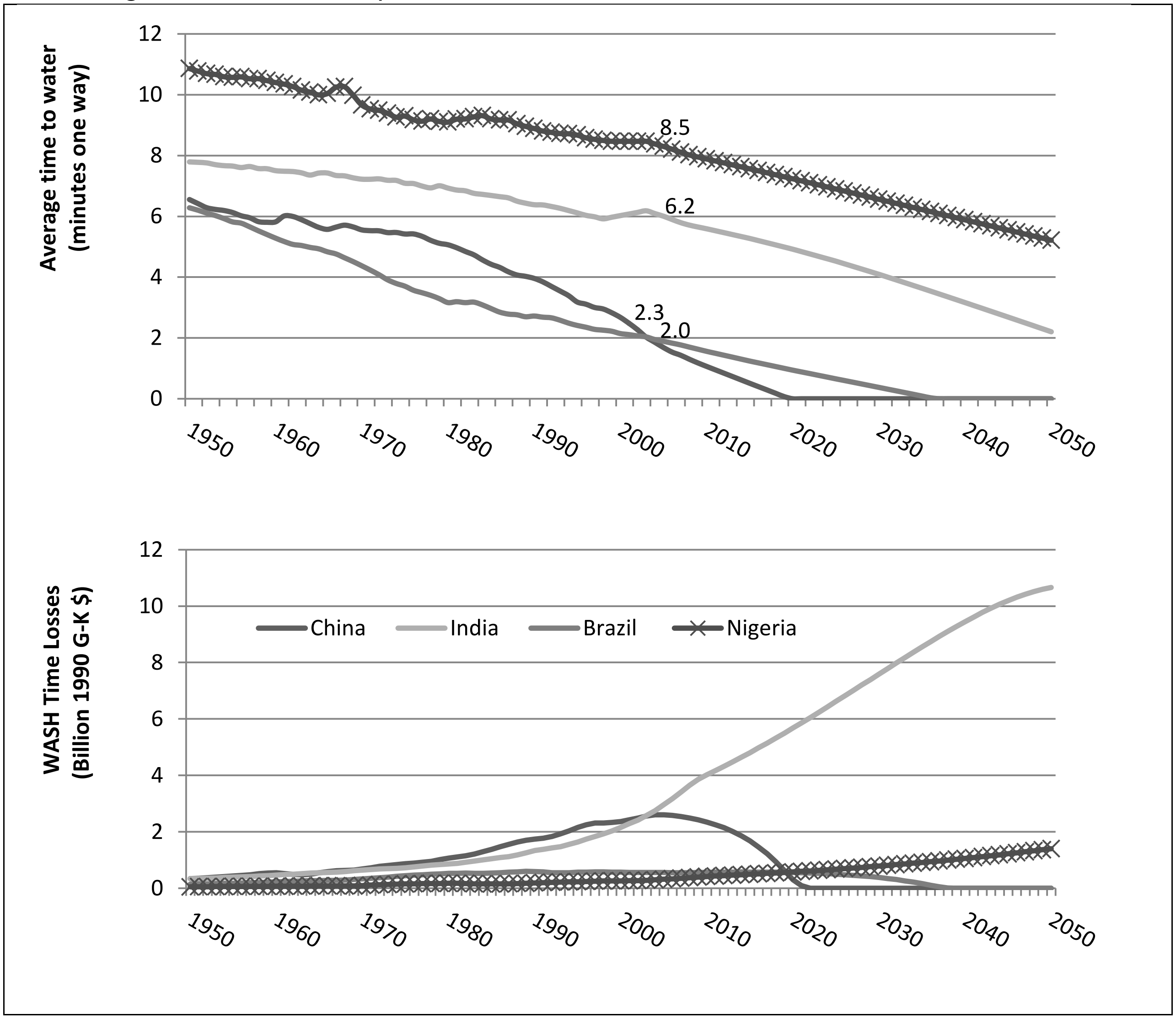


[18] We note that these results, and the issue of whether the peak in health losses in aggregate will lag the peak in deaths, are sensitive to the values of the parameters in the model (and the same also applies to time costs associated with poor access to water supplies). This is also illustrated by the variation across these countries with different baseline GDP and WASH-related mortality rates.

The data on average time to water suggests that the convenience of access to water supplies is also varied across these four countries. China and Brazil have the lowest one-way time to water, with 2.0 (in 2002) and 2.3 (in 2003) minutes, respectively. India is next, at 6.2 minutes (2003), followed by Nigeria (8.5 minutes in 2003). As with the WASH-mortality rate calculations, model projections for time to water over the simulation period are made from a single year of measurements (Figure 13 top panel), and forecasts (and backcasts) are driven by the associations with GDP and urbanization rates.[19] These suggest that average travel times will drop to zero in China just before 2020, and in Brazil about 10 years later. In India, average time to source is predicted to fall to 2 minutes on average by 2050, while Nigeria will decrease to about 5 minutes.

[19] Unlike the WASH-attributable mortality data, which is all for 2004, however, the time to source is available for different countries in different years, and several countries, for example Nigeria, India, and Benin, have measures in several years, since several of the surveys producing those data were conducted in those countries.

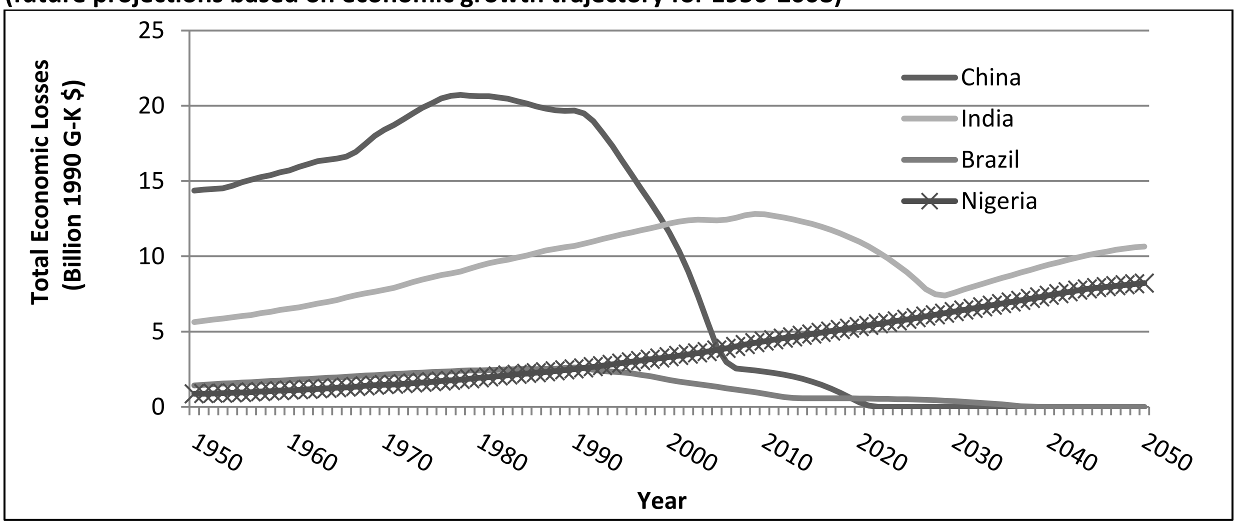
Figure 13. Predicted time to water (top) and "economic losses" due to time costs (bottom) in four large countries (Actual data points from which predictions are made are identified by diamonds; future projections based on economic growth from 1950-2008)



For these countries, the modeled trajectory of time costs for collection of water is somewhat different than that for health losses (Figure 13). Collection times are less strongly associated with income than are mortality rates (see Table 4), and thus remain well above zero for most of the simulated time period. Thus, falling average time to water does not so easily offset the higher aggregate costs associated with rising population and income. Only in China and Brazil time costs peak and then fall to zero in the base case (around 2002 and 2013, respectively). In India, time costs peak only around 2050. India's total time costs rise to very high levels (about G-K$10 billion per year) relative to the other countries, due to a combination of factors: 1) its low coverage with in-house water and sanitation, 2) its large population and 3) its relatively high income trajectory. In Nigeria, time costs rise steadily throughout the simulation period, owing to a similar combination of factors, and reaches about G-K$1.5 billion per year in 2050.

Finally, we turn to aggregate "economic losses", represented by the sum of the health losses and time costs from Figures 12 and 13 (Figure 14). For China, Brazil and India, there is an early peak that corresponds exactly with the peak in health losses, followed by a decrease over some period of time. Time costs, which start from much lower levels, lag behind the peak in health losses, and eventually lead to newly rising total costs in India. China and Brazil's trends slow but continue their downward trend, dropping to zero only when time costs also fall to zero. In contrast, aggregate costs in Nigeria are forecast to rise throughout the period because both health and time costs are increasing over the whole simulation period.

Figure 14. Predicted aggregate "economic losses" due to poor access to water services in four large countries (future projections based on economic growth trajectory for 1950-2008)



Before moving to our global projections, a few brief observations on limitations are necessary. First, coverage with piped water in these four countries over the data period (1990-2008) does not exactly follow the projected trends from our model. There are two primary reasons for these deviations. One is that the country forecasts are based on average associations across all developing countries in our data set between income, urbanization and coverage, and thus individual countries may see faster or slower expansions depending on their own particular situations, which are not captured by the co-variates in our regression model. Some of these particularities may have to do with individuals' demand for improved services, and some may be related to government intervention such as investment in infrastructure. As shown in Figure 10, coverage expansion in India, and especially Nigeria, has been slower than expected, while China's has been faster.

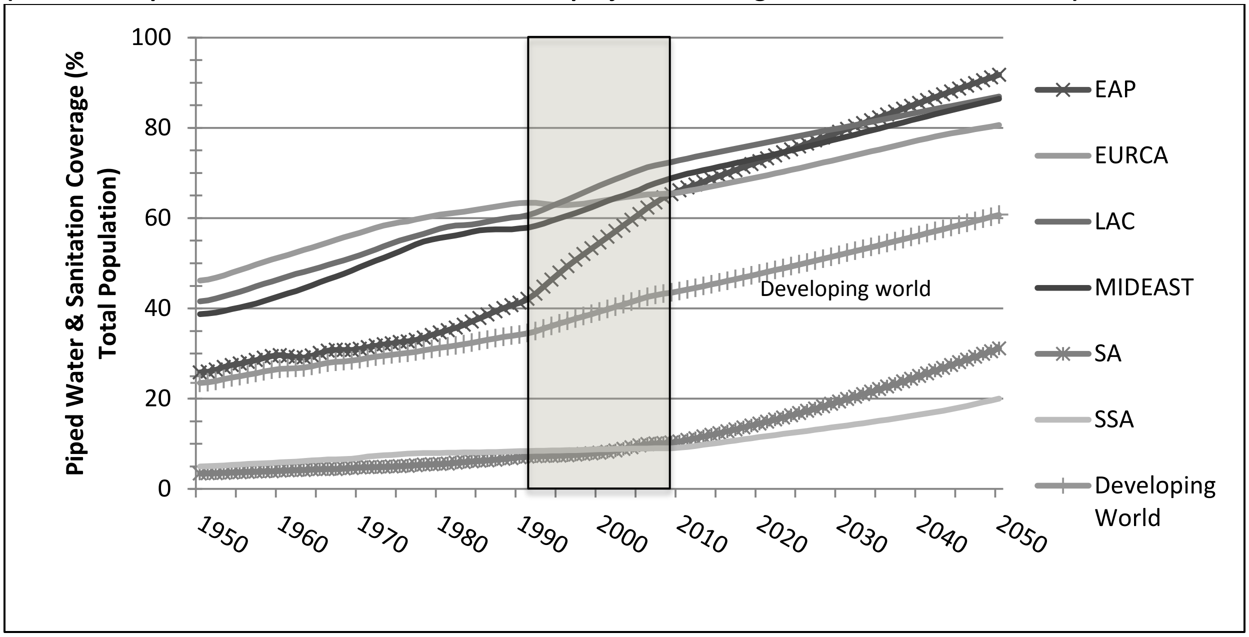
Another reason for these differences is that we use historical GDP growth from a longer period of about 60 years, rather than the 18-year period that coincides with the water and sanitation coverage data. During that period, China's economy grew very quickly. In fact, one might expect that rising economic costs (in time or health) would create pressure and demand for improved services. Our model does not account for such endogenous feedbacks, so it is unclear precisely how realistic it is to think that economic losses in Nigeria, or time costs in India, for example, would continue to rise until 2050. There is certainly nothing inevitable about such forecasts of economic losses. In the interest of space, we have not presented sensitivity analysis of the forward and backward projections for these four countries, though we do present such sensitivity analyses for the global analysis.

The progression of water and sanitation coverage in all developing regions

Figure 15 shows our base case estimates of the percentage of population with access to piped water and sewerage in different regions. These estimates are from the base case parameterization for the association between coverage and urbanization and historical GDP growth (see Table 4). There are four noteworthy aspects of these results. First, the backcasts for the transition from coverage levels between 1950 and 1990, like the forecasts starting from 2008, are highly uncertain; no data exist for this period so our estimates are based solely on changes in GDP and urbanization since 1950.

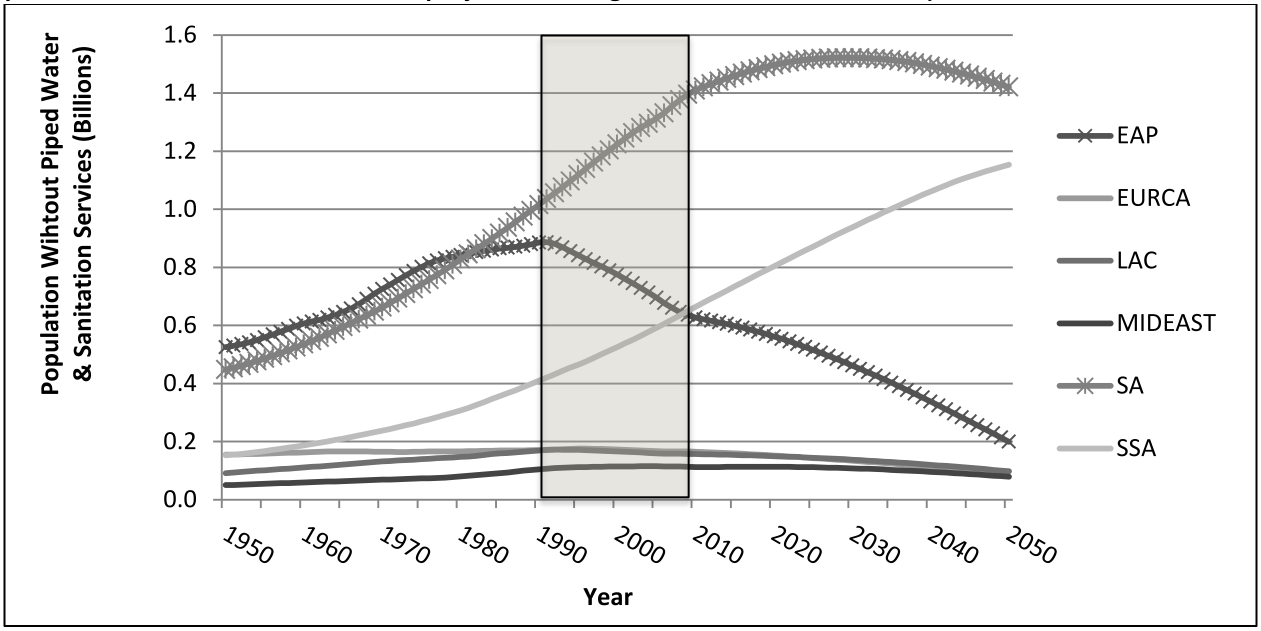
Second, the increase in global coverage (the double black line) from 1990-2008, appears slightly faster than our past and future projections. This increase was partly driven by robust economic growth of 6-7% in several regions: East Asia / Pacific (EAP), the Middle East (MIDEAST) and Latin America (LAC). The most dramatic expansion of piped water and sewerage occurred in East Asia and the Pacific, due largely to the changes in China discussed in the previous section, which may be related to factors besides economic growth. Since China is such a large part of the global population in the developing world, but only represents one data point in the multi-country regression used to obtain model elasticities, the rapid expansion of services there explains much of the difference between the observed data and the trends. In contrast, recent increases in coverage in South Asia (SA), Sub Saharan Africa (SSA), and Eastern Europe (EURCA) appear somewhat lower than our projected trends. SSA and SA stand out with their low baseline levels of coverage and slow rates of increase in coverage, despite recent accelerated economic growth in SA. If these trends continue, coverage with piped water and sanitation services will not exceed 30% in these regions, even in 2050.

Figure 15. Percent of population with piped water and sewerage, by region, with base case coverage elasticities (actual data period shown in shaded box; future projections use growth rates for 1950-2008)



Third, despite increases in global coverage rates, the total population without piped water and sanitation was actually increasing in most regions (except perhaps EURCA) up until the early 1990s, and has only recently begun to decline in the MIDEAST, EAP, and LAC regions, where the demographic transition has taken hold (Figure 16). The population without access continues to increase rapidly in SA and SSA. Our base case projections suggest 1.2 billion and 1.4 billion people still could be without piped services in 2050, in SSA and SA respectively. The population without coverage peaks in SA around 2030, and increases in SSA throughout the simulation. The base case projection shows global population without piped water and sanitation peaking just before SA does, around 2027.

Figure 16. Population not covered with piped water and sewerage, with base case coverage elasticities (actual data period shown in shaded box; future projections use growth rates for 1950-2008)



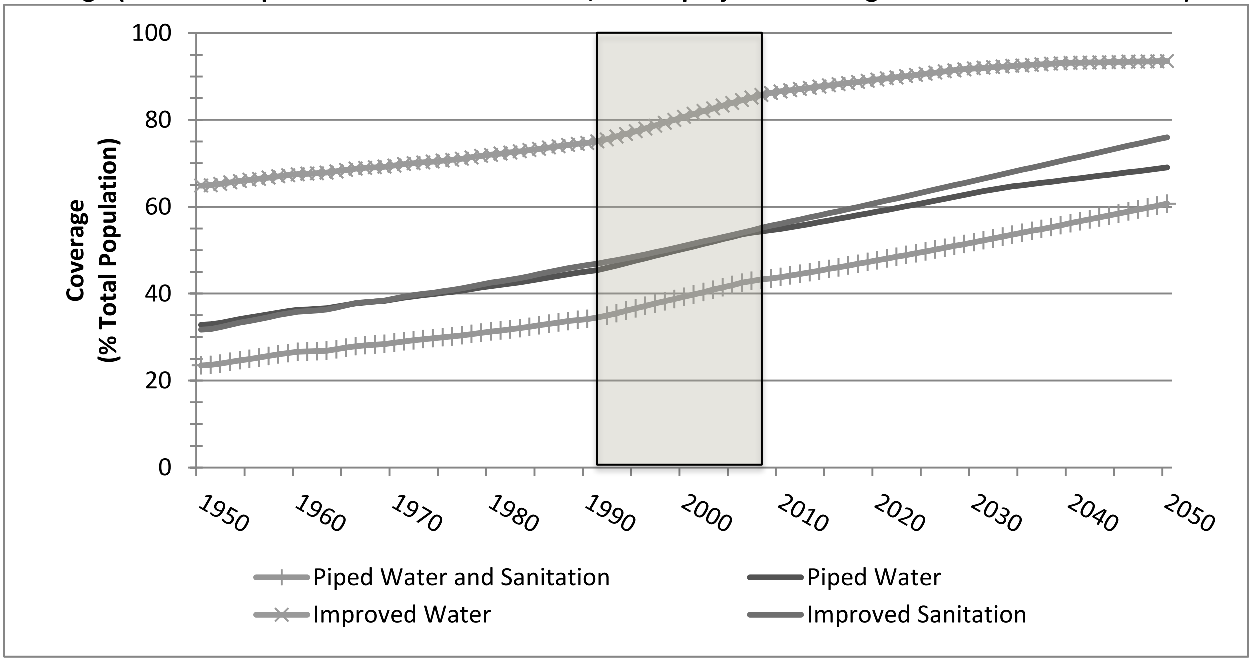
Fourth, if we consider global coverage with "improved water", "improved sanitation", or piped water only, rather than piped water plus sewerage, the percentages served look much better (Figure 17). Globally, coverage increases with improved water – up to 85% in 2008, and projected to rise to 94% in 2050 – in particular have been slightly faster during 1990-2008 than our base case projections predict. Again, this is partly the effect of expansion in water services in EAP, LAC and MIDEAST, but increased access to improved water has also been more broadly based than that for piped water. In SA, for example, access to improved water has risen dramatically over the data period.[20] Global coverage with improved sanitation and piped water (around 55% in 2008) is much lower than it is for improved water alone. Access to piped water plus sewerage is lowest, at about 42%. The association we use for our base case projections between improved sanitation and economic growth is stronger than it is for piped water, such that our predictions of improved sanitation coverage rise to about 76% by 2050 (in comparison with 70% for piped water and 60% for piped water and sewerage).

There are important regional differences in coverage with non-piped water and sanitation services. SSA lags far behind all regions in coverage with improved water (60% in 2008), despite large improvements from 1990-2008. SA is only slightly behind EAP, and all regions except SSA have improved water coverage exceeding 85%. Our base case simulations project coverage levels with improved water above 90% in 2050 in all regions except SSA, which could rise to nearly 70%. For improved sanitation, SA and SSA are similar, and both had coverage rates below 40% in 2008 (other regions are at 60% or better). The trend in coverage in SSA, however, is nearly flat, whereas coverage increases in SA were high from 1990-2008. Our base case simulations suggest that coverage

[20] See Appendix C for additional regional graphs for improved water and sanitation only.

with improved sanitation in 2050 could increase to 40% in SSA, nearly 60% in SA, and more than 90% in other regions.

Figure 17. Percent of global population with various levels of W&S services, assuming base case elasticities of coverage (actual data period shown in shaded box; future projections use growth rates for 1950-2008)



These projections are sensitive to the strength of association between economic growth and urbanization, and coverage with the different services (Table 6). Between 1950 and 2008, even while the percentage of people covered was increasing, high rates of population growth led to larger numbers unserved by any level of improved services. This was especially true for improved sanitation and piped water and sewerage services, for which the global population unserved increased by over 1 billion. We expect coverage rates with piped water and sewerage to increase from about 44% today to 50-69% in 2050. With the upper bound for the respective elasticities of coverage, and using the higher 1990-2008 growth rates, the percentage of people with piped water would rise to 76%; improved water and sanitation coverage levels could reach 95% and 85%, respectively. Conversely, with the lower bound elasticity and using long-term growth rates, coverage rates would increase slowly, to 62%, 70% and 92% for piped water, improved sanitation, and improved water. Accounting for population growth, whether the numbers unserved will increase or decrease depends on the type of service as well as the strength of associations between income, urbanization and coverage. For improved water, the numbers unserved will probably continue to decline; for improved sanitation and piped water alone, these numbers will either stabilize or decline. For piped water and sewerage, either decreases or increases are possible, and the total number unserved could move from 3.1 billion in 2008 to 2.4 – 3.4 billion people in 2050.

Table 6. Ranges of projected coverage with different levels of W&S services in 1950, 2008, and 2050 [a]

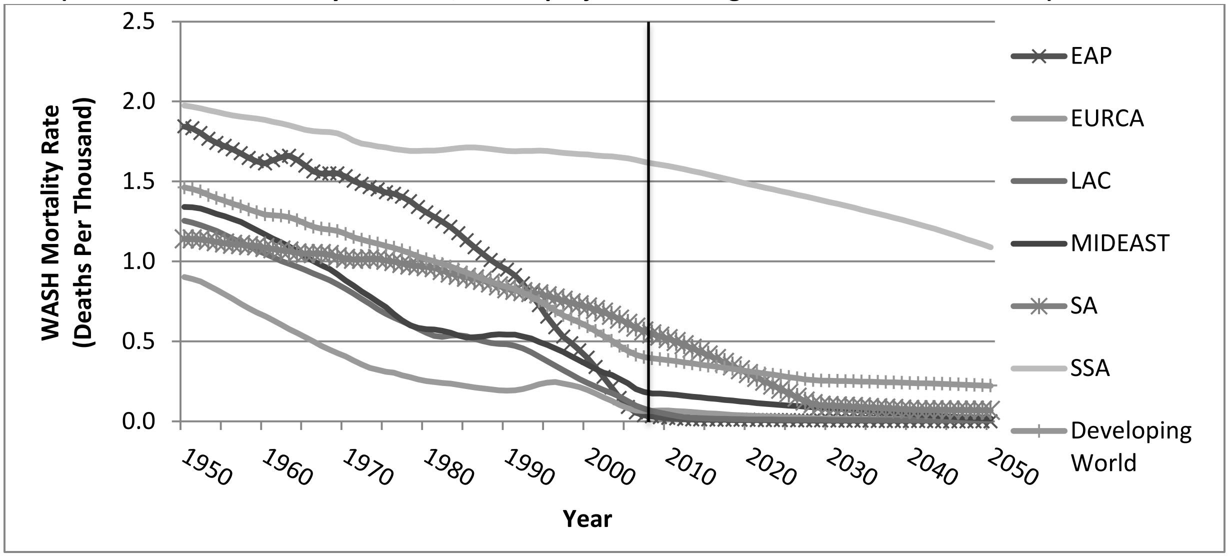
	Improved water	Improved sanitation	Piped water	Piped water + sewerage
Worldwide coverage (%)				
Backcast 1950	65 (61-69)	32 (26-37)	33 (26-40)	23 (17-30)
Year 2008 Data	86	56	55	44
Projection 2050	94 (92-95)	76 (70-85)	69 (62-76)	61 (50-69)
Population unserved (billions)				
Backcast 1950	0.7 (0.6-0.7)	1.3 (1.2-1.4)	1.2 (1.2-1.4)	1.4 (1.4-1.5)
Year 2008 Data	0.8	2.4	2.5	3.1
Projection 2050	0.5 (0.4-0.5)	1.9 (1.4-2.4)	2.4 (1.9-2.6)	3.0 (2.4-3.4)

[a] Low and high estimates shown in parentheses following base case; estimates derived using the elasticity parameters in Table 4, and with both economic growth scenarios.

Historical and Future WASH-Related Mortality

Our model simulations suggest that WASH-related mortality rates have been and will continue declining in most regions over much of the period 1950-2050, reflecting trends in economic growth and coverage with piped water and sanitation services (Figure 18). The mortality rate was 0.39 deaths per thousand across all developing country regions in 2008, down from 1.5 deaths per thousand in 1950 (at which time rates ranging from just under 1.0 deaths per thousand in EURCA to 2.0 deaths per thousand in SSA). Simulated declines are slowest in SSA due to its relatively low economic growth and low coverage with piped water and sanitation services. The drop is steepest in EAP, followed by the MIDEAST and LAC regions; these large declines are driven by the modeled associations with rapid economic growth and the coverage expansions in these regions (particularly China). At the end of the simulation period, the average mortality rate across developing regions is predicted to be 0.22 in the base case. The nonzero WASH mortality at the global level in 2050 is mostly driven by the high mortality rates in SSA, which becomes relatively more important as SSA's population continues to expand.

Figure 18. The WASH-related mortality rate, by region, assuming base case elasticities of WASH-related mortality rate (Data for 2004 shown by dark line; future projections use growth rates for 1950-2008)

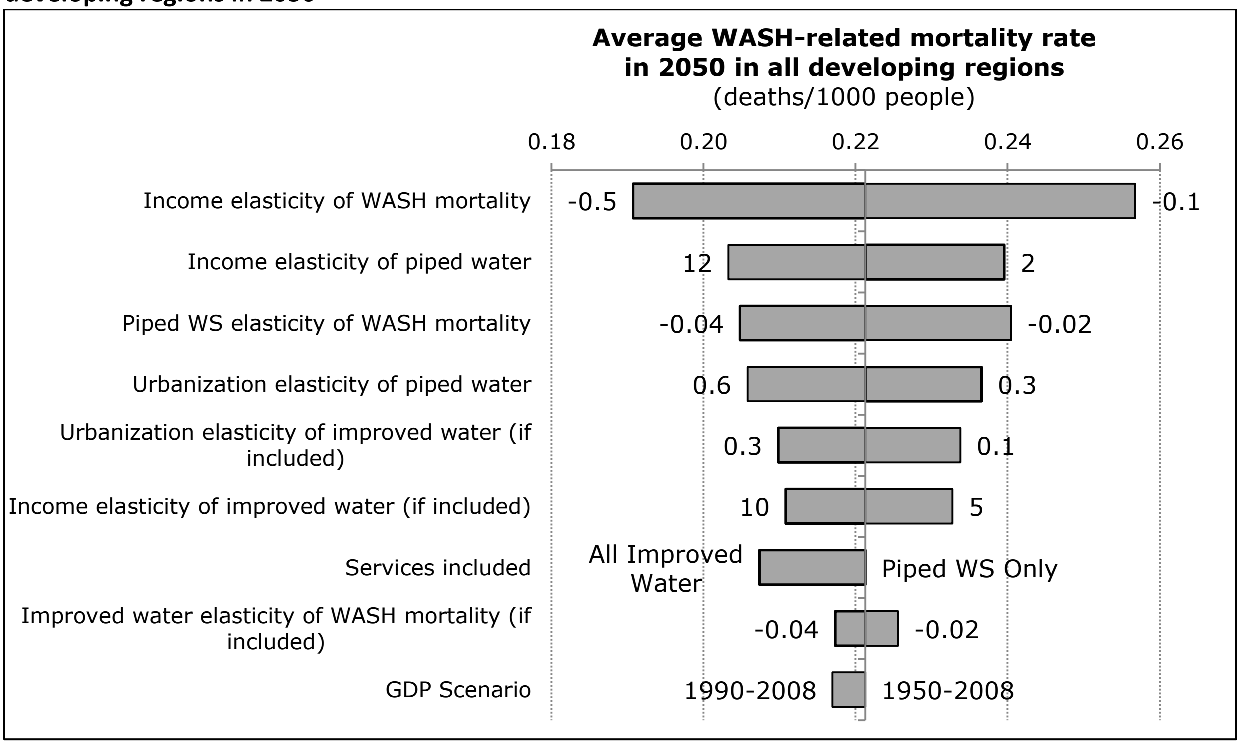


However, the data on which these projections are based, from the year 2004, contain several puzzles. In those data, the entire SSA region, like Nigeria by itself, stands out with its very high WASH-related mortality rate. This high baseline mortality is the primary factor driving the model result that WASH mortality remains much higher in SSA than in the other regions over most of the simulation period. In contrast, SA appears to have very similar levels of piped water and sanitation coverage to SSA, but much lower WASH-related mortality rates in 2004. By 2050 the model projections for WASH-related mortality in SA drop to nearly zero. It is not clear why the WASH-related mortality rates in the WHO data are so different in these two regions. The discrepancy could arise from real differences in access to other services, for example better health systems, treatments and technologies, greater access to “improved” (not piped) water and sanitation, or greater connectivity due to higher density. It could also be the result of measurement error or other limitations of the WHO analysis.

It is also difficult to know whether WASH mortality rates dropped as much as we predict in other regions. What we can say is that WASH-mortality rates in developing regions other than SA and SSA are currently low (relative to those regions), and that overall, non WASH-specific, mortality rates have been in decline across many parts of the globe over the past two decades. Thus, though we have doubts about the specific levels of mortality in SA and SSA, we believe that the trajectory in the model projections is probably realistic, and is consistent with other projections of declining mortality from infectious and diarrheal diseases (Kosek et al. 2003; Mathers and Loncar 2006). In most regions, WASH-related mortality rates will likely be very low by 2030, due to the many health improvements that come with economic growth, as well as higher coverage with water and sanitation services.

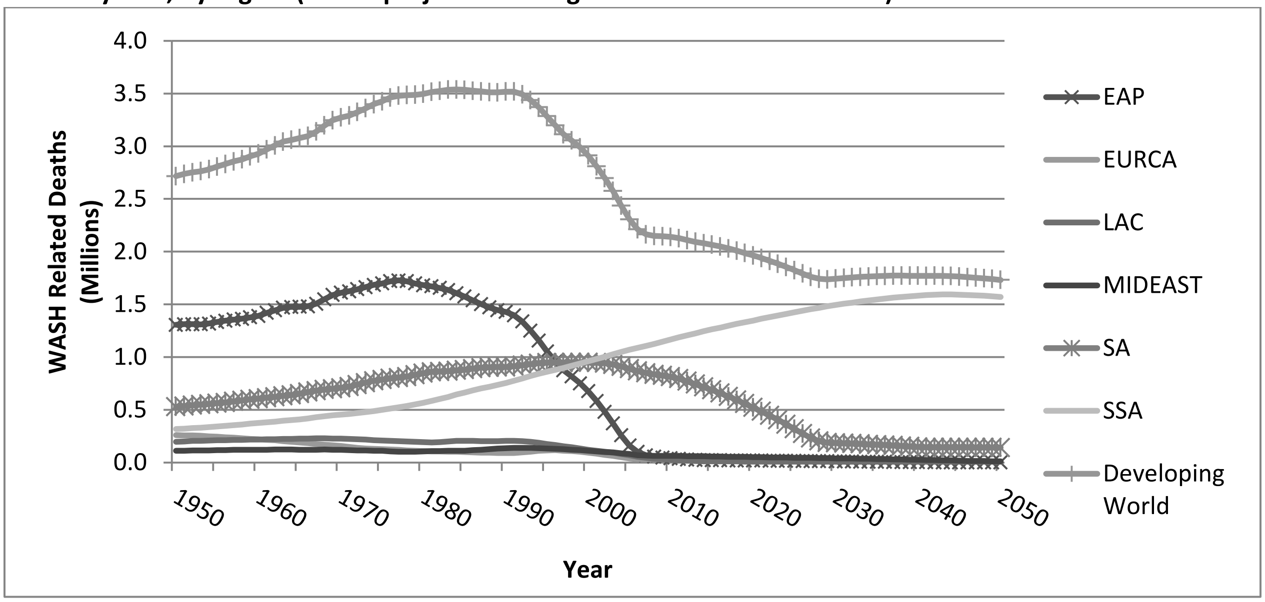
Our sensitivity analyses suggest that the projected global mortality rates due to WASH-related disease are most sensitive to their assumed association with income (Figure 19). The 90% confidence interval range from our empirical analysis, for the value of this parameter alone, implies a range in average mortality rates of about 0.19 to 0.26 deaths per thousand in 2050 (the base case estimate was 0.22). The other most important parameters driving uncertainty in our projections of mortality rates are the income and urbanization elasticities of piped water services, and the piped coverage elasticity of mortality. The inclusion of improved water, and its own income and urbanization elasticities, as well as the GDP projections, are relatively less important in driving variation in the predicted mortality rate. If we set all parameters to the values that lead to the highest projected mortality rate in 2050, we obtain a "worst case" value of 0.34 deaths per thousand, which would represent a very small decline in these rates (and the best case outcome is 0.13).

Figure 19. Ranking of factors influencing model projections of the average WASH-related mortality rate across developing regions in 2050



Combining population growth and these mortality rates, we next predict the WASH-related deaths over the simulation period. The base case calculations suggest that the number of deaths in SSA alone could increase from about 1.2 to about 1.6 million per year between now and 2050, peaking around 2045 (Figure 20). This is not much less than the global total of WASH deaths today (2.1 million). In 2050, the only other region with significant numbers of WASH-related deaths in the base case is SA, but this is due to a single country, Afghanistan, for which mortality rates (3.3 deaths/thousand) that start from levels that are higher than all but the three very highest mortality countries in SSA: Angola, Niger and Sierra Leone. The number of future deaths and the trajectory of mortality declines in SSA and SA vary substantially based on our parameter assumptions, and our sensitivity analyses suggest that the global number of deaths from WASH-related disease could range from 1.0 million/yr (high growth and high elasticities) to 2.7 million/yr (low growth and low elasticities) in 2050 (Table 7).

Figure 20. Estimated number of deaths due to WASH-related disease for base case parameterization of the mortality rate, by region (future projections use growth rates for 1950-2008)



Predictions of average time to water

As a result of gradually rising income and urbanization, our model shows declining average time to water in most regions and countries over the simulation period (Figure 21) – similar to the projections of WASH-related mortality rates. Because of the model structure, increases in time to water coincide only with either 1) periods of economic slowdown, or 2) a small set of individual countries for which several years of data are available and show rising collection times. Predicted one-way collection times in 1950 ranged from 4 to 5 minutes in EURCA and LAC in 1950, to about 11 minutes in SSA. By 2000, when these data first became available, the first two of these regions had average times of about 2 minutes, and SSA was at 9 minutes. We project continued declines to nearly zero in EAP, EURCA and LAC around 2030 (where economic growth projections are highest) and to 2-4 minutes in SA and MIDEAST by 2050.[21] Time to water remains somewhat higher in SSA in 2050, at about 7 minutes. The average one-way time to water across all developing regions decreases from about 7 minutes in 1950 to just over 2 minutes in 2050, and is most sensitive to the income elasticity parameter of average time to source.

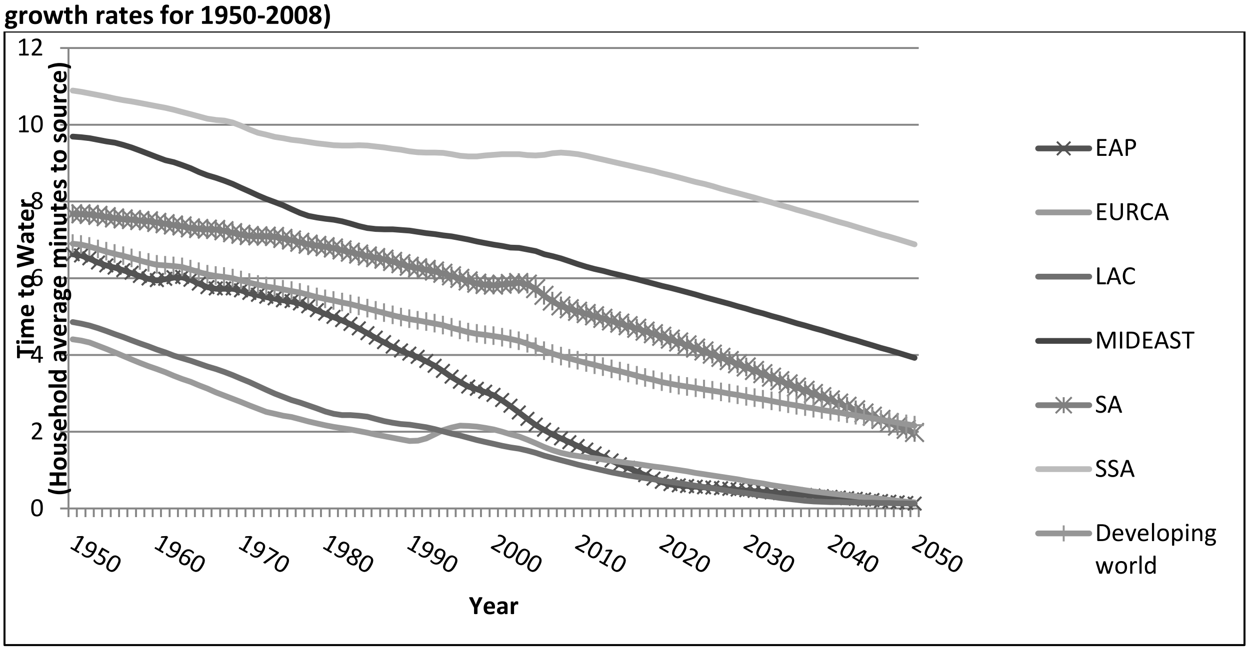
[21] Only three MIDEAST countries have data, however, and these are likely higher than in other countries. They are Yemen, Tunisia and Morocco.

Table 7. Ranges of projected WASH-related mortality and deaths in 1950, 2004 and 2050 [a]

	Year		
	1950	2004	2050
WASH-related Mortality rate (deaths/thousand)			
All developing regions	1.5 (0.82-2.1)	0.43	0.22 (0.13-0.34)
South Asia (SA)	1.1 (0.81-2.0)	0.64	0.1 (0.01-0.24)
Sub-Saharan Africa (SSA)	2.0 (1.8-2.7)	1.7	1.1 (0.60-1.5)
WASH-related deaths (millions)			
All developing regions	2.7 (1.5-3.9)	2.3	1.7 (1.0-2.7)
South Asia (SA)	0.53 (0.37-0.93)	0.9	0.14 (0.03-0.50)
Sub-Saharan Africa (SSA)	0.32 (0.29-0.43)	1.1	1.6 (0.87-2.1)

[a] Best and worst estimates shown in parentheses following base case; estimates derived using the elasticity parameters in Table 4, and with both economic growth scenarios.

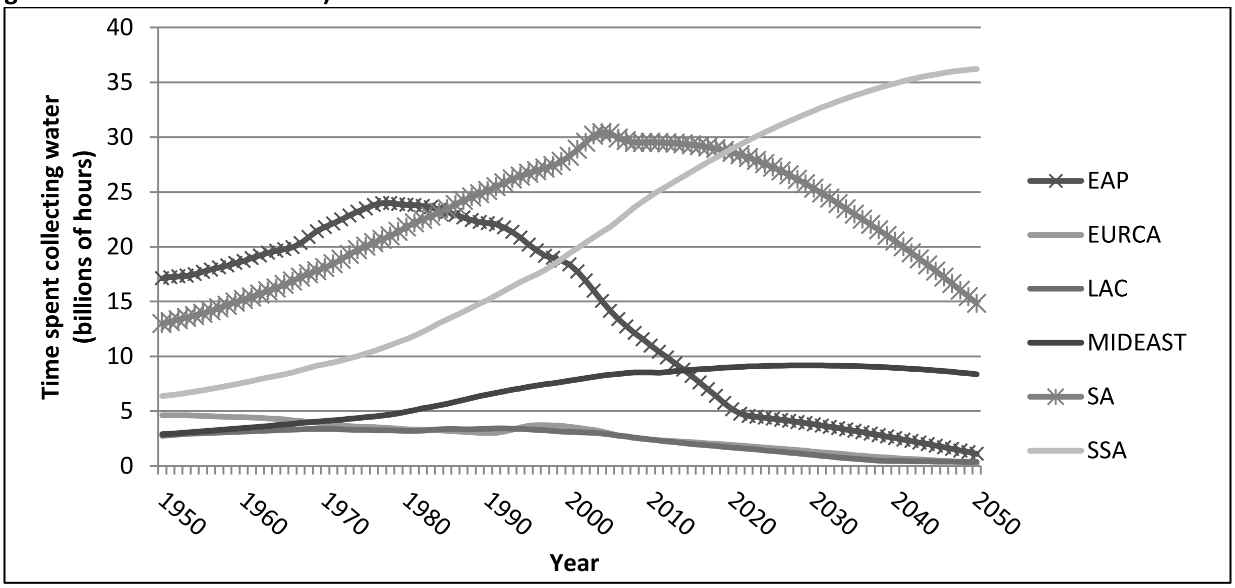
Figure 21. Estimated base case simulation of one-way time to source water, by region (future projections use growth rates for 1950-2008)



We convert these average collection times into total time spent collecting water by multiplying by the number of households, and the number of round trips per household per day, to yield the aggregate regional totals shown in Figure 22 (assuming base case parameter values from Table 5). The resulting trajectory shows that the total time spent collecting water in EAP, LAC, EURCA, and SA is now declining, but that it may still be climbing in the MIDEAST (to about 2030, though the data may overestimate average time to water in this region as mentioned in footnote 21) and SSA regions (no peak over the simulation period), due to population growth.

Total time spent collecting water is declining in the other regions (EAP and LAC) which are further along in the demographic transition or have lower average time to water. Globally, aggregate time spent collecting water for the base case simulation rose from about 47 billion hours in 1950 to a peak of 82 billion hours around 2003, and is projected to decline to 60 billion hours in 2050.

Figure 22. Estimated base case simulation of total time spent collecting water, by region (future projections use growth rates for 1950-2008)



"Economic Losses" from Lack of Piped Water and Sanitation Services

Finally, we turn to our calculations of the "economic losses" associated with WASH-related disease, to investigate how rising incomes, and thus the VSL and opportunity cost of time, interact with these various factors of declining mortality rates and time to water, as well as demographics. As shown in Figure 23, the VSL, or "economic losses" per statistical life lost, have been increasing over time across all regions, especially in EAP, because incomes have been increasing (these reach about 4 million 1990 G-K$ in 2050 in EAP, which is very close to levels in the developed world today). The countries in EURCA present an interesting exception to the general upward trend in VSLs since 1990. After the fall of the Soviet Union, real incomes declined in many of these countries; the VSL therefore decreased somewhat in the early 1990s.

If declines in mortality compensate for the rise in the VSL, it would still be possible for "economic losses" to increase on aggregate (not on a per-capita basis) due to population growth alone. Population in all developing regions increases rapidly throughout much of the period simulated in this study. Wherever the number of deaths was increasing over time (in EAP until the late 1970s, the MIDEAST until 1990, SA until 2000, and still in SSA), "health losses" would have been increasing over time as well, given the positive trend in real incomes. The same would also hold true with regard to time costs from collecting water wherever aggregate time to water and incomes were increasing. These population effects were shown in the previous sections.

Figure 23. Average value of a statistical life, by region (projections from 1950-2008 growth rates)

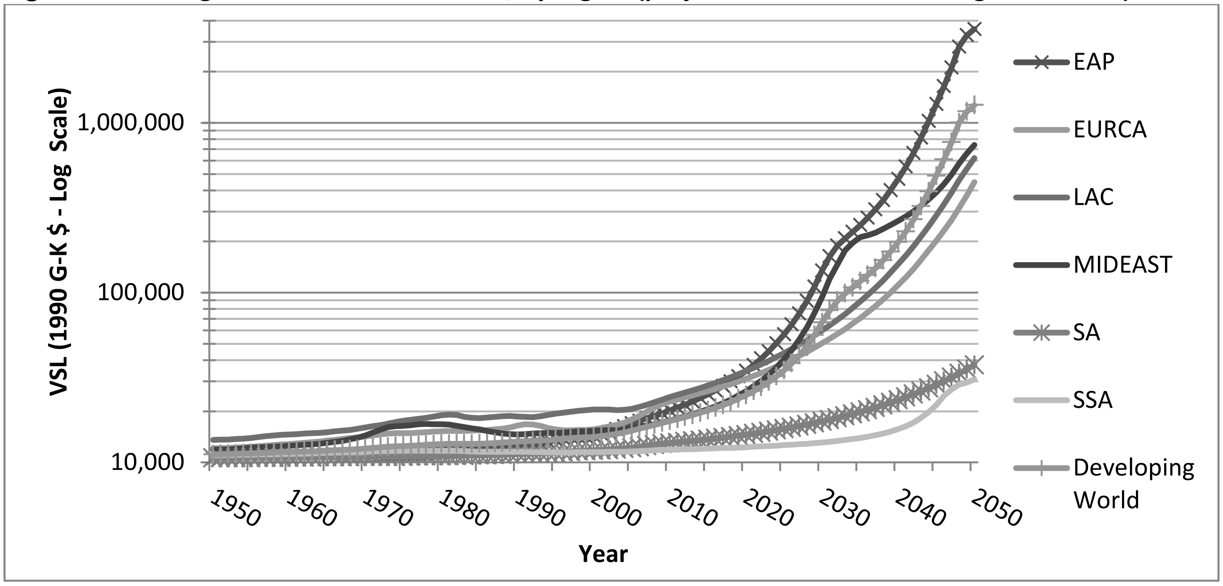


Figure 24 shows our base case estimations of "economic losses" by region, based on future GDP growth projections for 1950-2008. Panels A and B present health losses and time costs, by region, and Panel C presents the global totals (totals by region can be found in Appendix C). Total aggregate "economic losses" in trillions of 1990 G-K$ over the entire period are then summarized in Table 8, which also presents best and worst case sensitivity analyses (which spans a very large range).[22] In EAP, LAC, and the MIDEAST, economic losses due to WASH-related illnesses peaked in the early 1980s or 1990s. Health losses declined in EURCA until the late 1980s and then increased briefly after the fall of the Soviet Union before declining more quickly. Our base case simulations suggest that SA reached a peak in economic losses due to WASH-related illnesses of about G-K$14 billion around the turn of the century. In contrast, economic losses due to WASH-related illnesses for SSA only approach a peak of G-K$25 billion around 2050.

The trajectory of time costs is quite different because the average time to source declines much more slowly in our base case model than mortality, and does not always outpace the combination of increasing value of time and the mostly upward trend in population. In SA, MIDEAST and SSA, time costs rise throughout the period, such that the model predicts that total losses could begin to increase again in the period leading up to 2050. And whereas economic losses due to WASH-related illnesses seem to have been larger than time costs for much of

[22] Note that these aggregate losses are undiscounted and occur over a 100-year period, and are therefore perhaps hard to interpret. Considering the annual amounts at different points in time may be more intuitive: In the base case, we find that these losses are G-K$40, 56, 54, 45 and 57 billion in 1950, 1975, 2000, 2025, and 2050, respectively, as shown in **Error! Reference source not found.**.

the historical period when mortality rates were high, time costs will become relatively more important over time.

It is also useful to put the base case results in perspective by comparing them to the total GDP for the regions involved (Figure 25). We use GDP to contextualize predicted "economic losses" simply to provide a sense of the magnitude of these losses. Losses as a percent of GDP should not be interpreted as the net economic effect of improved service. In our base case this calculation shows that health and time cost have and are likely to decline as a fraction of GDP, even as the absolute "losses" go up. This is because population and economic growth also raise aggregate income, and do so faster than these "losses", at least in relative terms. In the base case "economic losses" start out at about 2% of developing world GDP in 1950, and decline to about 0.02% of GDP by 2050. A few of the countries with the highest losses at different points in time in the base case, for example Angola, Niger, Sierra Leone or Afghanistan, are in the range of 10-14% of GDP.

Figure 24. Base case "economic losses" associated with WASH: A) Health losses, by region; B) Time costs, by region; and C) Aggregate global losses (projections from 1950-2008 growth rates)

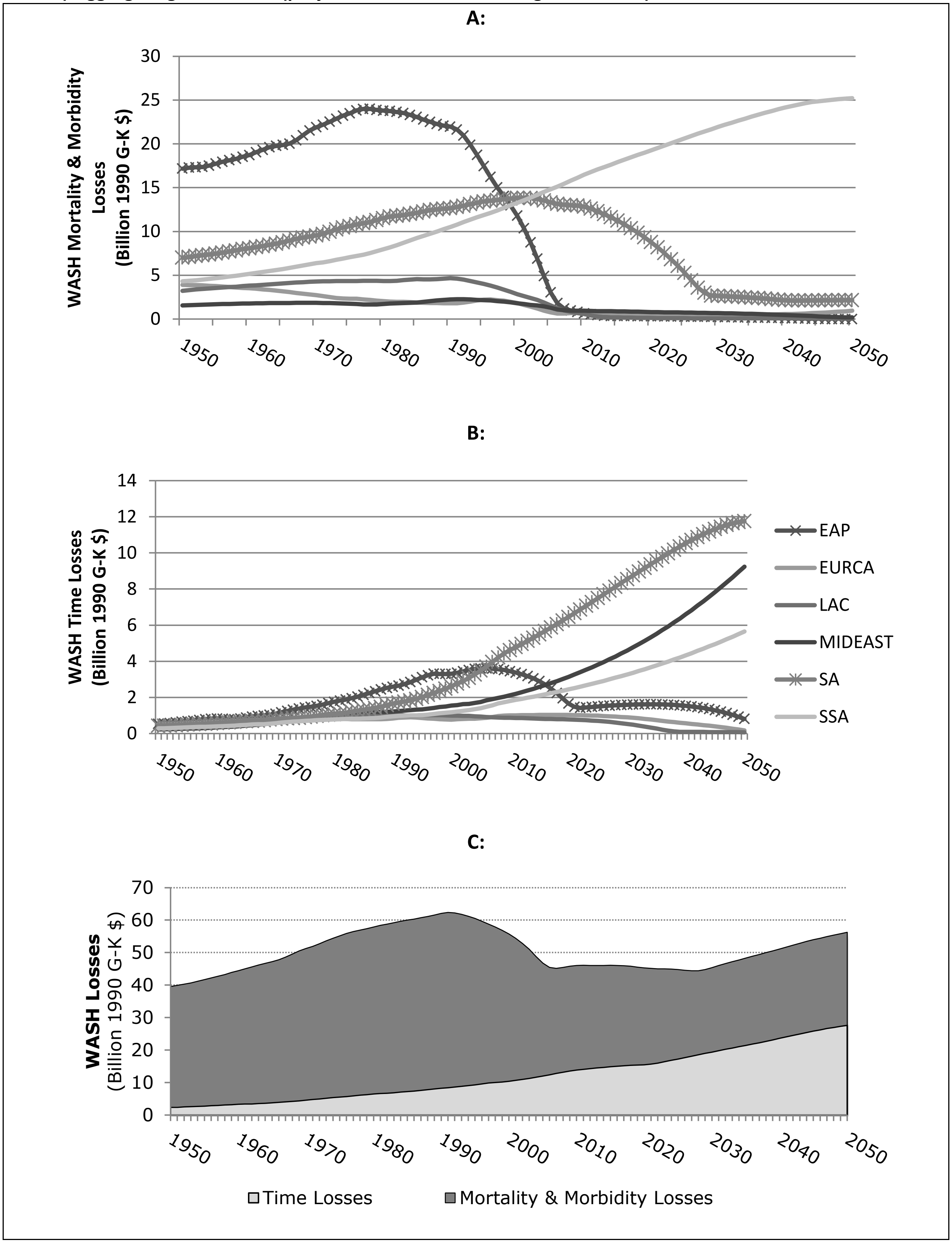
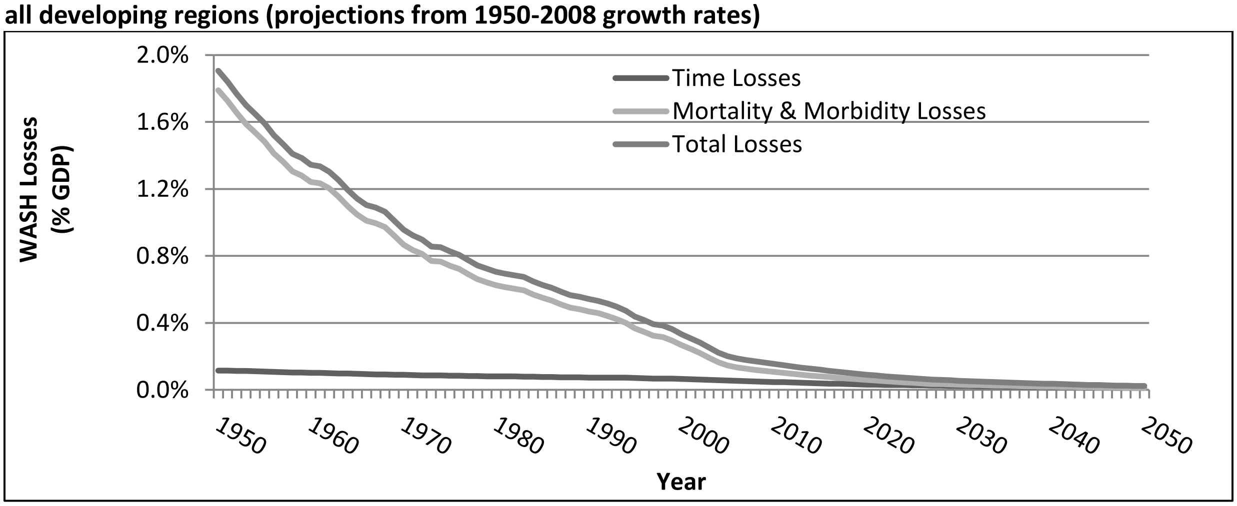


Table 8. Ranges of aggregate "economic losses" associated with WASH, summed over the time horizon 1900-2050 (in trillions of 1990 G-K$; and as % of GDP)

	Low		Base		High	
	Total	% of GDP	Total	% of GDP	Total	% of GDP
All developing regions	0.7	0.01	5.1	0.1	114	2.4
East Asia & Pacific	0.2	0.01	1.3	0.1	33.1	1.3
Europe & Central Asia	0.07	0.01	0.24	0.05	10.7	2.2
Latin America & Caribbean	0.1	0.02	0.29	0.05	10.1	1.8
Middle East & N. Africa	0.03	0.01	0.40	0.1	12.0	3.4
South Asia	0.09	0.01	1.3	0.2	36.5	5.9
Sub Saharan Africa	0.2	0.1	1.6	1.2	11.4	8.6

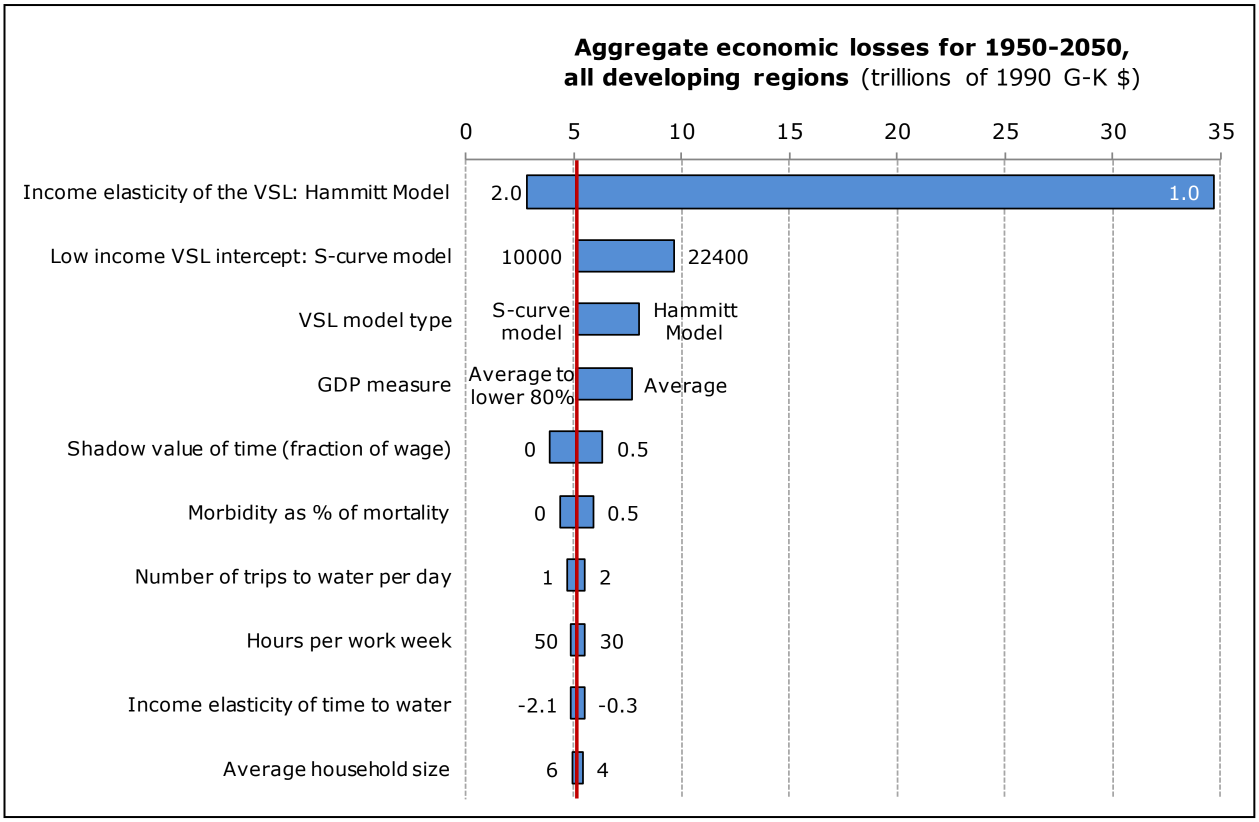
Notes: Derived using the elasticity parameters and other uncertain parameters in Table 4 and Table 5, for two scenarios of GDP growth, VSL assumptions (as outlined in the Appendix; high estimate uses Hammitt & Robinson extrapolation with an income elasticity of VSL = 1.5), inclusion of coverage type (improved water or piped water and sewer only), and use of alternative GDP measures (average GDP to lowest 80% or average GDP overall).

Figure 25. Base case "economic losses" associated with WASH-related diseases as a percentage of GDP for all developing regions (projections from 1950-2008 growth rates)



As shown in Table 8, the base case results are highly sensitive to the value of model parameters. Worst case model results project "economic losses" that are over one order of magnitude larger than those in the base case (and the best case outcomes are about 15% as large). For aggregate losses, by far the most critical factors for varying outcomes are those that determine the assumed relationship between the value of a statistical life (which scales health losses) and income (Figure 26). These are followed by several parameters related to the cost of time spent collecting water (i.e. the shadow value of time, GDP measure, and number of work hours used to derive the opportunity cost of time, and the number of daily trips to collect water) and the relative size of morbidity costs from WASH diseases. Inclusion of improved water access as well as piped water and sewer makes a relatively minor difference in these estimates. Finally, although aggregate losses are more sensitive to the valuation parameters in the model, the precise timing of the different regional maxima in health and time losses shifts considerably depending on the values of the elasticity parameters shown in Table 4. For this reason, one should not make too much of the points where the base case predicts those peaks to occur.

Figure 26. Ranking of factors influencing model projections of the aggregate economic losses over the simulation period 1950-2050



Assumptions about the VSL play a dramatic role in determining the "economic losses" predicted in our simulation model. Typically an analyst would assume a constant income elasticity and extrapolate from rich world VSLs to obtain developing country VSLs (an approach described by Hammitt and Robinson (2011) that is discussed more thoroughly in Appendix A). This is problematic from an analytical perspective because the choice of the appropriate income elasticity of the VSL for developing countries is not empirically-based, but rather relies on the judgment of the analyst. As shown in Figure 26, varying this parameter between 1 and 2 has an enormous impact on the economic analysis of the problem at hand, shifting estimates of "economic losses" from poor water and sanitation from about 3 to 35 trillion 1990 G-K$, and explains a great deal of the variation identified in Table 8. Some familiar with the literature on the relationship between the VSL and income might even advocate using an income elasticity of 0.5, which would raise aggregate losses over the period to 203 trillion G-K$. This would imply that losses in 1950, for example, were nearly 75% of developing world GDP, which is clearly unreasonable.[1] In contrast, variation in the intercept parameter of the more empirically-based S-curve relationship that we develop in the appendix generates a smaller, though still substantial range of uncertainty in loss estimates of 5.1 to 9.6 trillion dollars.[2]

We also note that there is considerable uncertainty in where the peaks in "economic losses" actually occur, though the trajectory of rising and falling economic costs appears consistent across most regions. Many poor countries initially experience high population growth and modest GDP growth, both of which raise per capita and aggregate losses, and often at a faster rate than declines in mortality rate and time to water sources. With growth, however, these declines begin to outpace the drivers of increasing health and time losses. With economic losses due to WASH-related illnesses, this seems to occur much earlier than with time losses, because the income and urbanization elasticities of mortality are larger than those of time to water sources. Due to the positive relationship between economic losses and GDP, we find that the peak in WASH-related health losses lags slightly behind, and is more pronounced than, the peak in deaths in many countries. (This is not the case in China which represents a special case where high growth and demographic changes occurred concurrently.) Similarly, because of the positive relationship between income and time losses, the peak in time losses lags (or will lag) the one in total time spent collecting water in these countries.

In addition, we find that assuming smaller elasticities or associations between income and urbanization and our model outcomes (coverage, mortality rates and time to water) tends to increase aggregate losses overall, and tends to push the peaks in losses further into the future. Indeed, in SSA, our base case model results do not show a peak in "economic losses" because a) population expansion continues to be high, b) the mortality rate and time to water is high and remains high over the simulation period, and c) economic growth pushes the "economic loss" per death and hour spent collecting water at a rate that exceeds these declines. This rising trend of "economic losses" in SSA is relatively robust to changes in the assumptions in the simulation model. Given our derived associations between coverage, mortality, and GDP growth, and assuming the data on WASH-related mortality rates are correct,

[1] Some might wonder why this is so unreasonable. After all, poor water and sanitation do seem like big problems. However, if losses were this large, it would so obviously be beneficial to invest in improved services that one would have to confront the odd reality that few individuals in these countries invest heavily in such services.

[2] We also note that the constant elasticity approach outlined in Hammitt and Robinson (2011), with an elasticity of 1.5, ultimately does not yield estimates that are so different from our empirical model

additional sensitivity analyses suggest that "economic losses" in SSA are only likely to peak before 2050 if at least two things happen: 1) GDP growth increases considerably, to at least 5-10%, and 2) the negative associations between time to water and income growth in SSA are much stronger than our empirical estimations would suggest.

Discussion

To the best of our knowledge, this paper describes the first attempt to estimate the global economic burden of health losses and time expenditures associated with poor water, sanitation and hygiene related illnesses over a long historical and future time horizon. The analysis provides what we believe to be a useful and broad perspective on the scope of this problem and on the transition that takes place as countries proceed along different economic and demographic growth trajectories. It also highlights important data gaps and methodological challenges. In this discussion we summarize the most important of these issues.

First, economic losses per case of WASH-related illness or death, and time losses per unit of time spent collecting water, both increase with income because of the positive relationships between income and the value of mortality risk reductions and the opportunity cost of time. At the same time, disease incidence, mortality rates, and time to sources decrease in income. It is therefore not clear *a priori* whether total economic losses will increase or decrease with economic growth. Indeed, the modeling conducted in this research shows that "economic losses" sometimes increase even as economic development is occurring and mortality rates are falling.

Second, the rise in "economic losses" can accelerate with development, and this creates endogenous pressure to invest in WASH technologies. So long as the income growth is broad based, this pressure may be especially important for the expansion of technologies that are subject to economies of scale such as piped water and sewerage. The massive expansion in coverage with piped and improved water and sanitation in China and Latin America between 1990 and 2008 did not occur by chance: it accompanied quickly rising incomes, which contributed to increased household demand for those services, and the public sector's financial resources to provide them. People in developing nations want piped water and sewer networks, and their ability to pay for these improvements increases sharply as their incomes rise. WASH-related health losses typically rise sharply when populations grow and countries transition to middle-income status, (between G-K$1000 and G-K$5000 income per capita) because the value of mortality risk reductions increases rapidly. Once demand pressures and subsequent investment kick in, there is a slowing of this rise in economic losses which is then followed by an eventual decline. This is shown by the regional peaks in our model simulations of health losses (see for example Figure 24). Wherever economic development is successful, as has happened in EAP, the problem of WASH-related mortality will likely be solved quickly from a historical perspective and without new technological breakthroughs. This is not to say, however, that such places will easily solve all of their water problems: this paper has not considered issues of industrial pollution, climate change, or water scarcity, for example.

Also, conventional piped water and sewerage are expensive, and impose large real resource costs on poor countries, so these "old world" technologies may not be the best solution in all places and at all times. Simply financing these services with upfront investment is not sufficient to ensure their long term success; operation and maintenance must be supported, debt repaid, and new capital infusions are continually required. It is useful to consider what it might cost to achieve the high levels of coverage with piped water and sewerage (found for example in EAP and LAC) in the regions that lag behind (i.e. SSA and SA). For this illustrative calculation, we use data from 2008, the last year for which we have coverage data. In that year, about 1.4 billion and 0.65 billion people did not have piped water and sanitation in SA and SSA, respectively, out of 1.5 and 0.7 billion total population. To raise coverage levels to 35-40%, as were found in EAP when mortality rates began to fall, a total of 0.6 billion and 0.3 billion people would need to have access to these services. This would entail providing these services to 0.45 and 0.25 billion new people. Assuming that the average household size is 5 people and that the full economic cost of piped water and sanitation per household is US$40/month (see Whittington et al. (2009) for an explanation of these costs), the annual costs of covering these additional people would be US$43 and US$24 billion, respectively. This amount represents 1.0% of GDP in South Asia and 2.3% of GDP in Sub-Saharan Africa in 2010.

Given our focus on piped water and sewerage, our projections of future "economic losses" associated with inadequate water and sanitation could be viewed as an upper bound because international donors such as the World Health Organization, UNICEF, and others are actively working to reduce the problems related to water and sanitation using lower cost innovations and interim solutions where piped services are unaffordable. One would hope that the uptake of such innovative technologies would be successful in providing economic benefits and therefore be subject to the same demand-side forces which push people with rising incomes to invest more heavily in piped water and sanitation. Then, mortality declines could accelerate independently of large-scale and costly initiatives to expand piped water and sewerage.

However, the empirical evidence reviewed in Section II of this paper suggests that the demand for cheap and decentralized interventions in the WASH sector is much lower than the demand for convenient piped services; thus, sustaining widespread use of these technologies may remain a major challenge.

At the national level, we find that there are important differences in the burden of WASH-related illnesses and time costs across the developing world. At the beginning of the simulation period, around 1950, when WASH-related mortality was much higher than it is today in most developing countries, we find that health losses associated with mortality make up a relatively larger share of the total costs of poor services. However, mortality has dropped quickly over the second half of the 20th century in many regions, in parallel with economic development and increases in coverage with better water and sanitation services. Our calculations suggest that this has reduced the relative fraction of losses due to poor health particularly in East Asia and the Pacific, Latin America and the Caribbean, the Middle East, and Eastern Europe. In contrast, in South Asia and especially Sub Saharan Africa, WASH-related mortality remains high today and still causes many deaths and economic losses.

These regional disparities are important because many parts of the globe have made tremendous strides in reducing the number of deaths related to inadequate water and sanitation, even without achieving universal coverage with piped water and sewerage. However, our simulation results suggest that it is unlikely that economic losses from WASH-related diseases will decrease soon in SSA. WASH-related mortality remains much higher in SSA than in other regions. Average incomes in SSA are also much lower than in other regions, such that the demand for preventative health improvements is limited. Also, the average statistics for South Asia, which has lower mortality rates than SSA, mask the fact that hundreds of millions of very poor people live there. For example in the Ganges Plain that spans from the Terai in Nepal across Bihar and Uttar Pradesh and into Bangladesh, there are more people living on less than US$2 per day than in all of SSA. As a result, health losses in sub-regions in SA and throughout much of SSA could accelerate over the next half century, especially given the projected rise in the populations of these areas. These trends seem likely to maintain strong pressure for government and donor action.

In addition, access to water remains inconvenient in many more countries than those in SA and SSA, and time expenses appear likely to grow over time relative to health losses. Because the average time to sources is less strongly associated with economic growth than is the WASH-related mortality rate, our analysis projects that the aggregate time spent collecting water will increase rapidly over the first half of the 21st century in many regions. This will be true particularly where coverage with convenient piped services is low or where water supplies in rural areas are inadequate, and where population growth remains high, e.g., in SA, poor countries in MIDEAST, and in SSA. In general, the mortality problems associated with poor water and sanitation are more quickly reduced than the time burden of water collection. Indeed, the only real way to decrease collection times for water is through in-house connections, whereas health gains follow from economic growth as well as uptake of such technologies.

We conclude by emphasizing that data constraints and measurement problems severely limit our ability to make accurate projections of "economic losses". As described in this paper, there are very large uncertainties associated with extrapolations of mortality data beyond the single year available from the WHO. The data on time to source in different countries are spotty and only cover a fraction of the countries in our model. Our coverage data, while better, are only for 18 of the 100 years in our simulations. If the associations we found in the data are unstable over time, our extrapolations back to 1950 and forward into the future will be erroneous. More work on collection and analysis of these data is needed, as is work on factors such as convenience and/or aesthetic costs unrelated to the time burden of collecting water. As summarized in Table 8, the ranges of the losses we calculate by varying parameter assumptions are very large, and the precise timing of the regional maxima in losses is unstable.

Climate change is another source of uncertainty that is ignored in our simulations. Climate change may affect both the costs of improved water supplies (and thus governments' financial resources to deliver such services) and the epidemiology of WASH-related illnesses. Finally, we especially caution against drawing any conclusions with regards to the causal nature of relationships between income, coverage with improved water and sanitation services, and reduced mortality from WASH-related diseases and average water collection times.

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Appendix A: Estimating the Value of the Statistical Life (VSL) for calculating global losses from inadequate water and sanitation

Introduction

This appendix provides a more detailed explanation of the value of a statistical life (VSL), the concept we use for valuing mortality losses associated with poor water and sanitation.). We review the literature on VSL estimation, focusing on developing countries, and explain the strategy we employ to develop VSL estimates for use in our simulation model. There are now numerous high-quality VSL estimates for industrialized countries (Viscusi and Aldy, 2003). These are methodologically sophisticated and typically use large data sets that include multiple variables associated with individuals' preferences for mortality risk reductions.

Preferences for mortality risk reductions are heterogeneous and vary across a number of important dimensions including income and wealth, level of background risk, and cultural preferences towards risk (Viscussi and Aldy 2003; Cropper, Hammitt, and Robinson 2011). One would not expect that individuals in countries at different stages of development would place the same value on mortality risk reductions. Economic theory and empirical evidence suggest that mortality risk reduction (and the corresponding VSL) is a normal good; individuals' willingness-to-pay (WTP) for mortality risk reduction increases as income increases. Thus, it would be inappropriate to use the same VSL estimates in developing countries as in industrialized countries. Our challenge in this paper is to develop VSL estimates for the more than 100 developing countries over a period of 100 years during which real incomes change dramatically so that we can estimate the economic value of mortality losses.

The next section of this appendix provides a brief overview of the concept of the VSL, describes the methods most commonly used to estimate VSLs, and then summarizes the principal limitations of these methods. Section 3 reviews the global literature on estimating the VSL, with special emphasis on studies from low and middle-income countries. Section 4 provides a critique of the benefit transfer strategy that is typically used to predict the VSLs in low and middle-income countries when primary data are not available. Section 5 then presents a different strategy that we employ to estimate VSLs in our analysis.

The Concept of VSL

Dreze (1962) first formulated the standard model for estimating the economic value of mortality risk reduction, often termed the value of a statistical life. This model relates individuals' marginal rate of substitution between mortality risk and wealth over a defined period of time. More formally, the VSL is the local slope of the indifference curve between wealth and mortality risk (Cropper, Hammitt, and Robinson 2011). The VSL does not represent the value of a specific life. Rather, the VSL is an economic measure derived from risk-income tradeoffs that individuals routinely make (e.g. investing in preventative health, purchasing smoke detectors, buying point of use water filters, etc.). The VSL represents the value of small changes in mortality risk spread across a specific population.[3]

The VSL is calculated by scaling individuals' willingness to pay (or accept compensation) for a small reduction (or increase) in mortality risk up to the unit of a statistical life. A typical formulation of VSL is presented in Equation A1, where ΔP represents a change in mortality risk.[4]

$$VSL \approx WTP/\Delta P \approx WTA/\Delta P \quad \text{(A1)}$$

For example, an individual willing to pay $600 per year for reducing their mortality risk by 0.0001 in that year would have an implied VSL of $6 million. This does not mean that a specific individual would be willing to pay $6 million to avoid certain death over that year, nor that she would be willing to accept $6 million in compensation for certain death during that period. The VSL of $6 million implies that 10,000 similar people would collectively pay $6 million to eliminate a risk that would kill one of them, selected at random, during that year or defined period of time (Hammitt 2000).

Because individuals have heterogeneous preferences, the VSL will vary both within and across populations. Various dimensions of heterogeneity that have been found to be associated with the VSL include income, age, the type and magnitude of risk considered, the level of background risk, and cultural attitudes or preferences towards risk. The most robust research findings on these VSL co-variates are age and income: specifically, the VSL has been found to increase in income and decrease in age (see Viscusi and Aldy (2003) for further details). In our study we are primarily concerned with the effect of income on the VSL and we ignore effects related to changes in the age structure of the population.

The two most commonly used approaches to estimate the value of mortality risk reductions have been (1) compensating wage differential (wage-risk) and (2) stated preference (SP) techniques.[5] The following sections briefly describe these approaches, and some of their most important limitations. We note, however, that there are very few applications of either method in developing countries.

1.1. Compensating Wage Differential (Wage-Risk) Approaches to Estimating VSL: Theory and Challenges

The value of mortality risk reduction is most commonly estimated via hedonic wage studies that examine the tradeoff workers make between job-related mortality risk and wages. This approach is based on the assumption that a competitive labor market should compensate workers in jobs with higher occupational mortality risks, holding other worker, firm, and job characteristics constant

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[3] Readers interested in a more thorough summary of the conceptual foundation of the VSL concept should refer to Hammitt (2000), Viscussi and Aldy (2003), Evans and Schauer (2010), and Belevance et al (2009).

[4] Critically, and more formally, the VSL is equal to the limit of WTP/ΔP or WTA/ΔP as ΔP approaches zero (Cropper, Hammitt and Robinson 2011). In other words, this expression is only valid for small (marginal) changes in risk. Also, this expression assumes that the value (or demand) function for changes in risk is symmetric, which may not be the case since individuals appear to treat economic gains and losses very differently (as discussed in the main paper).

[5] A third class of studies which generate VSL estimates are revealed preference studies which examine individuals' private spending for goods that reduce mortality risks, for example purchase of drinking water treatment technologies or vaccinations, see for example Kremer et al (2009) and Jeuland et al. (2008).

(Cropper, Hammitt, and Robinson 2011; Hammitt and Robinson 2010; Viscusi and Aldy 2003; Hammitt 2000). Workers' willingness to pay (accept) for marginal changes in job-related mortality risk (increase) is captured by the wage differential between jobs with different levels of risk.

Hedonic wage risk studies generally adopt the form of Equation A2 (Viscusi and Aldy, 2003):

$$w_i = \alpha + H_i'\beta_1 + X_i'\beta_2 + \gamma_1 p_i + \gamma_2 q_i + \varepsilon_i \qquad \text{(A2)}$$

where w_i is a worker's wage, α is a constant intercept term, H_i is a vector of individual characteristic variables for worker i (e.g. age, education, race, etc.), X_i is a vector of job characteristic variables for worker i (e.g. industry, whether the job is white collar or blue collar, the degree of physical exertion required, etc.), p_i is the fatality risk, q_i is the non-fatal risk of injury for worker i's job, and ε_i is a random error term.[6] β_1, β_2, γ_1, and γ_2 are parameters estimated via regression[7], and γ_1 represents the change in wage (or WTP) for a one-unit change in job-related mortality risk.

Wage-risk studies face both theoretical and econometric challenges. The VSL literature is rich with detailed discussions of estimation challenges, including model specification, omitted variable bias, the endogeneity of job-related mortality risk, the collinearity of fatal and non-fatal job-related mortality risks, and small sample sizes (Girard et al., 1992; Viscusi and Aldi 2003; Miller 2000; Black et al, 2003; Hintermann et al, 2010; Mrozek and Taylor, 2002; Viscusi, 2004; Cropper et al., 2011; Shogren and Stamland, 2002; Knieser et al., 2011).[8]

There are several other threats associated with using compensating wage differentials estimated from wage-risk studies to estimate VSLs in developing countries. First, workers may not be well informed about job-related mortality risk. Second, labor markets may not be competitive. With respect to the former, there is little convincing evidence that subjective perceptions of risk are biased (Mrozek and Taylor, 2002). However, Gaba and Viscusi (1998) do find that education affects whether individuals consider a job "dangerous". The assumption of competitive labor markets is problematic for some developing countries, given that they may have dual wage economies. It may be that labor markets for semi-skilled and skilled workers are competitive in some places. Several researchers have successfully used the wage-risk approach to estimate VSLs for sub populations in poor countries (see for example Liu et al (1997), Simon et al (1999), Shanmugam (2000; 2001), and Guo and Hammitt (2009)). However, one

[6] Studies employ a range of model specifications including log-linear and log-log to estimate the parameters in Equation (2). While individual studies and convention may favor a particular specification, Viscusi and Aldy (2003) there is no a priori theoretical basis for favoring a particular functional form.

[7] Studies often include additional covariates and interactions between covariates motivated by theory. For example, studies often include an interaction between nonfatal risk (q_i) and workers' compensation payable for an injury on the job.

[8] Because of these types of issues, Cropper, Hammitt & Robinson (2011) caution against using the results from studies conducted prior to 2000 because they often omitted important explanatory variables and did not address threats of endogeneity or unobserved worker characteristics. Hintermann et al. (2010) go so far as to say that "if compensating differentials for risk exists, econometric problems and the changing nature of labour [sic] markets prevent us from observing them" (1085).

should be cautious extrapolating these VSL to an entire country's population (or in our case the population of people most exposed to diarrheal disease risks).

Another problem with using estimates from wage-risk studies is that they only apply to a specific class of mortality risks from occupational hazards. Selection effects aside (e.g. the fact that not everyone chooses to work), people may not treat these risks as equivalent to infectious disease and environmental risks. Recent work by Scotton and Taylor (2011) suggests that even in the context of on-the-job mortality risk, workers place a higher risk premium on workplace homicide than on other types of job-related mortality risk. Industry and occupation dummies are consistently significant in wage hedonic regressions, which may reflect differences in the type of mortality in different employment contexts.

1.2. Stated Preference Approaches to Estimating VSL: Theory and Challenges

Stated preference techniques (e.g., the contingent valuation method) also have been used to estimate the value of mortality risk reductions, especially from risks such as air pollution and road hazards. Stated preference techniques have two primary advantages over hedonic wage methods. First, the scenarios presented to respondents in stated preference surveys can be tailored to specific mortality risks. As a result, stated preference techniques have been most widely used to estimate the VSL for a number of environmental risk applications, most notably air pollution and road safety. Second, stated preference techniques allow the researcher to specify and vary the magnitude of the risk reduction presented to respondents. Best practice in stated preference studies of the VSL is to consider the effect of varying these mortality risks, and determine whether results are consistent with standard economic theory (i.e., whether WTP depends on income, levels of baseline risk, etc.), as shown in Equation A3 below:

$$WTP_i = \alpha + p_i\beta_1 + \gamma_1 r_i + X_i'\beta_2 + \gamma_2 q_i + \varepsilon_i \qquad (A3)$$

where WTP_i is a dichotomous variable that takes a value of 1 if a respondent agrees to pay some price p_i for a good or policy intervention that reduces his/her mortality risk by an amount r_i, α is a constant intercept term, X_i is a vector of socio-economic characteristic variables for individual i (e.g. income, education, age, etc.), q_i is the baseline mortality risk (if it varies across individuals in the sample), and ε_i is a random error term.[9] The parameters in equation A3 are typically estimated using a probit or logistic regression model.

In spite of their flexibility, stated preference techniques, like wage-risk hedonic approaches, present econometric challenges (Alberini, 2005).[10] More generally, stated preference techniques are often criticized as being susceptible to a variety of biases (Carson et al. 2001, Whittington 2010). Perhaps most relevant in work on mortality risks are claims that respondents' answers in surveys may not reflect their

[9] As with the wage-hedonic models, stated preference models often consider a range of model specifications including log-linear and log-log to estimate the parameters in Equation 3.

[10] For example, using data reported in Johannesson et al (1997), Cropper, Hammitt and Robinson (2011) report a difference of more than six orders of magnitude in WTP estimates derived using different distributional assumptions about the demand for risk reductions.

true preferences because individuals misunderstand the hypothetical scenario (i.e. the nature of the risk reduction) with which they are presented. Risk reductions presented to respondents in stated preference studies are generally small, on the order of 1 in 10,000 or 1 in 100,000. Individuals often have difficulty understanding and valuing such very low probability risks, and stated preferences researchers commonly use visual aids such as colored grids representing risk and risk ladders to try to communicate the magnitude of the risk reduction to respondents (see Lindhjem et al 2010 for a more complete review of these types of tools).

Cropper, Hammitt and Robinson (2011) recommend various scope tests to check the validity of survey responses. Economic theory suggests that the willingness to pay for risk reductions should be sensitive to the magnitude of the risk reduction and should increase proportionally for small changes in risk, such that the VSL derived over a range of modest risk reductions should remain approximately constant. In a review of VSL studies using stated preference techniques, the US EPA (2010) found that only half of the studies incorporated such scope tests. Ninety percent of the studies that used to scope tests reported that WTP varied with the magnitude of risk reduction. However, only 15 percent reported changes in WTP that were roughly proportional to the change in risk reduction.

Perhaps surprisingly, stated preference techniques have yielded lower estimates of VSL than hedonic wage studies (Cropper et al 2011). However, it is unclear whether these results are artifacts of estimation technique, the type of risk examined in each study, or differences in the populations studied, including perceptions and comprehension of mortality risks.

Overview of VSL Estimates in Less Developed Countries (LDCs)

The majority of studies that seek to value mortality risk reduction have been conducted in industrialized countries and in particular in the US and Canada. In a review of VSL studies conducted globally, Miller (2000) lists 30 studies conducted in 12 countries, none of which were from developing countries. Viscusi and Aldy (2003) examine 50 studies (27 in the US), only three of which were in non-industrialized countries (and all in India). More recently, Robinson and Hammitt (2009) provide a review of international VSL studies to date, including 17 studies from nine countries, none of which is a low-income country.

Table A1 provides a summary of the 30 international VSL studies from 19 countries we identified in our literature review.[11] We found eleven wage risk studies in developing countries, none of which are classified as low-income countries by the World Bank, and all with very limited sample sizes[12]. Moreover, all of the studies focused on very specific sub-populations of individuals, and yield VSL estimates that are vary considerably. The high estimates are more than one order of magnitude greater

[11] We identified a total of 48 VSL studies published in the international literature. Eighteen studies were excluded from our sample due to the fact that they: 1) were conducted prior to 1995, before significant advances in both econometric and stated preferences methods of estimating VSL, or 2) presented a range of VSL estimates differed by more two orders of magnitude.

[12] These sample sizes are much smaller than the more than 100,000+ observations common in studies conducted in industrialized countries. Note: Shanmungam (1997) and Simon et al (1999) do not report a sample size.

than those obtained using other methods in similar countries e (Shanmungan (1997), Shanmungan (2000), Shanmungan (2001), Simon et al (1999) and Hammitt and Ibarraran (2006)). For example, Shanmungan (2000) developed VSL estimates from surveys of university employees in the city of Chennai; Hammitt and Ibarraran (2006) worked with a sample of approximately 600 urban workers from the industrial, commercial and public sectors in Mexico City. One should not rely on such wage-risk data to describe developing country VSLs that apply to the general population.

Table A1. Summary of international studies reviewed for this appendix

Study	Type	Country	Per Capita GDP	Reported VSL
Developing Countries				
Jeuland et al. (2008)	CV/SP	Beira, Mozambique	504	11,700
Kremer et al. (2009)	RP	Kenya (Rural)	892	500
Maskery et al. (2008)	CV/SP	Bangladesh (Rural)	896	12,075
Simon, Cropper, Alberini and Arora (1999)	WR	India	2,084	263,575
Shanmugam (2000)	WR	India (Chennai)	2,084	910,000
Shanmugam (2001)	WR	India (Chennai)	2,084	1,885,000
Bhattacharya, Abernini, and Cropper (2007)	CV/SP	India (Delhi)	2,084	9,068
Shanmugam (1997)	WR	India (Chennai)	2,084	877,500
Guo and Hammitt (2009)	WR	China (Urban)	4,547	52,650
Hammitt and Zhou (2006)	CV/SP	China (Urban & Rural)	4,547	78,163
Wang and Mullahy (2006)	CV/SP	China (Chonging)	4,547	28,470
Vassanandumrongdee and Matsuoko (2005)	CV/SP	Thailand (Bangkok)	5,558	1,072,500
Vassanandumrongdee and Matsuoko (2005)	CV/SP	Thailand (Bangkok)	5,558	1,105,000
Gibson et al. (2007)	CV/SP	Thailand (Rural)	5,558	182,000
Melhuish, Ross, Goodge et al (2005)	CV/SP	Malaysia	8,154	397,800
Hammitt and Ibarraran (2006)	WR	Mexico City	8,857	209,950
Ortuaz, Cifuentes, Williams (2000)	CV/SP	Chile (Santiago)	9,329	2,067,000
Ortuaz, Cifuentes, Williams (2000)	CV/SP	Chile (Santiago)	9,329	421,850
Giergiczny (2008)	WR	Poland	10,644	1,202,500
Kim and Fishback (1999)	WR	South Korea	17,098	650,000
Liu, Hammitt, Liu (1997)	WR	Taiwan	20,811	422,500
Liu and Hammitt (1999)	WR	Taiwan	20,811	455,000
Sibert and Wei (1998)	WR	Hong Kong	25,600	1,105,000
Industrialized Countries				
Meng and Smith (1999)	WR	Canada	26,505	3,380,000
Baranzini and Ferro Luzzi (2001)	WR	Switzerland	27,571	4,842,500
Lott and Manning (2000)	WR	US	30,225	2,346,570
Dreyfus and Viscusi (1995)	RP	US	30,225	3,598,075
Blomquist et al (1996)	RP	US	30,225	4,536,703
Gayer et al (2000)	RP	US	30,225	3,637,184
Jenkins et al (2001)	RP	US	30,225	1,916,366

Because there are few VSL studies in developing countries, researchers have often adjusted VSL estimates from industrialized countries, and then transferred these adjusted estimates to developing countries. Adjustments have been made for geographic and population characteristics (e.g. baseline risk, income, age, and health status) using the results of meta-analyses. Meta-analyses typically construct a pooled sample from existing primary studies, and estimate a regression that explains differences in estimated VSLs as a function of differences in research design, samples, and model specification (Viscusi and Aldy, 2003; Miller, 2000; Bowland and Beghin, 2001; Mrozek and Taylor, 2002). For example, in their meta-analysis, Mrozek and Taylor (2002) include covariates to capture variation in VSL, risk, and earnings, 12 dummy variables to control for variation in samples, eight variables to control for differences in specification across studies, and four industry/occupation variables. Published meta-analyses to date have included both old and relatively recent studies that vary considerably in quality and econometric sophistication.

Researchers who want to transfer VSL estimates from such meta-analyses to a range of developing countries could then use the parameter estimates from such a regression model to adjust for the characteristics of the population of interest, such as income. For this approach to work, it is essential to understand the relationship between income and the VSL. Several of the meta-analyses described above have attempted to estimate the income elasticity of the VSL, i.e. the percent change in VSL for a one percent change in income, as shown in Equation A4:

$$VSL_2 = VSL_1 * (Income_2/Income_1)^{\gamma} \qquad (A4)$$

Where γ is the elasticity of the VSL with respect to income. In this formulation an income elasticity of one implies that a one percent increase in income yields results in a one percent increase in the VSL. Similarly, an income elasticity of zero implies that the VSL does not change with income. Suppose for example that an individual in the US (per capita GDP of $45,600) were willing to pay $600 (or just over 1% of income) for a 0.0001 reduction in mortality risk, yielding a VSL of $6 million (VSL = $600/0.0001). An income elasticity of zero would imply that an individual in Bangladesh (with average PPP-adjusted income of $1500), would also be willing to pay $600. This would constitute 40% of annual income for the average Bangladeshi, which is clearly unrealistic.

As shown in Table A2, estimates of the income elasticity from meta-analyses of VSL studies conducted in industrialized countries range from approximately 0.4 (relatively insensitive to income changes) to 1.0[13], with a general consensus that the income elasticity associated with a range of incomes in industrialized countries is approximately 0.5 to 0.6. This implies that the VSL increases as income increases but at a decreasing rate (i.e., the relationship between income and the VSL is concave).

There are two main problems with extrapolating income elasticities derived from VSL studies in rich countries to low income populations. First, this assumes that individuals in developing countries have

[13] Bowland and Beghin (2001) report an income elasticity ranging from 1.5-2.3. However, using data from Viscusi and Aldy (2003) Robinson and Hammitt (2009) estimate an income elasticity of 0.6 using the model presented in Bowland and Beghin (2001). Similarly, Robinson and Hammitt (2009) provide a re-estimate of 0.5 for the income elasticity reported in Miller (2000).

the same basic preferences regarding mortality risk reduction as individuals in industrialized countries (i.e. all other covariates and unobserved differences across individuals are the same). However, it seems more reasonable to believe that safety and mortality risk reductions are normal goods, and that demand for them may be similar to the demand for coverage with improved water and sanitation services , for environmental quality (the environmental Kuznets curve), or for longevity (as in the Preston curve). The notion that preferences for mortality risk reduction change as countries progress through different stages of economic growth is in fact supported by longitudinal studies of VSLs in industrialized countries, as well as estimates of VSL across a range of low-income countries. Hammitt and Ibarraran (2006) and Wang and Mullahy (2006) report income elasticities for the VSL in Mexico and China of 1.4 to 2.0. Working with longitudinal data, Hammitt, Liu, and Liu (2009) and Costa and Khan (2003) estimate elasticities of 2.0 to 3.0 for Taiwan, and 1.5 to 1.7 for the US, respectively. Kniesner et al (2010) use quantile regression methods and report that income elasticity declines as income increases, from 2.2 in the lowest quantile and 1.2 in the highest quantile.

Table A2. VSL income elasticities from meta-analyses (Adapted from Robinson & Hammitt, 2009).

Study	Original reported elasticity	Re-estimate of elasticity
Liu, Hammitt, Liu (1997)	0.53	0.51
Miller (2000)	0.85 - 1.00	0.53
Bowland and Beghin (2001)	1.52 - 2.27	0.61
Mrozek and Taylor (2002)	0.37 - 0.49	0.52
Viscusi and Aldy (2003)	n.a.	0.46-0.60

Second, using income elasticities of 0.5 to 0.6 from industrialized countries to estimate VSLs in developing countries assumes, somewhat counter intuitively, that the percentage of income invested in the specific mortality risk reductions of interest will decrease as incomes increases.[14] This seems unlikely because poor households in developing countries spend much more of their income on basic needs such as food (the Engel curve), clothing and shelter. Note that increased expenditures by a very low income household on food, clothing, and shelter could reduce mortality risk, whereas marginal increases in such expenditures by a household in an industrialized country would be unlikely to affect mortality. Additionally an income elasticity in the range of 0.5 to 0.6 is inconsistent with much of the recent empirical evidence from VSL studies in developing countries, which is discussed further below.

Critique of the Standard Benefit Transfer Approach Based on Income Elasticity

If we accept the conventional wisdom and large body of evidence supporting the fact that the income elasticity of the VSL is between 0.5 and 0.6, we soon run into difficulties explaining empirical findings for the demand for mortality risk reductions in poor countries. Indeed, the recent literature recognizes that extrapolation from industrialized country VSLs using income elasticities greater than one may be

[14] Hall and Jones (2007) for example assert that health, and by extension mortality risk reduction, is a superior good with an income elasticity that should be greater than one.

appropriate when deriving VSL estimates for low-income countries (Hammitt and Robinson 2011; Robinson and Hammitt 2009).[15] Using a high-income elasticity to extrapolate VSLs to developing countries accommodates findings in the empirical literature for lower VSLs (see Table A1). However, this approach does not explain how the VSL changes with income or the stage of economic development—which is our focus.[16] Assuming a constant high income elasticity in low-income countries does not explain how or when a country transitions from a state where it is appropriate to use a high income elasticity to a state where it is appropriate to use the well-established low income elasticities used in industrialized countries. Changes in VSLs could be attributable not only to changes in income, or to changing attitudes towards risk that accompany economic growth, but also to reduced background mortality risk, and other changes that occur alongside the demographic transition.[17]

Figure A1 illustrates this point. It shows VSL estimates for PPP-adjusted per capita incomes ranging from 0 to $50,000. These are projected from a base VSL of $6.3 million for a GDP of $46,500, following Hammitt and Robinson (2011). The top curve shows VSL estimates assuming an income elasticity of 0.55, which is representative of income elasticities reported in meta-analyses for industrialized countries. The bottom curve shows VSL estimates derived using an income elasticity of 1.5, the main income elasticity used by Hammitt and Robinson (2011).

An approach that relies on a constant income elasticity for the VSL cannot generate reasonable estimates over a wide continuum of income. If individuals in industrialized and low-income countries have different preferences regarding mortality risk reduction, and if differences in these preferences can be captured by different income elasticities, it is unclear how a country (or population) will transition from the low- to high-income VSL curves. Wherever this transition is assumed to occur, there would appear to be a sharp change between VSL estimates on either side of the transition.

For example, suppose a policy analyst believes that the threshold at which one should transition from deriving the VSL with an income elasticity of 1.5 to an income elasticity of 0.55 occurs at a per capita GDP of $15,000. If a country has a per capita GDP of $14,990 at a particular point in time the analyst would apply an income elasticity of 1.5 to derive an estimate of the VSL, which would yield a VSL of approximately $1.4 million (Figure A1). However, if this country experienced economic growth and recorded a per capita GDP of $15,010 six months later, the analyst would then use an income elasticity of 0.55 to derive an estimate of the VSL. This would yield a VSL of approximately 2.8 million, twice the VSL estimated using an income elasticity of 1.5. It does not seem plausible that individual preferences towards mortality risk reduction could change so sharply over such a small increase in income. In many

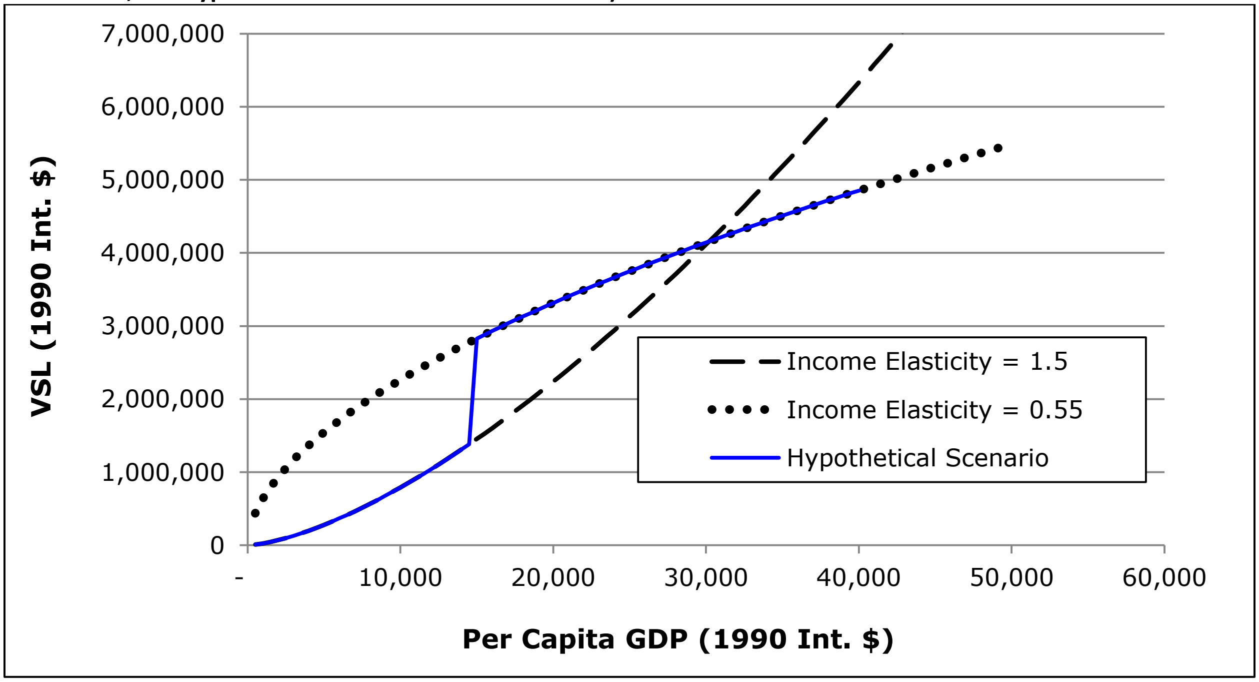
[15] These authors use a range of 1.0-2.0, but point out that VSL estimates derived with income elasticities above 1.5 may lie below expected discounted future earnings or consumption, which would be inconsistent with economic theory. In light of this, they recommend using expected future consumption as a lower bound for the VSL. However, implementation of this cutoff is difficult without detailed information on individuals' time preferences.

[16] Costa and Kahn (2003) find that the VSL in the US increased five fold in the United States from 1940 to 1980, a period which saw dramatic decreases in mortality and improvements to quality of life.

[17] Eeckhoudt and Hammitt (2001) find that high levels of background mortality and financial risk can substantially reduce the VSL. They argue, "…when the competing risk is large, willingness to pay to reduce the first [mortality] risk can fall nearly to zero. Intuitively, in the presence of a large background risk, there is little benefit to reducing the first source of mortality risk" (262). They term this the "why bother" effect.

benefit transfer applications, this would not be an issue because VSL estimation is not required in both low and high income countries in the same year. However, because our analysis projects changes in income over a long period of time, we inevitably find that some countries cross whichever ad-hoc transition point we define in our model. As a result, the constant income elasticity benefit transfer approach described in the recent VSL literature is insufficient for our purposes.

Figure A 1. VSL estimates derived from income elasticities (low income elasticity line is dashed; high elasticity line is solid; the hypothetical scenario is bolded in blue).



Our modeling approach for the economic analysis of global losses from inadequate water and sanitation

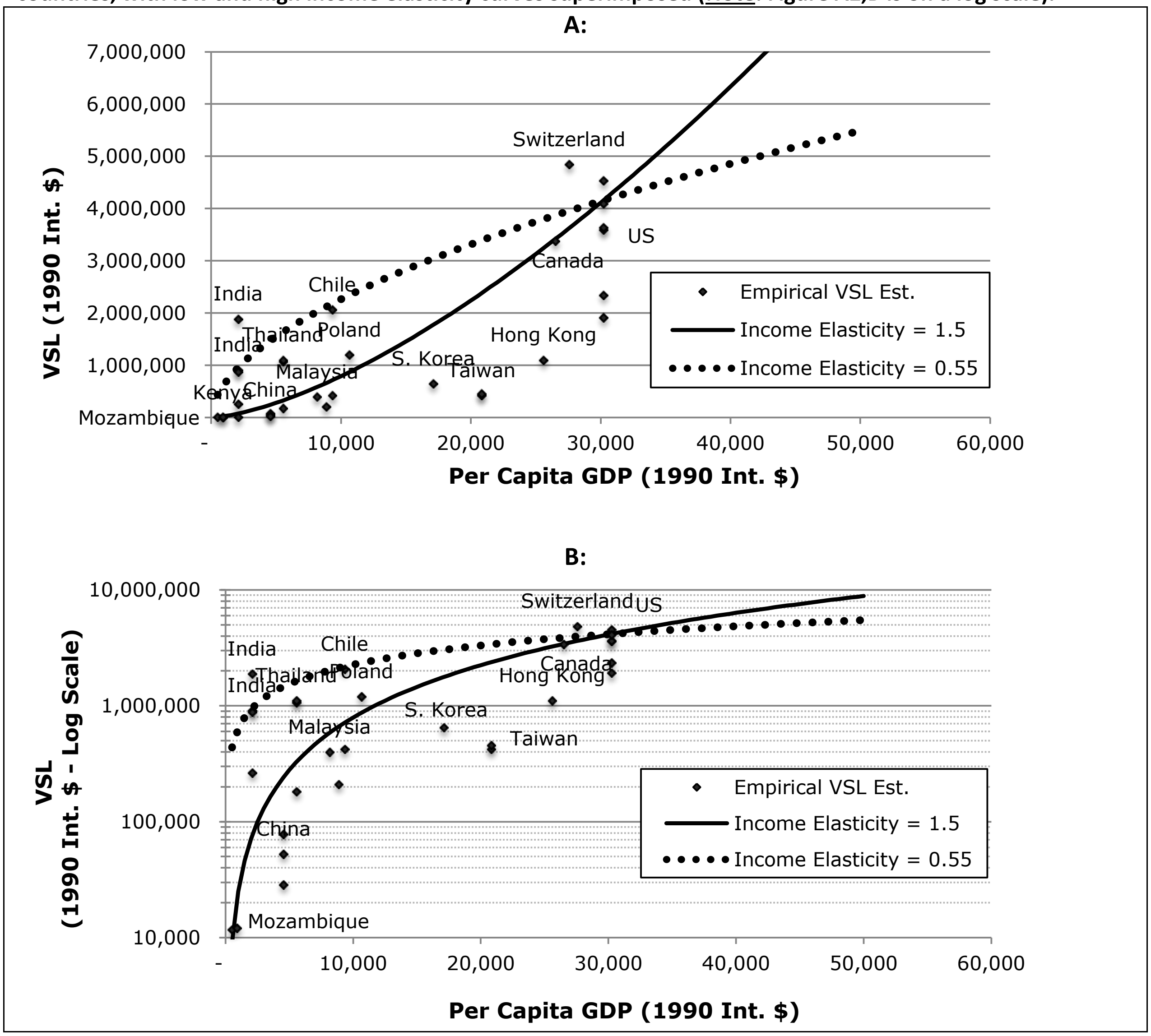
To address these challenges, we use an approach that incorporates the findings from both (1) the meta-analysis literature on the relationship between income and VSL in industrialized countries; and (2) the limited empirical data on the VSL for developing countries in Table A1. Figure A2-1 and A2-2 provide a scatter plot of these published VSL estimates expressed in 1990 international dollars, along with the high and low income elasticity curves presented above, which are estimated using the Hammitt and Robinson (2011) benchmark for VSL of 4.1 million USD at per capita GDP of 30,225.[18]

As shown, the estimates derived using an elasticity of 1.5 are generally consistent with the lower end of estimates for developing countries found in the literature up to a per capita GDP of about 10,000 USD. We do not believe that the VSL estimates for India, Thailand and Chile (that appear considerably larger than suggested by this curve) are representative of developing country VSLs because they were

[18] GDPs are in international dollars as reported in the Penn World Tables for 2007 deflated to 1990. Hammitt and Robinson (2011) use a base VSL of 6.3 million USD and a base GDP of 46,500. These figures have been deflated to 1990 for consistency with the chapter.

conducted in urban settings with semi-skilled or skilled workers, or among individuals owning motor vehicles. Also, even the high elasticity curve appears to overestimate VSLs over the range of per capita GDP of about 10,000 to 25,000. When deflated to 1990, the VSL estimates derived in recent studies for industrialized countries do indeed cluster around the 4.1 million USD benchmark used by Hammitt and Robinson (2011).

Figure A 2. Scatter plots of VSL estimates published since around 2000 for industrialized and middle income countries, with low and high income elasticity curves superimposed (<u>Note</u>: Figure A2,B is on a log scale).

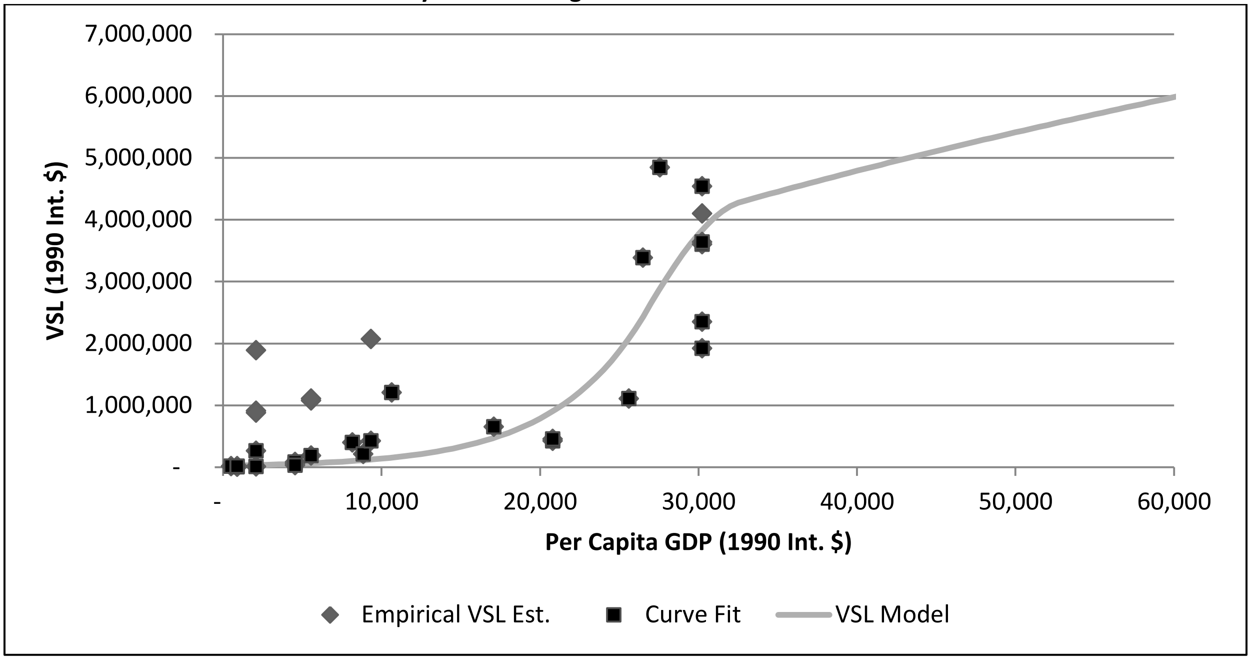


In order to preserve the relatively well-established VSL-income relationship for rich countries while acknowledging the empirical evidence from developing countries, we use a functional relationship that does not depend on constant income elasticities. Examining the published estimates, it appears that VSLs are initially very low, before rising steeply with incomes between 20,000-30,000 USD, and then leveling off with the income elasticities of 0.5-0.6 documented by Viscusi and Aldy (2003). To accommodate this S-curve relationship, we fit an exponential function to the low estimates for developing countries up to the end of this transition zone (approximately $30,000), and follow the results from the meta-analysis literature from industrialized countries thereafter, assuming that the income elasticity of the VSL is 0.55, as shown in Figure A3.[19] Although this S-shaped curve is admittedly ad hoc, we believe that it is the best characterization of the VSL estimates available in the published literature. The household budget shares available for investments in specific mortality risk reductions (e.g., bed nets, vaccines, point-of-use water treatment) are very low at low levels of income. Additionally, at low-income levels household's may face high levels of background risks, which can result in very low VSLs (Eeckhoudt and Hammitt, 2001). We speculate that after the demographic transition occurs, baseline levels of mortality risk decline and households then increase their expenditures (i.e., they place an increasingly high economic value) on mortality risk reductions up to the point where diminishing returns to investments in reduced mortality set in. This story is consistent with the recent literature (e.g. Hammitt and Robinson 2011) that suggests that income elasticities of the VSL in developing countries may exceed 1 over some ranges of income.

In the sensitivity analysis for our chapter, we use a relationship with a constant elasticity over all income levels at the central estimate of 1.5 used by Hammitt and Robinson (2011), and we also show separately using a tornado diagram the implications of varying this elasticity over a range of 1 to 2, which would still be higher than the estimate obtained from rich world meta-analyses.

[19] Five studies were excluded from the curve estimation. Four of the studies (Shanmugam 2001, Shanmugam 2000, Shanmugam 1997, Vassanandum and Matsuoko 2005) were conducted in urban areas among a relatively well-off segment of the population. Ortuaz et al (2000) presents two estimates of the VSL, one of which is 500 percent larger than the base estimate, and which is also excluded.

Figure A 3. **Hybrid S-shaped VSL curve used in this chapter, combining an exponential function fit to empirical VSL estimates and an income elasticity of 0.55 at higher incomes**



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Appendix B: Data sources for control variables in the regression models

This section describes the sources for the control variables included in the models (equations 11 – 13):

a. Urban population: Percentage of total population in a country that is located in an urban area. This variable was created by dividing urban population by total population, both of which were reported by the WHO/UNICEF JMP. Urban population projections for the future were obtained from: http://esa.un.org/unpd/wup/index.htm. We expect that higher levels of urbanization will be associated with higher piped water coverage.
b. World region dummy variables: We generated dummy variables for the major world regions in order to control for regional differences that might influence piped water coverage and WASH-related death rates. We use the following country groupings: 1) Sub-Saharan Africa (SSA); 2) Latin America and the Caribbean (LAC); 3) Middle East (MIDEAST); 4) Eastern Europe (EURCA); 5) South Asia (SA); and 6) East Asia and the Pacific (EAP). The full list of countries in each of these regions is included in the appendix.
c. Inequality. We obtained the percentage of national GDP for the lowest 80% of the income distribution from the World Bank database, as a measure of inequality. Higher percentages imply greater equality.
d. Fertility. Fertility rates were obtained from the United Nations. Only year 2008 rates are available.[1] Because fertility rates are highly endogenous, we use this variable mainly to test whether the associations of greatest interest to us (specifically the effect of improved water services on mortality rates) are robust to model specifications that include it.
e. Literacy. Adult literacy rates for 2005 were also obtained the United Nations. We expect that death rates will be negatively correlated with literacy rates.
f. Governance variables. Obtained from the Center for Systemic Peace's Integrated Network for Societal Conflict Research (INSCR).[2] We expect that higher coverage levels with infrastructure and lower deaths will be associated with positive governance and stability measures.
    1. Democracy-Autocracy score: This is a governance measure that seeks to account for the extent of democracy and autocracy in a country. The variable is derived by subtracting a country's autocracy score (-10 to 0) from its democracy score (0 to 10). A Democracy-Autocracy score of +10 indicates the most strongly democratic country possible; -10 is the most autocratic.
    2. Regime Durability. This variable indicates the number of years since the most recent regime change. A regime change is defined by a three-point change in the Democracy-Autocracy score over a period of three years or less.
    3. Coups d'Etat. We used the coup indicator to create a dummy variable indicating a successful coup in the last five years.
g. Bilateral aid for WASH. Data on total aid received for WASH by country was obtained from the OECD for many countries after 1996, in three categories: aid for large systems (water treatment

[1] http://www.un.org/esa/population/

[2] Obtained from: http://www.systemicpeace.org/inscr/inscr.htm. The INSCR data cover all independent countries with population of at least 500,000. In 2009, 163 countries were included in INSCR.

plants and networks), aid for basic systems, and water resources planning and management. As far as we know, these are the only comprehensive data available for WASH aid.

h. Linear time trend and/or year dummy variables. For the piped water coverage model, we defined a linear time trend variable as equal to the year of the observation minus 1990, which was the first year in our dataset. We also created dummy variables for each year to control for non-linear effects over time, and created a set of time-region interactions as additional controls for regionally-differentiated time effects.

Appendix C: Additional Tables and Figures

Table C1. Region groupings of countries in our analysis

Region	Countries included
Developed countries (DEV_ECON)	Australia, Austria, Belgium, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Malta, Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, United Kingdom, United States
Sub-Saharan Africa (SSA)	Angola, Benin, Botswana, Burkina Faso, Burundi, Cote d'Ivoire, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of Congo, Rwanda, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Uganda, Tanzania, Zambia, Zimbabwe
Latin America and Caribbean (LAC)	Argentina, Belize, Bolivia, Brazil, Chile, Columbia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Middle East (MIDEAST)	Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestinian Territories, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Yemen
Eastern Europe and former Soviet Union (EURCA)	Albania, Armenia, Azerbaijan, Belarus, Bosnia, Bulgaria, Croatia, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Poland, Moldova, Romania, Russia, Serbia, Slovakia, Slovenia, Tajikistan, Macedonia, Turkey, Turkmenistan, Ukraine, Uzbekistan
South Asia (SA)	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
East Asia and Pacific (EAP)	Cambodia, China, North Korea, Indonesia, Lao PDR, Malaysia, Mongolia, Myanmar, Papua New Guinea, Philippines, South Korea, Thailand, Vietnam

Table C2. OLS regression for mortality death rate (annual deaths per thousand people) due to inadequate WASH; alternative model specifications

	All Countries, log coverage terms		All Countries, higher order coverage terms	
	Coef.	**Std. Err.[1]**	**Coef.**	**Std. Err.[1]**
Log % Piped water coverage	-0.48***	0.12		
Log % Improved non-piped water coverage	-0.19***	0.073		
Log % Improved sanitation coverage	-0.11	0.22		
% Piped water coverage			-0.049***	0.013
% Improved non-piped water coverage			-0.0065	0.020
% Improved sanitation coverage			-0.0022	0.017
Squared % Piped water coverage			0.00024*	0.00012
Squared % Improved non-piped water coverage			-0.00022	0.00024
Squared % Improved sanitation coverage			0.000057	0.00012
Ln GDP per capita	-0.29***	0.11	-0.32**	0.094
% Urban population	0.0030	0.0053	0.0043	0.0053
Developed countries	-0.39**	0.25	-0.34*	0.19
Countries in LAC region	-0.54**	0.24	-0.54**	0.23
Countries in MIDEAST region	-0.28	0.32	-0.35	0.26
Countries in SOUTH ASIA region	-0.73***	0.21	-0.33	0.25
Countries in EAST ASIA / PACIFIC region	-0.66***	0.22	-0.63***	0.20
Countries in EASTERN EUROPE region	-0.34	0.25	-0.44**	0.19
Democracy-Autocracy Score	0.0041	0.0096	0.0086	0.0088
Years since last regime change	0.0018	0.0015	0.00046	0.00084
Constant	3.8***	0.86	3.0***	0.55
Number of observations	118		132	
Adjusted R^2	0.656		0.709	

*Significant at 90%, **Significant at 95%, ***Significant at 99% [1] Robust standard errors

Table C3. Estimation of population coverage with improved water and sanitation (clustered standard errors presented in parentheses), basic model specification

	Random Effects [a]				Fixed Effects			
	Improved water		**Improved sanitation**		**Improved water**		**Improved sanitation**	
Lagged ln (GDP per capita)	8.0***	(1.7)	12.6***	(2.9)	6.5**	(3.1)	9.4**	(4.6)
% of GDP to lowest 80% of population	-0.21*	(0.12)	-0.15	(0.12)	-0.30**	(0.13)	-0.13	(0.14)
% Urban population	0.20***	(0.06)	0.22*	(0.12)	0.27*	(0.15)	0.43*	(0.23)
Countries in LAC region	6.4*	(3.8)	17.7**	(7.1)				
Countries in MIDEAST region	7.1*	(4.1)	26.9***	(6.9)				
Countries in SOUTH ASIA region	16.7***	(3.8)	9.7	(9.2)				
Countries in EAST ASIA / PACIFIC region	3.1	(4.5)	15.0**	(6.4)				
Countries in EASTERN EUROPE region	12.4***	(4.5)	34.1***	(6.9)				
Linear time trend	0.30***	(0.08)	0.23**	(0.10)	0.29***	(0.10)	0.20	(0.13)
1995	-0.80	(0.70)	0.37	(1.18)	-0.72	(0.66)	0.50	(1.08)
2000	-0.38	(0.31)	-0.14	(0.44)	-0.35	(0.29)	-0.17	(0.41)
Democracy-Autocracy Score	-0.086	(0.17)	0.19	(0.33)	0.076	(0.19)	-0.18	(0.38)
Years since last regime change	-0.0073	(0.03)	-0.0030	(0.05)	0.010	(0.04)	-0.019	(0.06)
Coup	-1.44	(0.90)	-1.29	(1.16)	-1.29	(0.89)	-0.85	(1.23)
Constant	64.7***	(6.5)	28.3***	(8.2)	72.2***	(8.5)	33.0***	(12.9)
Number of observations	374		374		374		374	
Adjusted R^2 (overall)	0.676		0.749		0.586		0.629	
(within)	0.492		0.263		0.498		0.271	
(between)	0.688		0.765		0.593		0.640	

*Significant at 90%, **Significant at 95%, ***Significant at 99%.

[a] A random-effects tobit model that allows censoring at 0 and 100% coverage does not yield qualitatively different results, though coefficients for the income term are somewhat larger.

Figure A 4. Percent of population with improved water, by region, assuming base case elasticities of coverage and using 1950-2008 GDP growth for future projections (actual coverage data shown in shaded box)

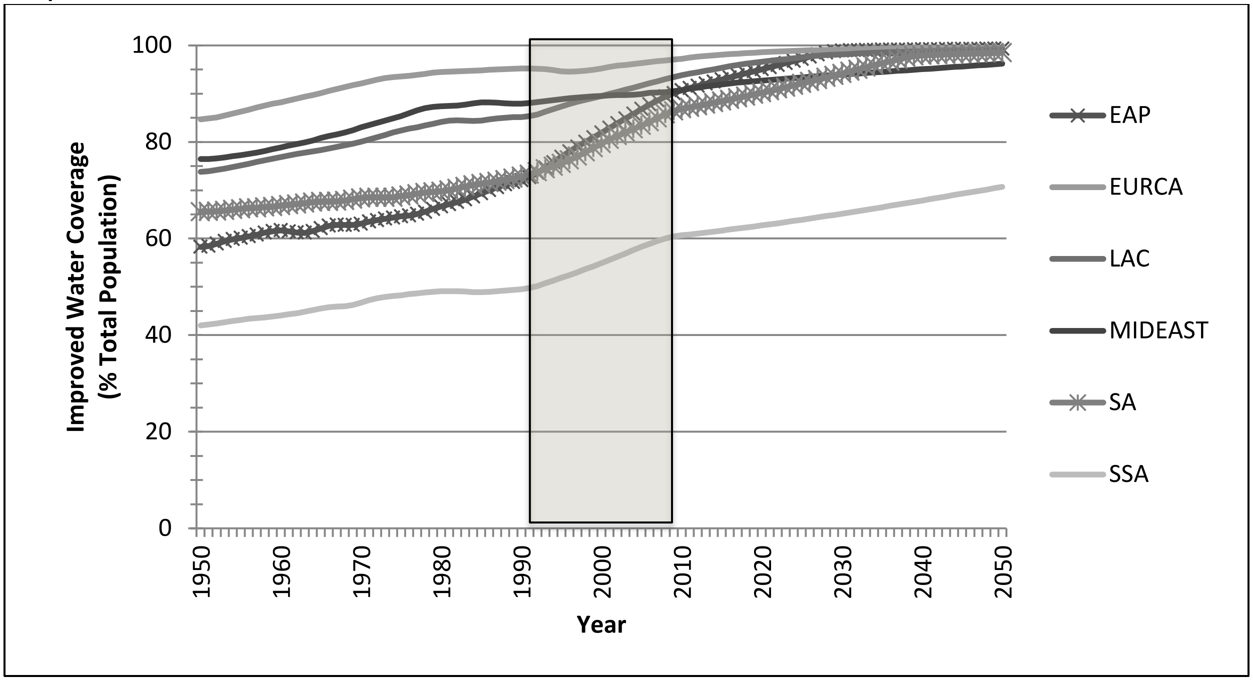

Figure A 5. Percent of population with improved sanitation, by region, assuming base case elasticities of coverage and using 1950-2008 GDP growth for future projections (actual coverage data shown in shaded box)

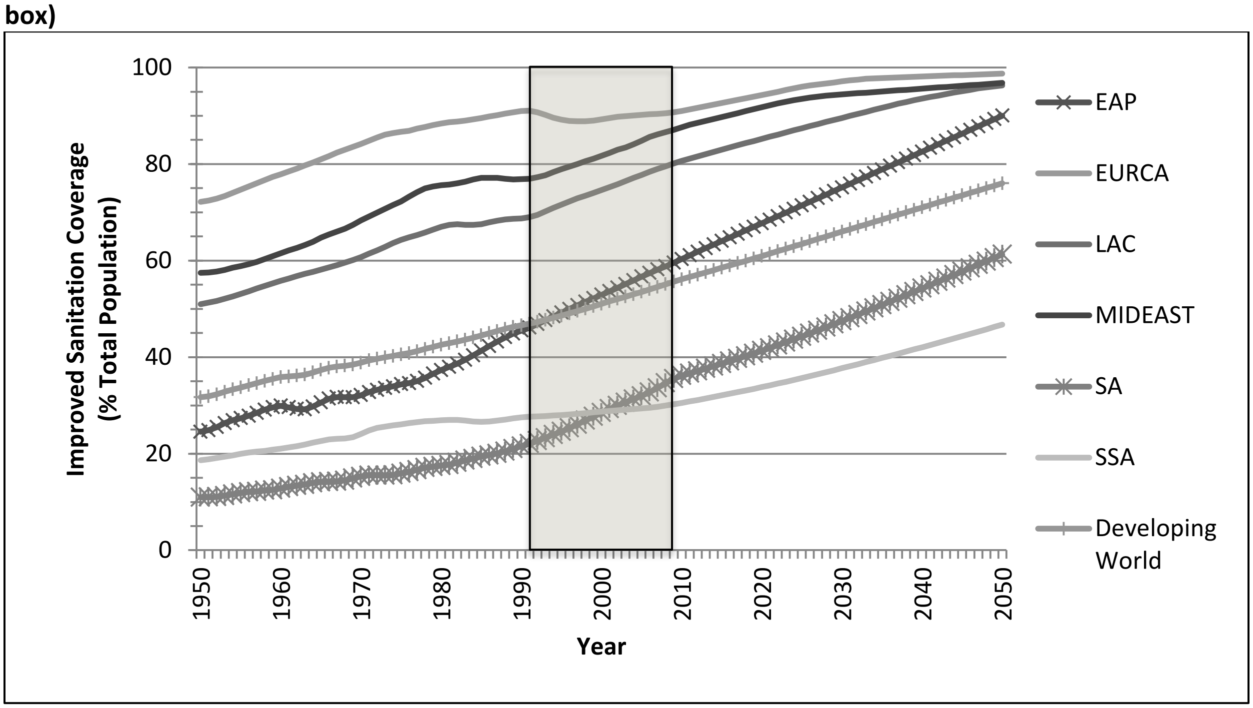

Figure A 6. Base case total "economic losses" associated with WASH, by region (projections from 1950-2008 growth rates)