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# WATER RESOURCES, HEALTH, AND THE SUSTAINABILITY OF INTERVENTIONS TO ACHIEVE WATER AND SANITATION TARGETS OF THE MILLENNIUM DEVELOPMENT GOALS IN A CHANGING WORLD

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# WATER RESOURCES, HEALTH, AND THE SUSTAINABILITY OF INTERVENTIONS TO ACHIEVE WATER AND SANITATION TARGETS OF THE MILLENNIUM DEVELOPMENT GOALS IN A CHANGING WORLD

By

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A DISSERTATION

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This dissertation, "Sustainable technologies for meeting the Millennium Development targets for water and sanitation", is hereby approved in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in the field of Environmental Engineering.

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# Table of Contents

# List of Figures

# List of Tables

# Preface

This dissertation is a compilation of either entire publications or significant portions of publications either in print, submitted, or in preparation. Chapters 2-5 have been coauthored, and the dissertation author's contribution to each of these chapters is described below.

Chapter 2 was published in Mihelcic, J. R.; Fry, L. M.; Myre, E. A.; Phillips, L. D.; Barkldoll, B. D. *Field Guide to Environmental Engineering for Development Workers: Water, Sanitation, and Indoor Air*. In ASCE Press: Reston, VA, 2009; p 550. This chapter was primarily authored by the dissertation author.

Chapter 3 was published as Fry, L. M.; Mihelcic, J. R.; Watkins, D. W. Water and Nonwater-related Challenges of Achieving Global Sanitation Coverage. *Environmental Science and Technology* 2008, 42 (12), 4298–4304. The dissertation author conducted the analysis, with the exception of the principal components analysis, and was the primary author of the article.

Preliminary work for Chapter 4 was published as Fry, L.; Watkins, D.; Mihelcic, J.; Reents, N., Sustainability of Gravity-Fed Water Systems in Alto Beni, Bolivia: Preparing for Change. In *World Environmental and Water Resources Congress 2010: Challenges of Change*, Providence, Rhode Island, 2010. Recent work will be submitted with the same coauthors for publication in a peer reviewed journal. The dissertation author led research in the field, conducted the analysis, and is the primary author of the printed and future publications.

Chapter 5 has been submitted in condensed form to *Environmental Science and Technology*. The author developed the analysis procedure, conducted the analysis, and was the primary author of the submitted manuscript.

## Acknowledgements

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Special thanks to my advisors, James Mihelcic and David Watkins, who encouraged creativity and provided guidance. Additional thanks to committee members Alex Mayer and Audrey Mayer, who contributed time and provided input on research.

Research conducted in Bolivia was made possible by the efforts of engineers and technicians from ACDI/VOCA non-governmental organization, and students and faculty from Michigan Tech University, the University of South Florida, and Universidad Tecnológica Boliviana who provided access to data or assisted in the 2008 and 2009 field campaigns. The level loggers and the algorithms for processing the data were designed by Mark Rowe, and technician Justino Mamani conducted required field work throughout the year. The family of Ing. Santiago Morales accomodated me during my stays in La Paz, and Ing. Nathan Reents and Gabriela Gemio made logistical arrangements during my stays in Palos Blancos.

Finally, I owe gratitude to my friends and family, especially my parents who supported me throughout my education. They have encouraged me in my international endeavors, taught me Spanish required for my research, and inspired me with their experiences as Peace Corps Volunteers in Kenya.

# Abstract

This dissertation addresses sustainability of rapid provision of safe water and sanitation required to meet the Millennium Development Goals. Review of health-related literature and global statistics demonstrates engineers' role in achieving the MDGs. This review is followed by analyses relating to social, environmental, and health aspects of meeting MDG targets.

Analysis of national indicators showed that inadequate investment, poor or nonexistent policies and governance are challenges to global sanitation coverage in addition to lack of financial resources and gender disparity. Although water availability was not found to be a challenge globally, geospatial analysis demonstrated that water availability is a potentially significant barrier for up to 46 million people living in urban areas and relying on already degraded water resources for environmental income.

A daily water balance model incorporating the National Resources Conservation Services curve number method in Bolivian watersheds showed that local water stress is linked to climate change because of reduced recharge. Agricultural expansion in the region slightly exacerbates recharge reductions. Although runoff changes will range from -17% to 14%, recharge rates will decrease under all climate scenarios evaluated (-14% to -27%). Increasing sewer coverage may place stress on the readily accessible natural springs, but increased demand can be sustained if other sources of water supply are developed. This analysis provides a method for hydrological analysis in data scarce regions. Data required for the model were either obtained from publicly available data products or by conducting field work using low-cost methods feasible for local participants.

Lastly, a methodology was developed to evaluate public health impacts of increased household water access resulting from domestic rainwater harvesting, incorporating knowledge of water requirements of sanitation and hygiene technologies. In 37 West African cities, domestic rainwater harvesting has the potential to reduce diarrheal disease burden by 9%, if implemented alone with 400 L storage. If implemented in conjunction with point of use treatment, this reduction could increase to 16%. The methodology will

contribute to cost-effectiveness evaluations of interventions as well as evaluations of potential disease burden resulting from reduced water supply, such as reductions observed in the Bolivian communities.

# 1 Introduction

## 1.1 Sustainability of water supply and sanitation

A global commitment to improve global water and sanitation access was established through Millennium Development Goal 7, Environmental Sustainability (Table 1-1). The water and sanitation target (Target 3) aims to reduce by half by 2015 the proportion of the population without "sustainable access to safe drinking water and basic sanitation" from the baseline year 1990. If this goal is to be met, then the proportion of people with access to sanitation should be increased to 77% by 2015. However, in 2006, only 62% of the population had access to basic sanitation, and the World Health Organization claims that the world is not on track to meeting the 2015 deadline (World Health Organization 2008).

**Table 1-1. Millennium Development Goal 7: Environmental Sustainability.**

| | |
|---|---|
| Target 1 | "Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources." |
| Target 2 | "Reduce biodiversity loss, achieving, by 2010, a significant reduction the rate of loss" |
| Target 3 | "Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation" |
| Target 4 | "By 2020, to have achieved a significant improvement in the lives of at least 100 million slum dwellers." |

The United Nations estimates that there are currently more than 2.5 billion people who lack access to adequate sanitation and more than 900 people without safe drinking water (World Health Organization 2008). According to the Millennium Development Goals Report of 2008 (United Nations 2008), about 1.6 billion more people will need to be served by sanitation by 2015. This will require a major acceleration in coverage, considering that in the past 18 years, only about 1.1 billion people have gained access to sanitation. The world is on track to meet the MDG Target for drinking water, although many countries in Sub-Saharan Africa and Oceania lag far behind their individual targets (World Health Organization 2008). As a result, accomplishing the water and sanitation target of the MDGs will require a major mobilization of political will, institutional support, financial resources, and natural resources.

Goal 7 requires that access to water and sanitation be sustainable. One early definition of sustainable development came from the Brundtland Commission in 1987 (World Commission on Environment and Development 1987) is development "which meets the needs of the present without compromising the ability of the future to meet its needs." More recent definitions incorporate the importance of three sectors in sustainability: environment, economy or industry, and society. For example, Mihelcic *et al.* (2003) defined sustainability as "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment."

According to the Mihelcic *et al.* (2003) definition of sustainability, the MDG requirement for sustainable access to safe drinking water and basic sanitation requires that the target be met without compromising the ability of future generations to meet their water and sanitation needs in an economical fashion and without adverse impacts on human health and the environment. This is no small task, considering that over 1.2 billion people are currently living under physical water scarcity (withdrawing more than 75% of river flows) and over 1.6 billion people are living under economic water scarcity (access to water is limited by human, institutional, and financial capital, despite adequate water resources) (United Nations 2008).

## 1.2 Research Objectives

The need for engineers to design solutions to address the challenges posed by the Millennium Development target to provide populations with sustainable access to water and sanitation led to the following five objectives of research for this dissertation:

1. Identify engineers' role in public health and achieving the MDGs;
2. Determine what are major challenges to achieving the MDG sanitation target;

3. Examine the sustainability of a major increase in worldwide sanitation coverage in the context of water scarcity under different technology implementation scenarios;
4. Analyze the impacts of the following change drivers on gravity fed water supplies at a local (watershed) scale: land use change, population growth, water and sanitation service expansion, and climate change; and
5. Estimate the improvements in health resulting from an intervention that increases household water availability.

## 1.3 Dissertation overview

The five research objectives address issues related to environmental, economic, and societal sustainability. The research resulted in two publications in print, one in review, and one in preparation. These publications, either in their entire form or in expanded form, make up the body of the dissertation. Results will be of interest to planners in developing communities, engineers designing water and sanitation technologies, nongovernmental organizations, and governmental and intergovernmental development programs.

The dissertation consists of four chapters that relate directly to each objective of the research:

Chapter 2 consists of a discussion of the rationale of the research and the role of engineering in public health. Chapter 2 appears in the field engineering book published by ASCE (Mihelcic et al. 2009).

Chapter 3 presents results from an analysis that related social, economic, and environmental indicators to global sanitation coverage and investigated the impact of sanitation on global water resources. This chapter was presented at the American Water Resources Association 2007 Annual Water Resources Conference (Fry et al. 2007) and was later published in *Environmental Science and Technology* (Fry et al. 2008).

Chapter 4 describes research conducted in Bolivia, in which population growth, water supply and sanitation service expansion, land use changes, and climate change were examined as potential factors affecting the sustainability of spring fed water supply. Research incorporated analysis of the water budget in watersheds using low cost field research methods conducted over two years. The methods were developed to be appropriate for participatory water resources research and are a contribution to sustainability research in water resources engineering in developing countries. Initial assessments of the change drivers were presented at the American Geophysical Union 2008 and 2009 Fall Meetings (Fry et al. 2008; Fry et al. 2009). Results from recently completed work analyzing the impact of these change drivers on the recharge and runoff in the watersheds will be presented at the 2010 World Environmental and Water Resources Congress (Fry et al. 2010) and will be submitted to the *Journal of Hydrology* or the American Society of Civil Engineers *Journal of Hydrologic Engineering*.

Chapter 5 explains the impact of water supply enhancement technologies such as rainwater harvesting on public health. Initial work was presented at the American Geophysical Union 2007 Fall Meeting (Cowden et al. 2007). Further work has been submitted to *Environmental Science and Technology* as a condensed version of Chapter 5.

Chapter 6 contains conclusions and recommendations resulting from the research conducted for all of the four preceding chapters.

# 2 Project Motivation: Public Health and the Role of Engineers[1]

Health, standard of living, and environmental conditions are not independent of one another. It is the engineer's responsibility to work with communities to reduce the disease burden caused by modifiable environmental factors. Engineers and other extension agents must take time to understand the actual health problems faced by a particular community. This work may involve health surveys, community mapping, community meetings, collaborating with social scientists or health workers, and informal discussions with members of the community. The better understanding of health issues and cultural practices and beliefs gained from these activities can maximize the health benefits of an engineered solution.

To fully understand the potential effect of environmental engineering technologies, a basic understanding of public health concerns is necessary. Box 2-1 lists definitions for common terms used to describe public health.

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[1] The material contained in Chapter 2 was previously published in Mihelcic, J.R., Fry, L.M., Myre, E.A., Phillips, L.D., and Barkdoll, B.D. (2009). *Field Guide to Environmental Engineering for Development Workers: Water, Sanitation, and Indoor Air.* Reston, VA: ASCE Press.

**Box 2-1. Common Definitions Used to Describe Public Health.**

**Morbidity:** Incidence of illness.

**Mortality:** "Mortality" and "death" are used interchangeably.

**Risk:** "Risk" can have various meanings. It is defined here using the following two definitions: probability of an adverse health outcome or a factor that raises the probability of an adverse health outcome (World Health Organization 2002).

**Relative risk:** A ratio of the risk of morbidity or mortality for a population receiving an intervention to the risk for a population not receiving the intervention.

**Population attributable risk or fraction:** The fraction of a disease or death that is attributable to a particular risk factor in a population.

**Disability adjusted life years (DALYs):** A measure of burden of disease. One DALY is equal to the loss of one healthy life year due to death or the inability to work because of illness. In 2001, there were almost 1.5 billion DALYs, or roughly 0.24 DALY per capita globally (World Health Organization 2002).

**Attributable burden of disease:** The fraction of a disease or injury burden that results from past exposure to a risk (World Health Organization 2002).

**Avoidable burden of disease:** The proportion of future disease or injury burden that is avoidable if exposure levels are reduced to an alternative distribution (World Health Organization 2002).

According to the World Health Organization (2004), at the global level, infectious and parasitic diseases account for 23.5% of the burden of disease. The largest contributors to this category are tuberculosis, HIV and AIDS, diarrheal diseases, childhood cluster diseases (e.g., pertussis, poliomyelitis, diphtheria, measles, and tetanus), and malaria. Infectious and parasitic diseases are followed by neuropsychiatric conditions (12.9%), cardiovascular disease (9.9%), unintentional injuries (8.9%), and respiratory infections (6.5%). Table 2-1 shows the distribution of burden of disease according to risk factor for two economic regions, according to the World Health Organization's *World Health Report (World Health Organization 2002)*. Three of the leading risk factors in high-mortality developing countries—underweight (14.9% of all DALYs); unsafe water, sanitation, and hygiene (5.5%); and indoor smoke from solid fuels (3.7%)—can all be directly improved by environmental engineering activities.

**Table 2-1. Ten leading risk factors contributing to burden of disease in 2000, according to economic region (World Health Organization 2002). Note: The elimination of the leading 5 risk factors would increase life expectancy by 14 years in African nations with high child and very high adult mortality, and 11 years in African nations with high child and high adult mortality**

| *Developing Countries* | | *Developed Countries* | |
|---|---|---|---|
| **Risk Factor** | **% DALYs** | **Risk Factor** | **% DALYs** |
| Underweight | 14.9 | Tobacco | 9.4 |
| Unsafe sex | 10.2 | Blood pressure | 7.2 |
| Unsafe water, sanitation, and hygiene | 5.5 | Alcohol | 6 |
| Indoor smoke from solid fuels | 3.7 | Cholesterol | 3.5 |
| Zinc deficiency | 3.2 | Overweight | 3 |
| Iron deficiency | 3.1 | Low fruit and vegetable intake | 2.8 |
| Vitamin A deficiency | 3 | Physical inactivity | 2.6 |
| Blood pressure | 2.5 | Illicit drugs | 2.5 |
| Tobacco | 2 | Unsafe sex | 2.5 |
| Cholesterol | 1.9 | Iron deficiency | 2.4 |

Other leading risk factors may also be indirectly affected by improvements in the environment. For example, the risk factor unsafe sex (10.2%) can be influenced by access to water and sanitation. Education level affects a woman's likelihood of becoming a sex worker, and girls are less likely to attend school if girls and boys do not have separate sanitation facilities. Zinc, iron, and vitamin A deficiency can all be exacerbated by infections resulting from unsafe drinking water and lack of sanitation (World Health Organization 2002).

A study by Prüss-Üstün and Corvalán (2006) used the World Health Organization's 2002 comparative risk assessment (Ezzati et al. 2004), along with expert opinion, to estimate that 24% of the global burden of disease (in terms of DALYs) and 23% of all deaths can be attributed to modifiable environmental factors. Table 2-2 lists the diseases with the largest absolute burden attributable to modifiable environmental factors. Also included in this table are the environmental causes of the diseases and examples of engineering activities that can modify the environment to decrease the burden of disease.

**Table 2-2. Diseases with the largest absolute burden of disease attributable to modifiable environmental factors and potential environmental engineering activities to lower the environmental burden. Note: Data are representative of conditions in 2002.**

| *Disease or Disease Group* | *Global Burden of Disease (% of all DALYs) (Ezzati et al. 2004)* | *Percent of Disease Burden Attributable to Modifiable Environmental Factors (Prüss-Üstün and Corvalán 2006)* | | *Environmental Factors Contributing to Disease BurdenTableTable (Prüss-Üstün and Corvalán 2006)* | *Engineering Activities to Lower the Burden of Disease* |
|---|---|---|---|---|---|
| Diarrhea | 4.3% | World<br>Developing countries<br>Developed countries | 94%<br>94%<br>90% | Water, sanitation, and hygiene (88%) of all cases | Improved water and sanitation; mitigation of climate change |
| Lower respiratory infections | 6.3% | World<br>Developing countrie<br>Developed countries | 41%<br>42%<br>20% | Indoor air pollution from solid fuel use;<br>outdoor air pollution;<br>tobacco smoke;<br>housing conditions;<br>hygiene | Improved cook stoves; air pollution controls; improved housing conditions |
| Other un-intentional injuries | 3.2% | World<br>Developing countries<br>Developed countries | 44%<br>45%<br>30% | Contact with heavy machinery or sports equipment;<br>off-road transportation accidents;<br>animal bites and venomous plants;<br>exposure to ionizing radiation or electric currents;<br>suffocation;<br>natural forces;<br>contact with hot substances;<br>complications from medical and surgical care | Improved safety during construction;<br>improved transportation;<br>mitigation of climate change;<br>flood control;<br>improved land use patterns;<br>improved building materials |
| Malaria | 2.3% | World<br>Americas<br>Eastern Mediterranean<br>Europe<br>Southeast Asia<br>Sub-Saharan Africa<br>Western Pacific | 42%<br>64%<br>36%<br>50%<br>42%<br>42%<br>40% | Stagnant or slowly moving freshwater | Improved drainage;<br>modified house design;<br>wastewater management;<br>improved irrigation;<br>vegetation management;<br>improved domestic water storage;<br>solid waste management;<br>maintenance of urban water supply and sanitation systems;<br>mitigation of climate change |

Causes of death and disease are different in developed versus developing regions. Lopez et al. (2006) showed that the percentage of deaths attributable to communicable diseases is five times greater in low- and middle-income countries than in high-income countries. Figure 2-1 shows the ten leading causes of burden of disease by broad income group (Lopez et al. 2006).

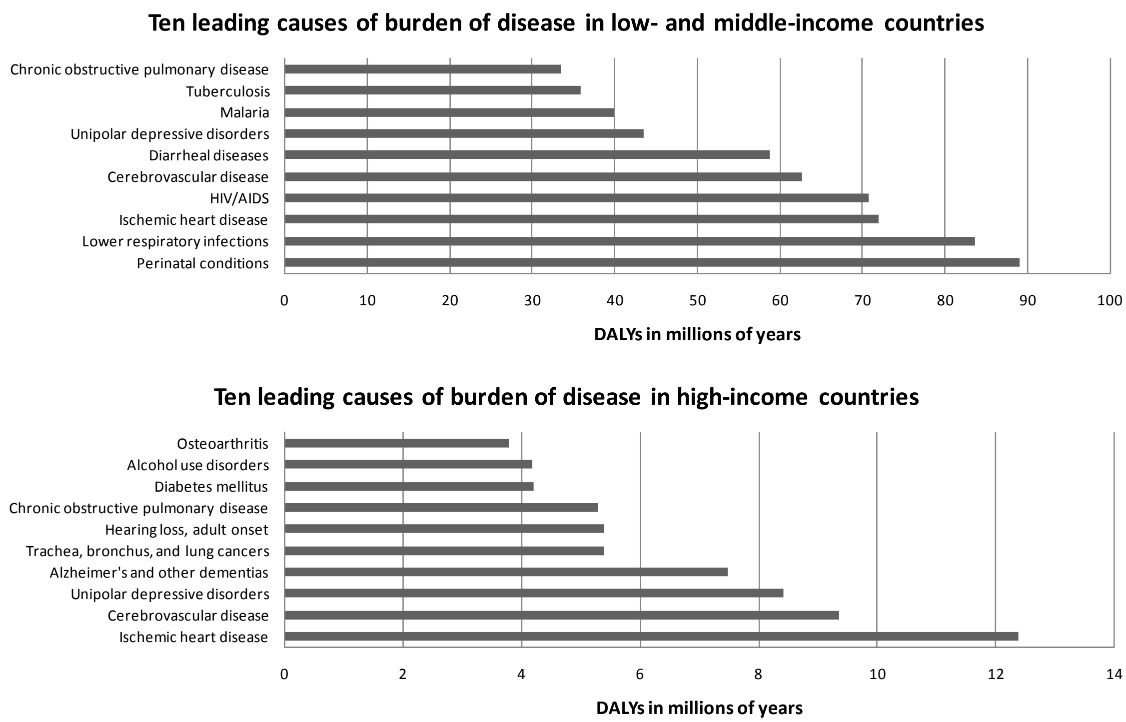


**Figure 2-1. The 10 leading causes of disease burden in low- and middle-income countries and high-income countries. Note: Low- and middle-income countries represent about 85% of the global population. Source: (Lopez et al. 2006).**

Sustainable development requires that engineers implementing solutions to current problems consider how risks in the community will change over time (e.g., with increasing income). Many noncommunicable diseases that are dominant in developed countries are, at least in part, attributable to environmental factors. The risk factors overweight and physical inactivity (Table 2-1) are examples of risks that can be improved by sustainable development (e.g., incorporating pedestrian-friendly routes into community development plans).

In the comparative risk assessment in Lopez et al. (2006), environmental risks were divided into five groups: unsafe water, sanitation, and hygiene; indoor air pollution from use of solid fuels; lead exposure; urban air pollution; and global climate change. The engineering solutions discussed by Mihelcic et al. (2009) directly reduce exposure to the risk factors unsafe water, sanitation, and hygiene; indoor air pollution from use of solid fuels; and urban air pollution. As a result, the interventions are appropriate for public health goals to reduce water-related diseases, respiratory diseases, and diseases that result from burning of open dumps because of poor solid waste management.

Additional indirect benefits may also result from these interventions. For example, a water project that reduces the time required for drawing water may allow mothers more time for food preparation and breastfeeding, which might lead to improved child nutrition. More time may also allow women to pursue income-generating activities to improve household economics (Esrey 1996). Environmental conditions can also have a significant indirect effect on other important disease groups, such as malnutrition, HIV, and AIDS, as well as on other risk factors, such as climate change.

## 2.1 Water-Related Diseases

The risk factor water, sanitation, and hygiene is responsible for 5.5% of all DALYs in low- and middle-income countries (World Health Organization 2002). In fact, 88% of all diarrhea is caused by unsafe water, sanitation, and hygiene (Prüss-Üstün and Corvalán 2006).

Diseases that can be directly affected by water, sanitation, and hygiene improvements fall under two broad disease transmission categories: water-related and fecal–oral transmission. Water-related diseases fall into four categories, according to their transmission routes: 1. water-borne, 2. water-washed, 3. water-based, and 4. insect–vector (Table 2-3). Fecal–oral diseases are considered water-related, but they are diseases that fall under both water-borne and water-washed, such as cholera and bacillary dysentery. In other words, fecal–oral diseases are transmitted by both direct ingestion of contaminated water and inadequate hygiene (Cairncross and Feachem 1993).

**Table 2-3. Water related diseases, according to transmission route (Cairncross and Feachem 1993). Note: the transmission routes described for diseases may not be the only means of transmission (see Figure 1-2 for an example of the complicated nature of disease transmission).**

| *Transmission Route* | *Definition* | *Preventive Strategies* | *Examples of Diseases* |
|---|---|---|---|
| Water-borne | Transmitted when a person or animal ingests water containing the pathogen | Improve drinking water quality; prevent casual use of unprotected sources of water | Cholera; typhoid; infectious hepatitis; diarrhea; dysentery |
| Water-washed | Transmitted because of inadequate amounts of water used for personal hygiene | Increase water quantity; improve accessibility; improve reliability; improve hygiene | Cholera; bacillary dysentery; bacterial skin sepsis; scabies; fungal skin infections; louse-borne epidemic typhus; louse-borne relapsing fever; trachoma |
| Water-based | Transmitted by a pathogen that spends part of its life cycle in a water snail or other aquatic animal. All pathogens causing these diseases are parasitic worms (helminthes). | Reduce the need for contact with infected water; control snail populations; reduce contamination of surface waters | Schistosomiasis; Guinea worm |
| Insect–vector | Transmitted by insects breeding or biting in or near water | Improve surface water management; destroy breeding sites; reduce the need to visit breeding sites; use mosquito netting | Malaria; yellow fever; dengue; onchocerciasis |

Fecal–oral transmission routes are often described by the *F-diagram*, so called because transmission is related to fingers, flies, fluids (i.e., water), food, and fields

(Figure 2-2). The F-diagram shows how diseases are transmitted and how engineering activities and personal hygiene act as barriers to the routes of transmission. Without sanitation and hygiene, human waste can directly enter surface water and wash onto fields, flies can land on uncovered feces, and fecal pathogens can be transmitted directly by human contact. In some cultures, fields may be considered the appropriate place for defecating. Humans can then ingest fecal pathogens through direct ingestion of contaminated water, eating contaminated foods, through contact with other infected people, or when people, especially children, put fingers in their mouths. Contamination of food results from washing or preparing it with fecally infected water; harvesting food from fields irrigated with contaminated water, polluted by runoff, or used for defecation; or through preparation of food with unwashed hands.

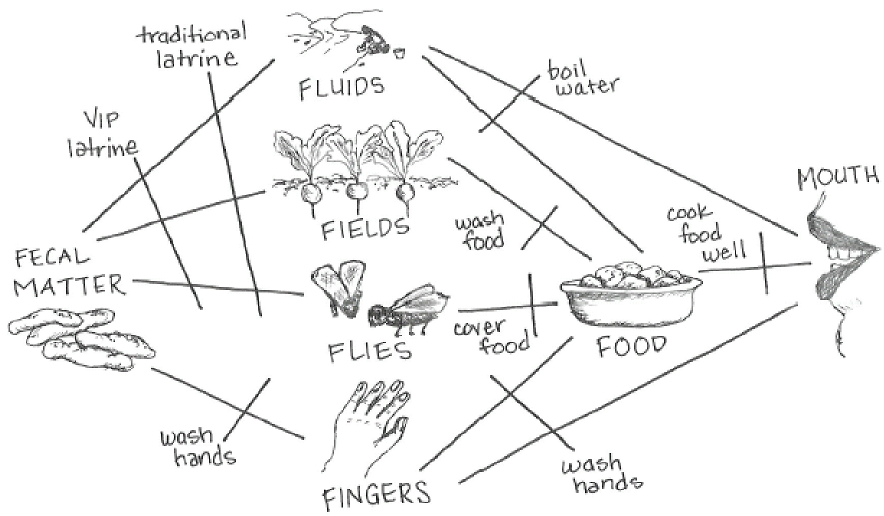


**Figure 2-2. The F-diagram. Note: Fecal–oral transmission results from contamination of fluids (water), fields, flies, food, and fingers. A combination of engineering activities and hygiene education, such as the interventions depicted on this diagram, can effectively act as barriers to all routes of transmission. There are a greater number of hygiene interventions than engineered barriers (e.g., latrines) to ensure 100% prevention. Source: Drawing by Linda Phillips, with permission, Adapted from Wagner and Lanoix (Wagner and Lanoix 1958).**

A combination of engineering activities and personal hygiene can act as barriers to every route of fecal–oral transmission. For example, traditional latrines prevent feces from contaminating surface water and fields. If properly sited, they also prevent feces from contaminating groundwater. Ventilated improved pit (VIP) latrines go a step further and prevent flies from entering or leaving the pit. Treating drinking water prevents ingestion of contaminated water as well as contamination of foods during preparation. The F-diagram also shows the great importance of hygiene education because even if engineered barriers are in place to prevent transmission through water, fields, or flies, a major transmission route remains if hand washing does not take place after defecation, before preparing foods, or before and after personal contact with others.

Engineering activities that are strategies to prevent water-related diseases are discussed throughout the field engineering book (Mihelcic et al. 2009). These activities include water supply and treatment technologies, as well as latrines and other small-scale wastewater treatment solutions. The question of which type of intervention to implement is discussed in Box 2-2.

**Box 2-2. Water, Sanitation, or Hygiene?**

**The Historical Perspective**

In the 1980s and 1990s, Steven A. Esrey published several studies evaluating the reduction in diarrheal morbidity following water, sanitation, and hygiene interventions (Esrey et al. 1985; Esrey et al. 1991; Esrey 1996). His work showed that improvements in water quality alone resulted in a smaller reduction in diarrhea than sanitation or hygiene improvement. For example, the expected reductions in diarrheal disease morbidity from a multicountry study in 1991 are listed in the following table (table courtesy of Thomas Clasen, London School of Hygiene and Tropical Medicine).

| | *All Studies* | | *Rigorous Studies* | |
|---|---|---|---|---|
| **Route** | **No. of Studies** | **Reduction** | **No. of Studies** | **Reduction** |
| Water and sanitation | 7 | 20% | 2 | 30% |
| Sanitation | 11 | 22% | 5 | 36% |
| Water quality and quantity | 22 | 16% | 2 | 17% |
| Water quality | 7 | 17% | 4 | 15% |
| Water quantity | 7 | 27% | 5 | 20% |
| Hygiene | 6 | 33% | 6 | 33% |

The meta-analyses conducted by Esrey (Esrey et al. 1985; Esrey et al. 1991; Esrey 1996) provided a clear message: sanitation and hygiene interventions are more important than water quality interventions, and water quality improvements should be accompanied by sanitation and hygiene improvements. Further research, however, suggests that the implications of Esrey's results may not be as simple as these conclusions imply.

**The Question Reexamined**

More recently, there has been increased focus on point-of-use treatment of drinking water (treating drinking water at the home, rather than at the source), which was not included in Esrey's studies. A recent review showed reductions in diarrhea morbidity between 35% and 46% following point-of-use water quality interventions (Clasen and Cairncross 2004). Unfortunately, these studies did not include other water, sanitation, or hygiene interventions to compare their effect or their combined effects. It should also be noted that the point-of-use studies mentioned above4 did not consider effects on water-washed diseases, such as trachoma. Point-of-use systems have only been evaluated for their effectiveness in reducing diarrhea, which is usually water-borne.

In 2005, Lorna Fewtrell and others conducted a meta-analysis that included point-of-use treatment, improved water supply, improved hygiene, improved sanitation, and multiple interventions. Although all interventions resulted in significant reductions in morbidity from diarrhea, the surprising result of their study was that multiple interventions did not have a greater effect than a single intervention implemented alone, but they suggest that this result may be a result of "piecemeal implementation of more ambitious intervention programs." Fewtrell et al. (2005) advise that a better method might involve phased implementation of multiple projects, giving each component sufficient attention.

### 2.1.1 Diseases Related to Air Pollution

Among the leading 10 disease groups contributing to the global burden of disease are lower respiratory infections, ischemic heart disease, stroke, and chronic obstructive pulmonary disease. For all of these diseases, urban air pollution and indoor air pollution from use of solid fuels have an appreciable population attributable fraction. Table 2-4 shows these fractions, which demonstrate how disease burden changes with development.

**Table 2-4. Percent attributable fractions for the risk factors, "indoor air pollution from use of solid fuels" and "urban air pollution" for four of the ten leading diseases (Lopez et al. 2006). Note: in developed countries, lower respiratory infections are not among the 10 leading diseases. Not listed on this table however, is "trachea, bronchus, and lung cancers," which is among the top 10 disease groups in developed countries. Urban air pollution is accountable for 3% of these diseases in developed countries, which suggests that as countries develop, they experience a shift in the diseases that are important. This notion should be a consideration for sustainable development.**

| *Percent Attributable Fraction* | *Lower Respiratory Infections* | *Ischemic Heart Disease* | *Stroke* | *Chronic Obstructive Pulmonary Disease* |
|---|---|---|---|---|
| **Global** | | | | |
| Indoor air pollution from use of solid fuels | 35% | | | 30% |
| Urban air pollution | 1% | 2% | 3% | 2% |
| **Low- and middle-income countries** | | | | |
| Indoor air pollution from use of solid fuels | 36% | | | 35% |
| Urban air pollution | 4% | 2% | 4% | 2% |
| **Developed countries** | | | | |
| Indoor air pollution from use of solid fuels | N/A | | | |
| Urban air pollution | N/A | 1% | 1% | 1% |

In developed countries, indoor air pollution from use of solid fuels is not an important risk factor, and lower respiratory infections do not appear as one of the 10 leading disease groups. However, trachea, bronchus, and lung cancers are among the top 10 disease groups for developed countries, and 3% of these diseases are attributable to urban air pollution (Lopez et al. 2006). Urban air pollution is a major environmental justice concern in developed countries and thus should be a consideration for sustainable development.

Engineers can play a role in preventing diseases resulting from indoor smoke from solid fuels and urban air pollution. For example, engineers can improve urban air quality in developing countries through solid waste management, which reduces the need for burning of open dumps. Mihelcic *et al.*(2009) discuss solid waste management technologies and practices.

In Mihelcic et al. (2009), improved cook stoves are presented as an appropriate technology for regions where households' primary source of cooking fuel has been firewood. By improving the efficiency of burning and including ventilation of smoke away from the kitchen, women and children can greatly reduce their exposure to indoor smoke from solid fuels. An additional advantage of reducing the amount of required fuel wood is reduced deforestation, an important public health topic that relates to climate change risks, malnutrition, water resource and land management, and traditional lifestyles.

### 2.1.2 Diseases and Risks Affected Indirectly by Environmental Engineering Activities

Although they are not the main focus of the field engineering book (Mihelcic et al. 2009), health outcomes that are indirect results of environmental engineering activities do provide further motivation for environmental engineers to be engaged in public health development. Examples of diseases and risks that can be indirectly affected by the environmental engineering activities presented in this book include malnutrition, HIV and AIDS, and climate change risks.

#### *2.1.2.1 Malnutrition*

Despite the fact that food production increased by 25% during the second half of the 20th century (United Nations - Water World Water Assessment Programme 2006), nutritional deficiencies still accounted for 2.3% of all DALYs worldwide in 2002 (World

Health Organization 2004). The risk factor underweight accounts for 14.9% of all DALYs in high-mortality developing countries and 3.1% of DALYs in low-mortality developing countries. The fact that 3% of all DALYs in developed nations is attributable to overweight is yet another striking contrast showing how disease burden and risks shift as a result of development (Table 2-1). Malnutrition can be improved in several ways, including improved food production and improved nutrient uptake through the reduction of infectious diseases.

On average, worldwide food production requires 3,000 L of water per day per capita, 10% of which is supplied by irrigation (United Nations - Water World Water Assessment Programme 2006). Engineers can increase food production by improving water resource management and irrigation technology. Related engineering activities are watershed management and water supply systems.

Malnutrition is exacerbated by diarrhea, which reduces dietary intake, increases fecal and nutritional loss, reduces intestinal transit time, resulting in reduced absorption of nutrients, and increases protein catabolism caused by acceleration in the basal metabolic rate. This fact is especially true for children under the age of two, as they are being weaned from breast milk to solid foods (Braghetta 2006). Parasitic infections such as hookworm, giardia, and schistosomiasis also influence malnutrition by causing diminished appetite, nutrient loss, and decreased nutrient absorption (Stephenson et al. 2000). By improving water supply, sanitation, and hygiene, the resulting reduction in diarrhea will improve child nutritional status.

#### *2.1.2.2 HIV and AIDS*

HIV and AIDS is the fourth leading cause of DALYs in low- and middle-income countries (Lopez et al. 2006). According to the Joint United Nations Programme on HIV/AIDS (Joint United Nations Programme on HIV/AIDS 2006), sub-Saharan Africa, Asia, and Latin America accounted for 34.4 million of the 38.6 million people worldwide who were living with HIV in 2005. In the *2006 Report on the Global AIDS Epidemic,* UNAIDS (2006) states that "mitigation efforts need to address the root causes of child labor, including poverty, illiteracy and food shortages."

Engineering activities can have an indirect effect on HIV and AIDS by improving education, family economics, and food consumption. Water supply projects and improved cook stoves not only reduce the burden of diarrheal disease and respiratory infections, respectively, but also save time by decreasing the distance to collect water and reducing the need for firewood collection for solid fuel burning (Joint United Nations Programme on HIV/AIDS 2006). In addition, such technologies can improve the standard of living of people living with HIV and AIDS.

It is widely understood that people infected with HIV and AIDS are at greater risk for malaria and that bouts of malaria are more severe for people living with HIV and AIDS. Recent studies have also shown that malaria actually increases the risk of transmission of the AIDS virus. A study of HIV-infected women in Uganda found that mother-to-child transmission of HIV was significantly associated with both the AIDS viral load and placental malaria infection (Brahmbhatt et al. 2003). Additional research in Kenya has shown that a person infected with both HIV and the malaria parasite has an increased viral load during malaria episodes, which results in increased likelihood of HIV transmission (Abu-Raddad et al. 2006). Therefore, engineering efforts that reduce the transmission of malaria, such as surface water management and projects that destroy mosquito breeding grounds, may also have an effect on transmission of the AIDS virus.

#### *2.1.2.3 Climate Change Risks*

The risk factor global climate change is defined by McMichael et al. (2004) as "current and future changes in global climate attributable to increasing atmospheric concentration of greenhouse gases." Climate change is expected to bring some health benefits, such as lower cold-related mortality and improved crop yields in temperate regions. However, many adverse health outcomes are also expected as a result of climate change, and these outcomes will outweigh the benefits (McMichael et al. 2004). Even today, climate change is considered to be an important risk: climate change risks are accountable for 5% of all environmental risk factors (Ezzati et al. 2004).

Climate change affects many health outcomes, including malnutrition, diarrhea, malaria, injuries and deaths due to floods, and cardiovascular diseases. For example, in seasonally dry and tropical regions at lower latitudes, food production is expected to decrease with even small increases in local temperature (Intergovernmental Panel on Climate Change 2007). The analysis by McMichael et al. (2004) suggests that climate change affects the burden of disease from malnutrition, diarrhea, and vector-borne diseases significantly more than it affects the burden from flooding or deaths due to thermal extremes. These negative effects will likely be the most pronounced among poorer populations at low latitudes, where climate-sensitive health outcomes are already common and for whom vulnerability is greatest.

Studies have been conducted to predict how climate change will affect water supply and use (e.g., (Alcamo et al. 1997; Arnell 1999; Meigh et al. 1999)). Although in many areas precipitation and runoff will increase as a result of climate change, other regions will experience a decrease. For example, Alcamo et al. (1997) predicted that under the best estimate, 75% of the earth's land area will experience increases in runoff from 1995 levels, but 25% will experience decreases. This study indicated that decreases in runoff of more than 50 mm/year were possible outcomes for northern Brazil, Chile, Taiwan, and the Indian west coast. Countries such as Cyprus, Israel, Jordan, and Morocco, which are already experiencing water scarcity, will see an even further intensification of water scarcity.

Whereas it increases water availability, increased precipitation in the other regions will also create public health challenges. The expected increase in temperature, precipitation, and runoff in most regions is expected to increase the geographical range of vector-borne diseases, the frequency of contamination of drinking water, and the frequency of weather disasters (McMichael et al. 2004).

Engineers are already working to mitigate emissions of greenhouse gases, which in the long run will decrease the health risks related to global climate change. Although limiting greenhouse gas emissions is the most important step in reducing health risks resulting from climate change, such actions must be accompanied by development of adaptation strategies to cope with the damage that has already been done and the irreversible warming trends that have been initiated.

The African Development Bank and other development organizations have come to the agreement that integrating adaptation responses into development planning is an important way to address climate change effects on the poor (African Development Bank and Other international organizations 2003). Projects to improve water, sanitation, and air quality should, therefore, incorporate adaptation planning and assessment into project design. For example, is a sanitary sewer an appropriate technology in a city that will move into water scarcity by 2025? Sewers require up to 75 L/capita-day, whereas sanitation technologies also exist that require no water to convey waste (Gleick 1996). If a sewer project is deemed appropriate, what should the community do to prepare for the effects of climate change?

Traditional knowledge and coping strategies already exist in many places to deal with the effect of changing climates, and interventions should take these strategies into account (African Development Bank and Other international organizations 2003). Engineers and communities interested in developing climate change adaptation strategies can learn more from the UNDP's *Adaptation Policy Frameworks for Climate Change* (Lim and Spanger-Seigfried 2004).

# 3 Water and Nonwater-related Challenges of Achieving Global Sanitation Coverage [1]

## 3.1 Abstract

Improved sanitation is considered equally important for public health as is access to improved drinking water. However, the world has been slower to meet the challenge of sanitation provision for the world's poor. We analyze previously cited barriers to sanitation coverage including inadequate investment, poor or nonexistent policies, governance, too few resources, gender disparities, and water availability. Analysis includes investigation of correlation between indicators of the mentioned barriers and sanitation coverage, correlations among the indicators themselves, and a geospatial assessment of the potential impacts of sanitation technology on global water resources under six scenarios of sanitation technology choice. The challenges studied were found to be significant barriers to sanitation coverage, but water availability was not a primary obstacle at a global scale. Analysis at a 0.5° grid scale shows, however, that water availability is an important barrier to as many as 46 million people, depending on the sanitation technology selected. The majority of these people are urban dwellers in countries where water quality is already poor and may be further degraded by sewering vast populations. Water quality is especially important because this vulnerable population primarily resides in locations that depend on environmental income associated with fish consumption.

[1] The material contained in Chapter 3 was published in *Environmental Science and Technology.*

## 3.2 **Introduction**

### 3.2.1 Background

In 2002, diarrhea contributed 4.3% of global disease burden (World Health Organization 2004), of which 88% is caused by unsafe water, sanitation, and hygiene (Prüss-Üstün and Corvalán 2006). Although not separated when considering risk, development of the water supply and sanitation sectors have followed different paths – the water supply sector has been more successful at providing coverage to large numbers of people. This is despite strong epidemiological evidence suggesting that water supply projects alone will not sufficiently decrease the risks of water-related diseases. For example, the multi-country study by Esrey (1996) showed that improvements in water did not result in health impacts if sanitation remained unimproved, but improvements in sanitation had positive health impacts for diarrhea at all levels of water supply. Additional studies confirm that a combination of water, sanitation, and hygiene improvements have a larger impact on reducing diarrhea prevalence than water improvements alone (Esrey et al. 1985; Cairncross 1990; Quick et al. 1999).

The Millennium Development Goals aim to halve the proportion of people without access to safe water and adequate sanitation from 1990 benchmarks by 2015. The world is on track for meeting the water supply target, except for Sub-Saharan Africa (World Health Organization and United Nations Children's Fund 2005). However, despite global commitments such as the U.N. Decade for Water and Sanitation, the world is not on track to meet the sanitation target by 2015. For the world to meet the sanitation target by 2015, an additional 300 million people should have gained access between 1990 and 2004 (United Nations 2006). Furthermore, the World Health Organization and UNICEF (2005) claim that a 58% acceleration in sanitation coverage would be required to meet the sanitation target by 2015.

### 3.2.2 The challenges for achieving sanitation coverage

This article discusses challenges to global sanitation coverage (Table 3-1), as well as water-related considerations for providing global sanitation access in coming decades.

Through analysis of social and economic indicators, and the environmental indicator of water stress, reasons for the gap between water and sanitation coverage are determined. Montgomery and Elimilech (2007) have described the need for "evidence-based policies that allow for effective investment" in water and sanitation. Our analysis provides such evidence by indicating how the selection of a particular sanitation technology impacts populations living under water stress, and also water quality that much of the world depends on for food and income. These issues are especially important as the world moves toward sanitation coverage targets set for 2015 and world's population approaches 9 billion.

**Table 3-1. Challenges to meeting sanitation coverage targets outlined in Goal 7 of the Millennium Development Goals (Briscoe 1996; Esrey 2002; World Bank 2003; Montgomery and Elimelech 2007)**

| |
|---|
| Inadequate investment |
| Lack of political will |
| Avoiding new technologies |
| Poor/nonexistent policies |
| Too few resources |
| Neglect of consumer preferences |
| Gender disparities |
| Governance and accountability |
| Water availability |
| Supply-driven approach |
| The collective action problem |
| Maintenance difficulties |

## 3.3 **Methods**

### 3.3.1 Indicators of challenges cited in literature

To our knowledge, quantitative analyses of the impacts of the challenges in Table 3-1 on sanitation coverage at a global scale are not widely available. Six of the challenges in Table 3-1 were chosen for rigorous analysis based on the availability of meaningful, widely used indicators (Table 3-2). Note that poor/nonexistent policies and governance are combined in Table 3-2 because they had common indicators. Separate correlation analysis was done between each indicator and sanitation coverage, followed by a principal components regression analysis to better understand the individual importance of several explanatory variables with significant cross correlations.

**Table 3-2. Indicatiors used in this study relating to the challenges for sanitation coverage.**

| *Challenge* | *Indicator(s)* | *Indicator definition* | *Source* |
|---|---|---|---|
| Inadequate investment | World Bank investment priority | Comparison of World Bank spending on water projects vs. sanitation projects, as well as the number of projects financed the water and sanitation sectors. | World Bank Projects Database (World Bank 2007) |
| Poor/nonexistent policies and governance | Social and Institutional Capacity (SIC) | Measurement of a country's science and technology; capacity for debate; regulation and management; private sector responsiveness; environmental information; eco-efficiency; and reducing public choice distortions | Esty and Cornelius (2002) |
| | Corruption Perception Index (CPI) | Ranks countries by their perceived level of corruption using expert assessments and surveys. | Transparency International (2006) |
| Too few resources | GDP/capita (Purchasing Power Parity) | Gross domestic product, converted to international dollars, with an international dollar having the same purchasing power as a U.S. dollar has in the United States. | UNEP (2006) CIA (2007) |
| | Foreign Direct Investment (FDI) | Net inflows of investment | UNEP (2006) |
| Gender disparities | Gender Empowerment Measure (GEM) | Measurement of women's and men's percentage shares of: parliamentary seats; positions as legislators, senior officials and managers; professional and technical positions; and women's and men's estimated earned income (PPP US$). | UNEP (2006) |
| Water availability | Water stress | The ratio of freshwater withdrawals to total available freshwater resources. | UNEP (2006) |

### 3.3.2 Water availability methods

Water stress, defined as the ratio of total withdrawals to total runoff, is used as an indicator of non-sustainable water use. Gridded industrial and agricultural water use maps from the year 2000 were adopted from a previously published analysis (Vörösmarty et al. 2005). Long term average annual runoff (Q) was used to represent renewable water resources (Fekete et al. 2002). In previous studies, domestic use has been projected at the grid scale based on population, economic level, and projections of water efficiency (Vörösmarty et al. 2000; Shiklomanov and Penkova 2003), and in some cases, national sanitation and/or drinking water coverage data (Alcamo et al. 1997; Alcamo et al. 2007). In this analysis, domestic water use was estimated at the 0.5° grid level based on drinking water access and sanitation technologies. Table 3-3 provides the scale, availability, and detail for drinking water and sanitation coverage data used to determine domestic use for the current situation (year 2000), using several assumptions (discussed below).

**Table 3-3. Data scale, availability, and detail. All data describe the year 2000, which was used to represent the baseline situation.**

| *Data* | *Scale and Source* | *Availability* | *Detail* |
|---|---|---|---|
| Drinking water coverage | National (UNEP (2006)) | 150 Countries | Rural improved drinking water coverage |
| | | 191 Countries | Urban improved drinking water coverage |
| | | 163 Countries | Rural population with household connection |
| | | 185 Countries | Urban population with household connection |
| Sanitation coverage | Regional (WHO and UNICEF (2000) | Asia<br>Latin American and Caribbean<br>Oceania<br>Europe<br>North America | Proportion of households in major cities connected to sewers and septic tanks |
| | National (UNEP (2006) | 178 Countries | Urban basic sanitation coverage |
| | | 174 Countries | Rural basic sanitation coverage |
| | | 13 Countries | Sewer coverage |
| | National (UN-HABITAT (2003) | 23 Latin American and Caribbean countries | Urban access to sewers and non-sewered in situ sanitation |
| | City (UN-HABITAT (2003) | 38 African cities | Proportion of the population connected to sewers and septic tanks |
| Population | Grid (Vörösmarty et al (2000) | Global | Rural population |
| | | | Urban population |
| World Bank Income Group | National (World Bank (2007) | 205 countries | Lower income, lower-middle income, upper-middle income, and high income countries |

National urban and rural basic drinking water coverage and household access were taken from UNEP (2006). Where national coverage was unknown, it was assumed equal to the average of all other countries in the same World Bank income group. Countries with unknown income group were assigned an income group based on GDP/capita (Central Intelligence Agency (CIA) 2007).

National sewer coverage (United Nations Human Settlement Programme 2003; United Nations Environment Programme 2006) was first assigned to urban populations. Any remainder was assigned to rural populations. For countries without this data, the following procedure was used: 1) For African countries with city data available (United Nations Human Settlement Programme 2003), the major city in the country is assumed representative of all urban areas of the country. 2) For Latin American countries, urban sanitation coverage was taken from UN-HABITAT (United Nations Human Settlement Programme 2003). 3) All other countries used regional averages (World Health Organization and United Nations Children's Fund 2000), except for New Zealand and Australia, which were assigned the average of high income country sewer coverage (92%).

In non-African countries, urban septic coverage was assumed equal to regional averages reported by WHO and UNICEF (2000). African urban septic coverage was assumed equal to septic coverage reported for major cities by UN-HABITAT (2003). Rural septic coverage in low and lower-middle income countries was assumed to be zero. In upper-middle and high-income countries, rural septic coverage was assumed equal to national rural sanitation coverage. Where national rural sanitation coverage was unknown, it was assumed equal to the average rural sanitation coverage of other countries in the same World Bank income group.

For the 14 African countries with known pour-flush sanitation coverage in their largest cities, this coverage was assumed equal throughout the country. For all other countries, urban coverage was assumed equal to the regional average reported by WHO and UNICEF (2000). Pour-flush coverage was not assigned to rural populations.

Rural sanitation coverage that is neither sewer nor septic was assumed to use non water-based technology i.e. simple pit, ventilated improved pit (VIP), and composting latrines. Any urban sanitation coverage that was not sewer, septic, or pour-flush was assumed to be a non water-based technology.

Technologies in this study are considered "improved" by the WHO. However, all sanitation technologies may not have the same health benefits. For example, populations with access to both water and sanitation in countries where there is wide sewer and piped water supply coverage have less risk of exposure to diarrhea than populations with access to both water and sanitation where there is not wide sewer and piped water supply coverage (Pruss et al. 2002). The impact on health is also affected by the implementation and appropriateness of the technology at the local setting. For example, septic systems are considered improved, but they can have negative impacts if improper design, maintenance, or implementation results in direct discharge into water.

Sanitation water use varies from 0 to 66.25 L/capita-day. Water use data were obtained for conventional and high efficiency toilets, pour-flush latrine, urine diversion toilet, VIP latrine, and composting latrine (McGarry 1982; United Nations Environment Programme 2002; EPA 2007; WELL 2007). In developing countries, most sewage is discharged untreated into surface waters. Therefore, we assume that all water used for added sanitation coverage is unavailable for other users. The values for minimum and maximum water use for the various technologies were used to allocate water use to grids, based on levels of urban and rural coverage (specifics in Appendix B). The outcome is summarized in Table 3-4, showing expected water use of populations with different combinations of sanitation and drinking water coverage.

**Table 3-4. Domestic water use as a function of sanitation technology for low to upper-middle income countries.**

| *Sanitation Technology* | *Household connection to drinking water* | *Basic access to drinking water* | *No drinking water access* |
|---|---|---|---|
| Sewer or septic system | 72.5 to 116.25 L/capita/day | 38 to 81.75 L/capita/day | 27.5 to 71.25 L/capita/day |
| Pour-flush latrine | 60 to 75 L/capita/day | 25.5 to 40.5 L/capita/day | 15 to 30 L/capita/day |
| No access or non-water consuming sanitation | 50 L/capita/day | 15.5 L/capita/day | 5 L/capita/day |

The ratio of domestic, industrial, and agricultural water withdrawals to runoff (DIA/Q) was used to indicate water stress. A DIA/Q above 0.2 indicates moderate water stress, and a DIA/Q above 0.4 indicates severe water stress (Vörösmarty et al. 2000).

Projections of future water and sanitation coverage under six different development scenarios (Table 3-5) were made following procedures used for the current situation. Scenarios 1, 2, and 3 correspond to achieving the Millennium Development Goals in 2015, and Scenarios 4, 5, and 6 correspond to achieving 100% coverage by 2025, an optimistic outlook based on Sachs' rationale that ending extreme poverty by 2025 is possible (Sachs 2005). Estimates of rural and urban populations in 2015 and 2025 were available at the national level (United Nations Environment Programme 2006). To allocate rural and urban populations to grid cells, national urban and rural growth rates were assumed to be the same for every cell in the country.

**Table 3-5. Scenarios of future sanitation coverage based on level of water consumption of a particular sanitation technology. Projections of urban and rural populations were used for the year 2015 (Scenarios 1-3) and 2025 (Scenarios 4-6).**

| | |
|---|---|
| Scenario 1 | Meeting the MDG target for sanitation in 2015, with the added sanitation coverage (%) being non water consuming technology |
| Scenario 2 | Meeting the MDG target for sanitation in 2015, with the added *urban* coverage (%) being pour flush sanitation technology and the added *rural* coverage (%) being non water consuming technology |
| Scenario 3 | Meeting the MDG target for sanitation in 2015, with the added *urban* coverage (%) being sewer and the added *rural* coverage (%) being septic. |
| Scenario 4 | 100% coverage in 2025, with added coverage (%) being non water consuming technology |
| Scenario 5 | 100% coverage in 2025, with the added *urban* coverage (%) being sewer and the added *rural* coverage (%) being non water consuming technology |
| Scenario 6 | 100% coverage in 2025, with the added *urban* coverage (%) being sewer and the added *rural* coverage (%) being septic. |

Agricultural and industrial water use were held constant at 2000 levels, with added urban and rural drinking water coverage assumed to be basic (not household connections). Water availability, Q, was held constant at 2000 levels. Drivers of increasing water stress were therefore limited in this study to urban and rural population growth and drinking water and sanitation development (Table 3-5). Differences among scenarios are solely due to the type of sanitation technology implemented.

## 3.4 Results and Discussion

### 3.4.1 Non-Water Challenges of Sanitation Coverage

Since 1961, the annual World Bank contributions to water projects have exceeded contributions to sanitation projects by as much as 1.5 billion U.S. dollars (converted to 2006 U.S. dollars), suggesting there may be inadequate investment in sanitation. The difference was greatest in the 1980s and has been improving through the 1990s and 2000s; however, spending on water projects is still greater than sanitation. Inadequate investment may result from other interrelated factors such as lack of political will, too few resources, or user preferences.

The Social and Institutional Capacity (SIC) component of the Environmental Sustainability Index (Esty and Cornelius 2002) provides a general measure of institutional capacity for development. We assume that SIC is an appropriate measure for development capacity, because better institutions are more likely to implement good policies. Esty et al. (Global Leaders for Tomorrow World Economic Forum et al. 2002) assign countries to clusters based on common patterns across all 20 indicators of the ESI (described in the Figure 3-1a caption). These clusters are used to represent SIC groups. Here, SIC is used as an indicator for both poor/nonexistent policies and governance. Later, corruption and SIC are each evaluated in a principal components regression analysis.

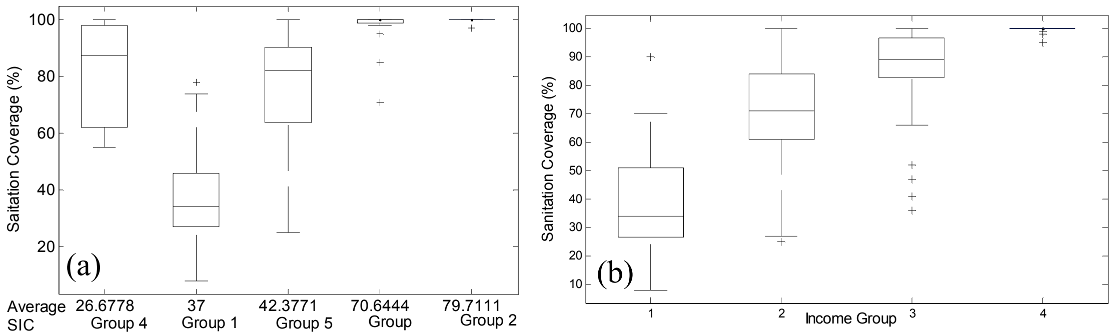


**Figure 3-1. (a) Sanitation Coverage (United Nations Environment Programme 2006) related to Social and Institutional Capacity for the five country clusters in the Environmental Sustainability Index Report (Esty and et al 2002). Boxes represent the 25th, 50th and 75th percentiles. Whiskers extended to minimum and maximum values, except for outliers (+). Group 1 countries are generally poor, vulnerable to corruption, undemocratic, and economically uncompetitive. Group 2 countries tend to show the opposite characteristics of Group 1. Group 3 is similar to Group 2, except with lower scores on environmental systems and stresses. Group 3 countries typically have higher population densities and smaller territory size. Countries in Group 4 are on average less democratic countries. They score lower on most environmental sustainability measures than other poor countries; however, they have slightly better vulnerability scores than the more democratic countries of Group 5. The main difference between Group 4 countries and Group 5 countries is that Group 5 countries are typically more democratic. (b) Sanitation Coverage (United Nations Environment Programme 2006) vs. World Bank Income Group (World Bank 2007). World Bank Income Group numbers correspond to: (1) Lower Income, (2) Lower-Middle Income, (3) Upper-Middle Income, and (4) High Income countries. Boxes represent the 25th, 50th and 75th percentiles. Whiskers extended to minimum and maximum values, except for outliers (+).**

Figure 3-1 (a) shows that countries with higher SIC are more likely to have higher sanitation coverage, except in the case of Group 4 countries, which are primarily less democratic. Although a statistically significant difference (at $p$ = 0.10) was not found between Groups 2 and 3, rank sum tests showed that sanitation coverage for Groups 2 and 3 combined was significantly higher than for Group 1 ($p = 2.375\text{x}10^{-8}$ ) and Group 5 ($p = 1.78\text{x}10^{-10}$ ). This indicates that democratic countries with greater capacity are more likely to have better sanitation coverage.

Figure 3-1(b) demonstrates an obvious limiting factor for sanitation coverage: economic resources. Rank sum tests showed that sanitation coverage for each income group is significantly less than for the next higher income group ($p < 0.0001$ for each case).

Because Income Group 4 countries all have nearly 100% sanitation coverage and their economic situation is so different from the other income groups, these countries were eliminated from the gender disparities analysis. There is a positive correlation (shown in Appendix B) between gender empowerment and sanitation coverage for countries in Income Groups 1-3. More empowered women can have a greater role in development projects, and it is widely accepted among development workers that inclusion of women throughout a project's life cycle increases the sustainability of projects. Women may also be advocates of projects that improve community and household health.

Due to the significant correlation among variables (cross-correlations range from 0.19 to 0.65), a principal components regression model was developed using a subset of the entire data set ($N = 106$) to predict sanitation coverage as a function of the following five Table 3-2 predictors: GDP (PPP), SIC, FDI, GEM, and CPI. The first principal component (PC) explains 49% of the variance and assigns significant weights (0.33-0.55) to each of the predictor variables, indicating that each variable serves as a predictor of sanitation coverage, with GDP (PPP) and CPI serving as the strongest predictors. The weights assigned in PC 2 through 4 indicate that the other three predictors (SIC, FDI, and GEM) all serve to explain a significant portion of the variance (11-18%) *independently* of GDP (PPP) and CPI. While PC 5 explains only 6% of the variance, the strong negative weight placed on CPI helps explain sanitation coverage for less democratic (Group 4) countries, and thus there may be good reason for keeping this PC in the regression model. Retaining the first four principal components in the model results in a cross-validated correlation coefficient of 0.62 ($p < 0.0001$). Additional details are provided in Appendix B.

### 3.4.2 Water-Related Challenges to Sanitation Coverage

At a national scale, average annual water availability was not correlated with sanitation coverage (see Appendix B). This is likely a problem of scale, both spatially and temporally. An accurate study requires grid-level data on sanitation coverage and water availability, and perhaps an indicator of intra-annual water availability. The following sections describe results from the grid-scale analysis of sanitation impacts on water resources and water quality, recognizing these limitations.

Our analysis shows that 33.4% of the global population lived under severe stress conditions in 2000 (Figure 3-2(a)). Similar maps of water-stressed populations under our future scenarios are not shown because differences were too small to visually recognize. Results compare well with 29% in 1995 (Alcamo et al. 1997). Another gridded stress data set (Vörösmarty et al. 2000) was overlaid with the same population data and resulted in 29% of the population living under severe stress in 1995.

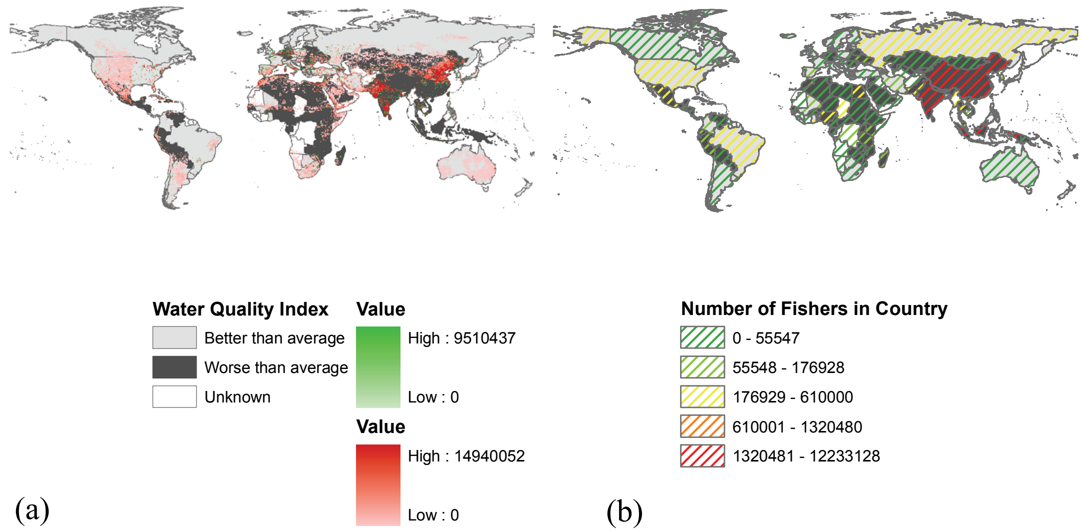


**Figure 3-2. (a) Populations under moderate and severe water stress in 2000, overlaid with the Environmental Sustainability Index's Water Quality Indicator (Esty and Cornelius 2002). (b) Number of fishers (World Resources Institute et al. 2005) overlaid on the Water Quality Indicator (Esty and Cornelius 2002). Visually, the 2015 and 2025 scenarios do not change significantly from this 2000 map, so maps are not shown for 2015 and 2025.**

For the six scenarios, the global population living under moderate water stress is predicted to range from 380 to 510 million, and the global population living under severe stress will range from 2 to 2.8 billion (detail in Appendix B).

Providing global sanitation coverage does not greatly increase the future population projected to live under moderate or severe water stress. For example, as shown in Table 3-6, achieving the Millennium Development Goals through sewer coverage in urban settings and septic coverage in rural settings (Scenario 3) (compared to using dry sanitation technology of Scenario 1) results in 17 million more people living under moderate water stress and 8.7 million more people living under severe water stress. Likewise, assuming 100% coverage by 2025, 20 million additional people are estimated to live under moderate water stress and up to 46 million people are estimated to live under severe water stress if similar sanitation technology is implemented. For these populations, water availability will be an important challenge to sanitation development.

**Table 3-6. Number of urban and rural inhabitants increasing their water stress after sanitation provision to move into the moderate or severe water stress categories based on Table 5 scenarios. Note that when moving from Scenario 1 to Scenario 2, the negative number of additional people under moderate stress results from those people moving into the severe stress category.**

| | *Additional people under moderate stress* | *Additional people under severe stress* |
|---|---|---|
| Scenario 1 to 2 | $-3.90 \times 10^{6}$ | $3.90 \times 10^{6}$ |
| Scenario 2 to 3 | $2.09 \times 10^{7}$ | $4.80 \times 10^{6}$ |
| Scenario 1 to 3 | $1.70 \times 10^{7}$ | $8.70 \times 10^{6}$ |
| Scenario 4 to 5 | $5.98 \times 10^{6}$ | $4.81 \times 10^{6}$ |
| Scenario 5 to 6 | $1.39 \times 10^{7}$ | $4.14 \times 10^{7}$ |
| Scenario 4 to 6 | $1.99 \times 10^{7}$ | $4.62 \times 10^{7}$ |

Affected populations are more urban than rural. For example, up to 32 million urban dwellers (compared to 14 million rural people) move into the severe water stress category progressing from Scenario 4 to Scenario 6. Rapid urbanization presents particular challenges for sanitation coverage. In Buenos Aires, lack of sewer coverage in informal urban settlements was partially blamed on the irregular urban layout of the settlements and the fact that many low-income settlements are in low-lying areas (United Nations Human Settlement Programme 2003). Urban settings are different from rural areas because sewers transport waste with water, which is effective in preventing fecal-oral diseases. Before sewers were constructed in industrialized countries in the 19$^{th}$ and early 20$^{th}$ centuries, infant mortality rates of 100 to 200 per 1,000 live births were common (United Nations Human Settlement Programme 2003). Public latrines are not included in the definition of improved sanitation and urban space constraints can prevent household latrine coverage.

Populations identified in this analysis living under water stress were based solely on water withdrawals and water availability. If water quality is considered, the picture may change drastically, considering that many sewers in developing countries discharge directly into surface water. The cost of secondary and tertiary treatment is beyond the capacity of many countries.

Surface water pollution resulting from sanitation coverage is critical where poor populations depend on the environment for a significant fraction of their economic welfare, notably from food provided by fields, forests, and fisheries (World Resources Institute et al. 2005) . Water used for sanitation returns to the environment where, if untreated, it makes water unavailable for other uses. For example, in the Brantas Rivier Basin in Indonesia, freshwater pollution from sewage is often too high to be adequately treated by water treatment plants (Ramu 2004). In the Lake Titicaca Basin, untreated wastewater has made water unavailable for ecosystems by causing eutrophication and parasites in fish (United Nations World Water Assessment Programme 2003). In fact, it has been estimated that every 1 $m^3$ of wastewater discharged to surface water makes 8 to 10 $m^3$ of freshwater unusable (Shiklomanov 2000).

People relying on freshwater and near-shore coastal waters are especially vulnerable to water quality problems associated with wastewater discharges. For example, increases in nutrients and the resulting hypoxia in coastal waters damages fisheries (Niemi et al. 2004). We selected number of fishers (World Resources Institute et al. 2005) as an indicator of how dependent a population is on the environmental income derived from local fisheries, and the Water Quality Indicator of the Environmental Sustainability Index (Esty and Cornelius 2002) as a measure of water quality. The WQI was chosen over the Water Poverty Index (WPI) (Sullivan et al. 2003), because the WPI combines measures of water availability and quality with socio-economic factors. For this analysis, it is more useful to study water quality alone.

Figure 3-2(b) shows that there are large populations relying on fishing, and therefore good water quality, in water stressed countries. Twelve countries have both poor water quality and stressed populations of more than 1 million, and have significant numbers of fishers: Morocco, Egypt, Niger, Sudan, Pakistan, Libya, India, Algeria, Saudi Arabia, Mexico, Kazakhstan, and China. In these countries, more than 19 million people rely on fisheries for their livelihood (see Appendix B). Ten of these countries are also low to lower-middle income countries. Another indicator of dependency on water quality for subsistence is the percent of a population's protein that comes from fish. Six countries rely on fish for more than 20% of their protein and had water stressed populations over 1 million: Egypt, Peru, Tanzania, Uganda, Senegal, and Nigeria (see supplementary materials). These are primarily developing countries, where decisions are being made on the type of water consumptive technology to be used to meet sanitation targets.

Our analysis confirms that inadequate investment, poor or nonexistent policies, governance, lack of resources, and gender disparities are real challenges to sanitation coverage. Results also show that lack of sufficient water resources is not a major challenge in achieving sanitation coverage for much of the world. However, tens of millions of people (especially urban dwellers) will experience moderate or severe water stress directly because of sanitation coverage targets. This number depends on the specific sanitation technology that is implemented.

For populations affected by water stress, technological innovations for sanitation provision will be necessary in order to expand sanitation coverage—conventional technology demanding large quantities of water may not be appropriate or even feasible in some parts of the world. Energy requirements for domestic water use associated with collection, storage, treatment, and transport, as well as providing water in sufficient quantities to transport human waste, also need to be considered. Given that agriculture represents 70% of total use in developing countries, water reuse strategies, properly designed to protect water quality, may offset sanitation's water use. Future analyses should incorporate wastewater treatment capacity and efficiency factors for sewers, rather than assuming water used to transport human waste is taken out of use due to pollution.

# 4 Sustainability of gravity fed water systems in Bolivia[1]

## 4.1 Abstract

In the Alto Beni region of Bolivia, as in much of the developing world, gravity-fed distribution systems supply domestic water needs. However, sustainability of these sources depends on whether discharge can accommodate present and future water needs. There is a perception that agricultural expansion in the region is resulting in reduced spring discharge. We incorporate low-cost field methods for hydrologic data collection, which can be applied to other developing communities where data are scarce, and we include an analysis of two satellite-derived precipitation data products (CMORPH and TRMM-3B42) for use in the hydrological modeling in the region. Although CMORPH has more bias than TRMM-3B42 in the region, when bias-adjusted it performs better when compared with data from a local gauge. A daily water balance model is used to predict recharge rates in eleven watersheds, with incorporation of the NRCS curve number method to separate recharge from runoff. The curve numbers are calibrated using observed discharge at two streams, resulting in a curve number of 61.4 for forest and 63.2 for agriculture. The recharge is then modeled under scenarios of climate change and predicted agricultural expansion. Although runoff changes range from -17% to 14% depending on climate scenario, recharge is predicted to decrease under all scenarios (14% to 27% decrease). The modeled impacts from climate change are larger than those from agricultural expansion, contrary to perceptions that spring flow has declined because of agricultural growth. The ratio of water use to availability under all scenarios of climate change and water and sanitation service expansion suggests that use of groundwater is sustainable in the region. However, the small recharge areas of the springs may result in insufficient recharge to support planned water and sanitation expansion, if springs are the sole water supply.

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[1] Some of the material contained in Chapter 4 has been published in the conference proceedings *World Environmental and Water Resources Congress 2010: Challenges of Change*, Providence, Rhode Island, 2010. Posted ahead of print with permission from ASCE.

## 4.2 Introduction

Until the 1950s, the Alto Beni region (Figure 4-1) in Bolivia was inhabited mainly by the Moseténes people. Since 1950, the Bolivian government has encouraged colonization of the region for agriculture. While there is interest in the region to adopt low impact farming techniques, sustainable agroforestry has not been adopted at a large scale. Most farming is monoculture cacao or citrus farming. Communities with improved drinking water in the region rely primarily on natural springs as sources. Gravity-fed systems distribute water to household or communal taps. Gravity-fed distribution systems are often seen as an appropriate improved water supply in developing countries for their ease of operation and maintenance. Over time, however, the Alto Beni communities have perceived a decline in spring flow, and they suspect that this is due to reduced infiltration and recharge following agricultural expansion.

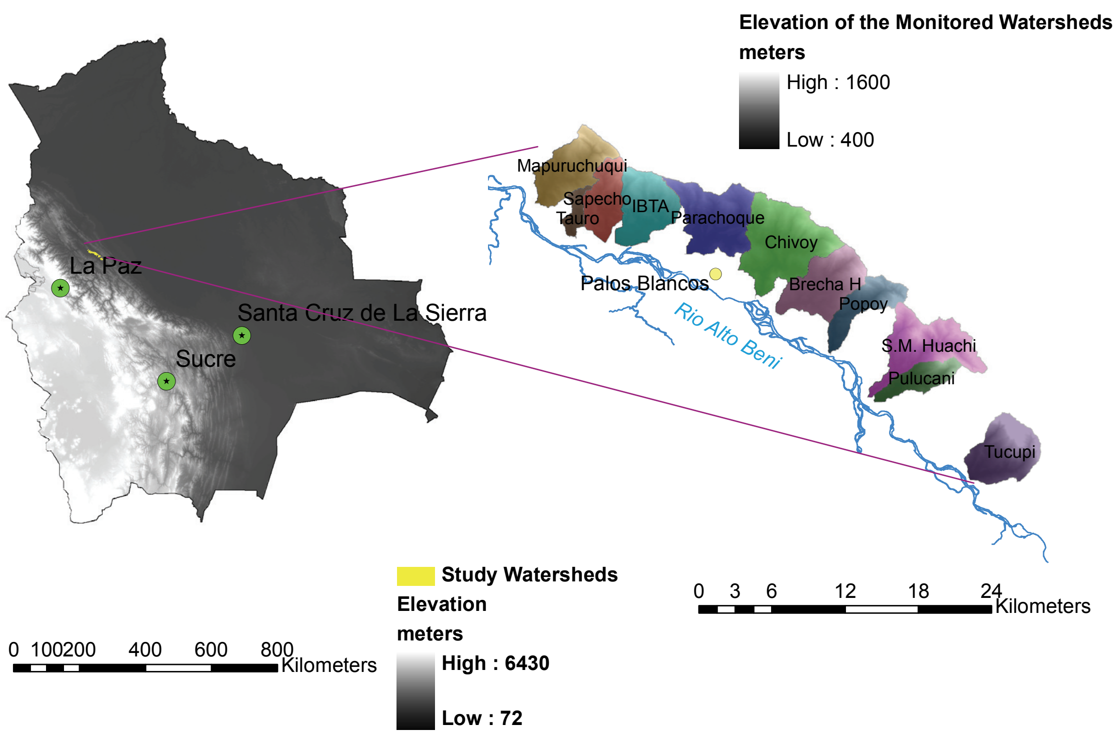



**Figure 4-1. The eleven study watersheds are in the Alto Beni Region, northeast of La Paz.**

At the same time that the groundwater resource may be declining, water use is expected to increase due to population growth and improvements in water and sanitation coverage. Most of the anticipated sanitation projects involve the construction of sewers, which use large amounts of water and can increase water stress (Fry et al. 2008).

We present results from an analysis examining the sustainability of the groundwater resource in eleven watersheds in the Alto Beni region under influences of climate change, land use change, population growth, and water and sanitation service expansion. The analysis incorporates two years of hydrological data collected in the field using low cost methods. The Alto Beni region is scarce in data required for hydrological studies at the scale necessary for this analysis (tens of square kilometers). Data scarcity is a recurring problem in hydrology, and is amplified in developing countries where hydrologic budgets are often the most uncertain. An important and unique aspect of this study is that we incorporate hydrological field methods that are feasible for a local technician with limited time and budget, and with limited meteorological data. These methods can be applied to other watersheds in regions where data and financial resources are scarce and the sustainability of water supply from groundwater recharge is uncertain.

Water availability is represented by recharge, which is predicted with a daily water balance model. In order to separate recharge and runoff in the water balance model, we incorporate the NRCS curve number method to estimate runoff and calibrate the curve numbers using daily runoff data measured in the field. Although the NRCS curve number method is routinely used to estimate runoff from precipitation, it is less common to use the method for predicting recharge. Erickson and Stefan (2009) have demonstrated the use of NRCS curve number method within a daily water balance model to predict recharge in a Minnesota watershed. Our analysis takes this work further by calibrating curve numbers for land use types using daily discharge observations and incorporating data that are obtained through low-cost field methods and freely available satellite products.

The water balance model requires only daily estimates of precipitation and temperature, land cover in terms of percent used for agriculture (cacao and citrus), initial soil moisture, and soil classifications as inputs, all of which are either available from global data sets (e.g. precipitation and temperature) or can be measured or estimated using field methods that are feasible for local participants.

## 4.3 Water Balance Model

Erickson and Stefan (2009) described a method to estimate groundwater recharge using a water budget approach in which runoff is estimated using the NRCS curve number method (Soil Conservation Service (SCS) 1973). The water balance model tracks soil moisture and movement of water through the root zone. Equation 4-1 shows how the water balance model calculates recharge, $R_i$.

$$R_i = I_i - ET_i - D_{w,i-1} \geq 0 \tag{4-1}$$

where $I_I$ is infiltration, $ET_i$ is evapotranspiration, and $D_{w,i-1}$ is the soil water depletion, all in units of depth (mm). The soil water depletion represents the depth of water that is necessary to fill the soil to field capacity, $\theta_{fc}$, shown in equation 4-2.

$$D_{w,i} = \left(\theta_{fc} - \theta_i\right) d_r \tag{4-2}$$

where $d_r$ is the depth of the root zone. The water budget equation allows recharge to occur only if the soil moisture in the root zone is above field capacity. At each time step, the soil water depletion can be determined using equation 4-3.

$$D_{w,i} = D_{w,i-1} - I_i + ET_i + R_i \geq 0 \tag{4-3}$$

Infiltration is equal to the precipitation minus runoff. Runoff, $Q_i$ (mm), is estimated using the NRCS curve number method, shown in equation 4-4.

$$Q = \frac{\left(P_i - 0.2S\right)^2}{P_i + 0.8S}, S = \frac{2540}{CN} - 25.4 \tag{4-4}$$

where $P_i$ is the precipitation (mm) and $CN$ is the curve number, which depends on land cover, hydrologic condition, and soil classification.

## 4.4 **Model Data and Parameters**

The water balance model requires the following inputs: daily precipitation and evapotranspiration, land cover in terms of percent used for agriculture (cacao and citrus), and soil parameters including field capacity and initial soil moisture content.

### 4.4.1 Precipitation

A meteorological station operated by the cacao cooperative El Ceibo in Sapecho provided monthly precipitation data for the months from February 2008 to June 2009. Daily data were not provided, however. As a result, freely available satellite-derived precipitation data were used. Two satellite precipitation data sets were compared to evaluate their potential for use in this study: CMORPH (Joyce et al. 2004) and TRMM-3B42 (Tropical Rainfall Measuring Mission (TRMM)). CMORPH is available at spatial and temporal resolutions of 0.25°×0.25° at 3 hourly or daily intervals and 8km × 8km at half hourly intervals from 2002 to present. TRMM-3B42 comes at 0.25° spatial resolution and 3-hour temporal resolution. These data products are described in more detail in Appendix C 1.

CMORPH and TRMM-3B42 data are compared for use in the daily water balance model in the Alto Beni Region. First, the satellite-derived data for February 2008 to June 2009 are aggregated to monthly totals to compare with the monthly totals provided by the

Sapecho gauge. A bias correction factor is calculated as the ratio of the gauge-based monthly total precipitation to the satellite-derived monthly precipitation. The daily satellite-derived data are then adjusted for bias by multiplying by the bias correction factor, and the resulting bias-adjusted satellite-derived daily precipitation estimates are then used in the daily water balance model. The steps for downloading and reading the CMORPH and TRMM data are included in Appendix C 1.

### 4.4.2 Evapotranspiration

Evapotranspiration was estimated by tracking soil moisture, following Alley (1984). It is assumed that evapotranspiration is equal to the potential evapotranspiration (PET), and soil moisture can increase, if the water input (rainfall) is greater than or equal to PET. If the rainfall is less than the PET, however, ET is equal to the water input plus some increment of water removed from storage in the soil. Because of the lack of meteorological data, PET (mm) was determined using the Hamon method (Hamon 1963) described in equation 4-5.

$$PET = 29.8D\frac{e_a^*(T_a)}{T_a + 273.2} \tag{4-5}$$

where $D$ is the day length (hrs) and $e_a^*(T_a)$ is the saturation vapor pressure (kPa) at the mean daily temperature (°C). The mean daily temperature was estimated from the temperature measurements collected at the gauging stations in the IBTA and Mapuruchuqui watersheds. ET is not affected by land cover in the water balance model, though in reality, differences likely exist between ET from cacao and citrus orchards and the tropical forest of the Alto Beni region.

### 4.4.3 Soil Parameters

Field capacity was estimated following methods used by Vörösmarty et al. (1989) as the moisture content at 30-kPa water potential, calculated using empirical relationships with the sand and clay content in soil described by Saxton et al. (1986). Field capacity represents the water content below which drainage is negligible, which is defined arbitrarily to be at around 30-kPa. Soil parameters were determined during field work in 2009 by field observation, jar settling tests to determine percent sand and clay, and a soils map created from landscape data and associated soil types provided by our collaborating nongovernmental organization (ACDI/VOCA 2007). The methods and the resulting soil parameters are described in Appendix C 2. Soils in the region are predominantly sandy clay loam, which according to empirical relationships (Saxon et al. 1986) have a moisture content at 30-kPa of about 21%.

## 4.5 Calibration of the Model

The model is calibrated to determine curve numbers for forest and agriculture by minimizing the difference between the runoff derived from the CN method and the observed runoff over a seasonal time scale. Daily measured runoff was estimated from hourly discharge estimates at the Mapuruchuqui watershed and IBTA watershed. Discharge was estimated from water surface elevation by applying Manning's Equation. Channel characteristics (slope, cross-sectional shape and area) were measured using tape measures and a clinometer during field work conducted in June 2008 with the assistance of students and faculty from Michigan Technological University and Universidad Tecnológica Boliviana (Appendix C 3), and the water level was recorded every 5 minutes by level loggers employing sonic range finders (Rowe et al. 2009). The 5-minute water level data were downloaded each month by local technician, Justino Mamani, and averaged with a one-hour timestep. The one-hour averaged water level data were used to compute hourly discharge. These discharge estimates were then aggregated to daily discharge, and runoff was calculated as the discharge minus the baseflow.

Calibrated parameters include the curve numbers for forest and agriculture. The curve numbers are calibrated because soils in the watershed range from NRCS Group B to Group C, and soil was only well classified at one location in the watershed. The curve numbers for agricultural land use (orchard) and forest are calibrated parameters bounded by $58 \leq CN_{ag} \leq 82$ and $55 \leq CN_{for} \leq 77$, respectively (National Resources Conservation Service (NRCS) 1986). The composite curve number is calculated based on the percent of the watershed used for agriculture. Because there is not a unique solution, calibration was accomplished using Excel Solver by starting with 500 different combinations of random starting values of agriculture curve number ($58 \leq CN_{ag} \leq 82$) and forest curve number ($55 \leq CN_{for} \leq 77$). The calibrated parameters that resulted in the minimum difference between observed and modeled total runoff over the data collection period (80 days for Mapuruchuqui and 160 days for IBTA) were used for the daily water balance model.

## 4.6 Modeling Groundwater Recharge Under Scenarios of Change

The calibrated water balance model was then used to estimate changes in runoff and recharge that might result from climate change and agricultural expansion. Table 4-1 shows the regional averages of temperature and precipitation responses from 21 multi-model data sets (MMD) for the Intergovernmental Panel on Climate Change (IPCC) A1B scenario for the Amazon region (20S, 82W to 12N, 34W). The A1B scenario represents a storyline of rapid economic growth, population growth that peaks in midcentury and declines thereafter, and rapid introduction of new, more efficient technologies that rely on a balance of different types of energy sources. According to the IPCC, the global temperature responses are in the ratio of 0.69:1:1.17 for the B1:A1B:A2 scenarios and the corresponding ratios for regional responses are similar (Solomon et al. 2007). The B1 scenario represents a more optimistic storyline in which the economy transitions to a more service-based economy with less material use and cleaner, more efficient fuel sources. The A2 scenario is a higher emissions scenario in which the population is continuously increasing and economic growth and technological change are generally slower than in other storylines (Nakicenovic and Swart 2000). This analysis uses temperature and precipitation responses resulting from the A1B scenario.

The climate responses in Table 4-1 represent differences between the periods of 1980-1999 and 2080-2099. Agricultural expansion estimates were derived from a regional development plan (ACDI/VOCA 2007), and the resulting land area devoted to agriculture is shown in Figure 4-2. The agricultural extent is predicted to expand from 22% to 64% in the Mapuruchuqui watershed and from 37% to 69% in the IBTA watershed, although no timeframe is provided. We assume that the agricultural extent will expand to the entire future extent within 30 years, after which time it will remain constant.

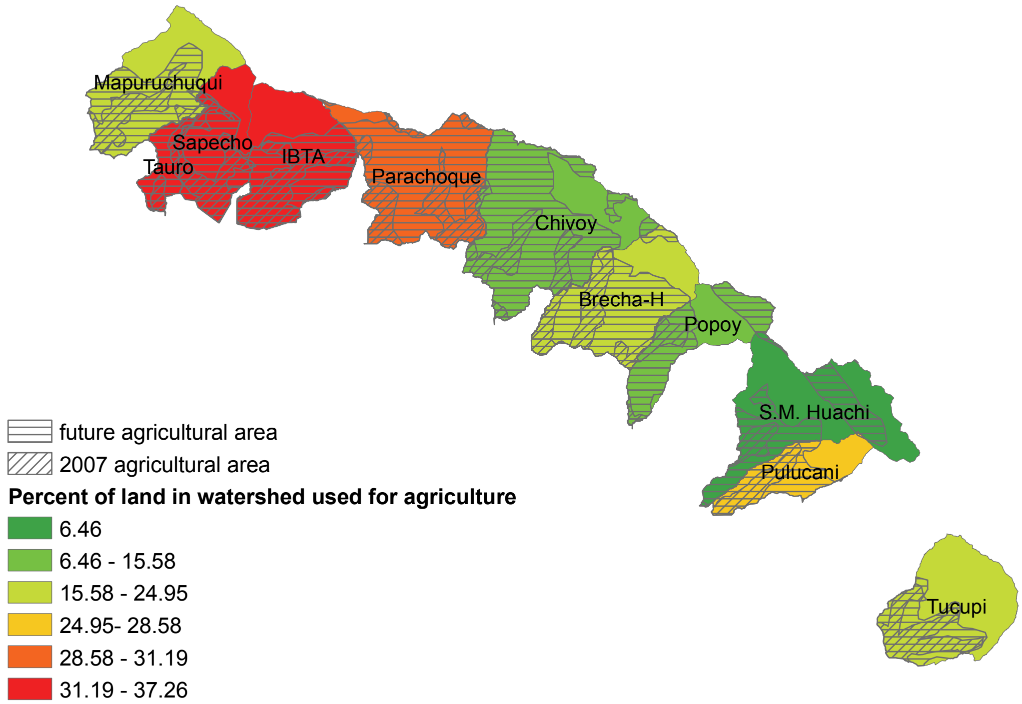



**Figure 4-2. Land use in the study watersheds. Current (2007) land use and projected (unknown date) land use were provided by ACDI/VOCA (ACDI/VOCA 2007). Original data are shown in Appendix C 4.**

**Table 4-1. Average temperature and precipitation responses between 1980-1990 and 2080-2099 predicted for the Amazon region under Scenario A1B (Solomon et al. 2007). Shown are the minimum, maximum, and 25th, 50th, and 75th percentiles from the 21 models.**

| | *Temperature Response (°C)* | | | | | *Precipitation Response (%)* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Season** | **Min** | **25%** | **50%** | **75%** | **Max** | **Min** | **25%** | **50%** | **75%** | **Max** |
| DJF | 1.7 | 2.4 | 3 | 3.7 | 4.6 | -13 | 0 | 4 | 11 | 17 |
| MAM | 1.7 | 2.5 | 3.0 | 3.7 | 4.6 | -13 | -1 | 1 | 4 | 14 |
| JJA | 2.0 | 2.7 | 3.5 | 3.9 | 5.6 | -38 | -10 | -3 | 2 | 13 |
| SON | 1.8 | 2.8 | 3.5 | 4.1 | 5.4 | -35 | -12 | -2 | 8 | 21 |

## 4.7 Changes in Domestic Water Use

Water is primarily used for domestic purposes in the Alto Beni region. The changes in water use will therefore be a result of changes in population, affluence, and development of water and sanitation services. Population densities were calculated from populations of the *centrales* and the areas of these *centrales* of the region, provided by ACDI/VOCA (ACDI/VOCA 2007), described in Appendix C 5.

The 2007 population densities are shown in Figure 4-3. Population in the region is expected to grow at a rate of 3.64% (ACDI/VOCA 2007).

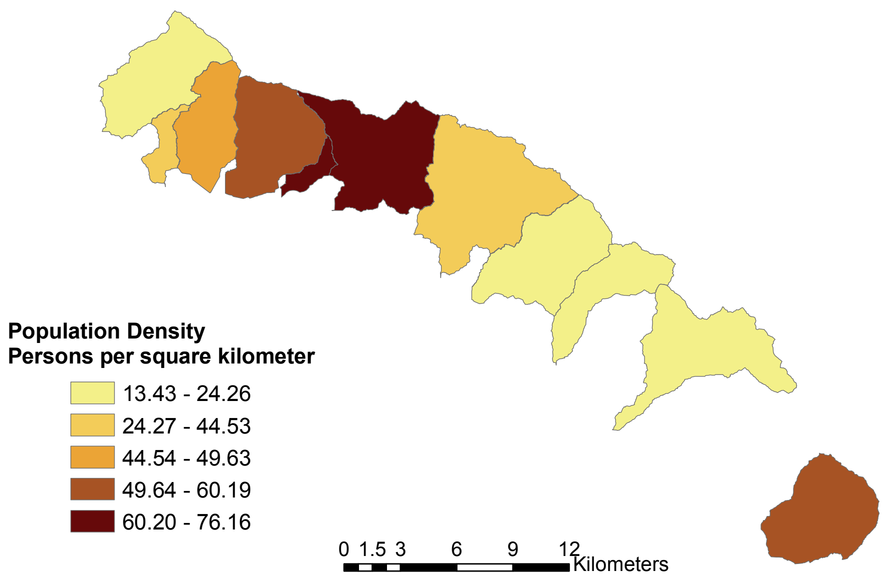



**Figure 4-3. Population densities of the eleven watersheds in 2007. Population densities were estimated from data for the *centrales* of the region (ACDI/VOCA 2007).**

Because there is no data on current domestic water use, water use is estimated by assuming that the use depends on the population served by water and sanitation and the available technology. ACDI/VOCA has included water and sanitation system expansion in its development plan for 2012, depicted in Figure 4-4. Without specific details on location of the water supply used for the current and future water supply and sanitation systems, we take the approach of simply assuming the overall coverage targets are met under different scenarios of technology type, described in Table 4-2. We assume that there will be 100% coverage in 2085, and estimate the coverage 30 years from now by assuming linear growth in coverage between 2012 (a date for which ACDI/VOCA has set coverage targets) and 2085. Based on Figure 4-4, if the development of water and sanitation services follows the development plan, then most of the new water systems will be household taps and the majority of the new sanitation coverage will be sewers, which corresponds to Scenario 1.

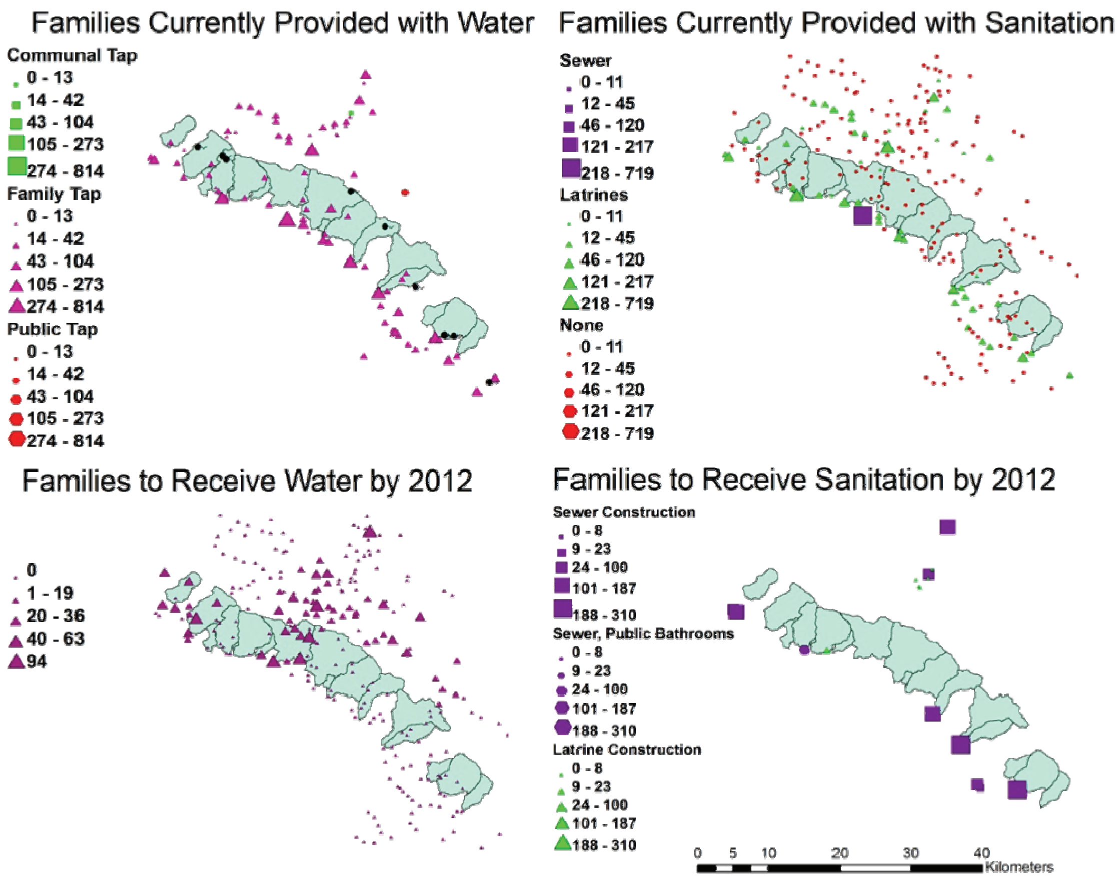



**Figure 4-4. Current and planned water and sanitation services in the region, according to data supplied in the ACDI/VOCA development plan (ACDI/VOCA 2007).**

**Table 4-2. Scenarios of water and sanitation service expansion and associated water use. Water use values are from (Fry et al. 2008) and Chapter 4 of this dissertation.**

| *Scenario* | *Type of water access* | *Water use (L/capita/day)* | *Type of sanitation access* | *Sanitation use (L/capita/day)* |
|---|---|---|---|---|
| 1 | Household access | 50 | Sewer or septic system | 44.4 |
| 2 | Basic access (within 1 km) | 20 | Sewer or septic system | 44.4 |
| 3 | Household access | 50 | Pour-flush latrine | 17.5 |
| 4 | Basic access (within 1 km) | 20 | Pour-flush latrine | 17.5 |
| 5 | Household access | 50 | Waterless sanitation | 0 |
| 6 | Basic access (within 1 km) | 20 | Waterless sanitation | 0 |

## 4.8 **Results**

### 4.8.1 Calibration of CMORPH and TRMM-3B42 Precipitation Data

Biases for the CMORPH and TRMM-3B42 data are similar, despite the fact that TRMM-3B42 has been corrected using gauge data. These biases appear to vary seasonally (Figure 4-5), with a very high positive bias during the rainy months of November to April and small positive or negative bias during the dry seasons. One possible explanation for the large positive bias during rainy months may be that the Sapecho gauge is located at a low elevation, so it may not be representative of precipitation that occurs at higher elevations.

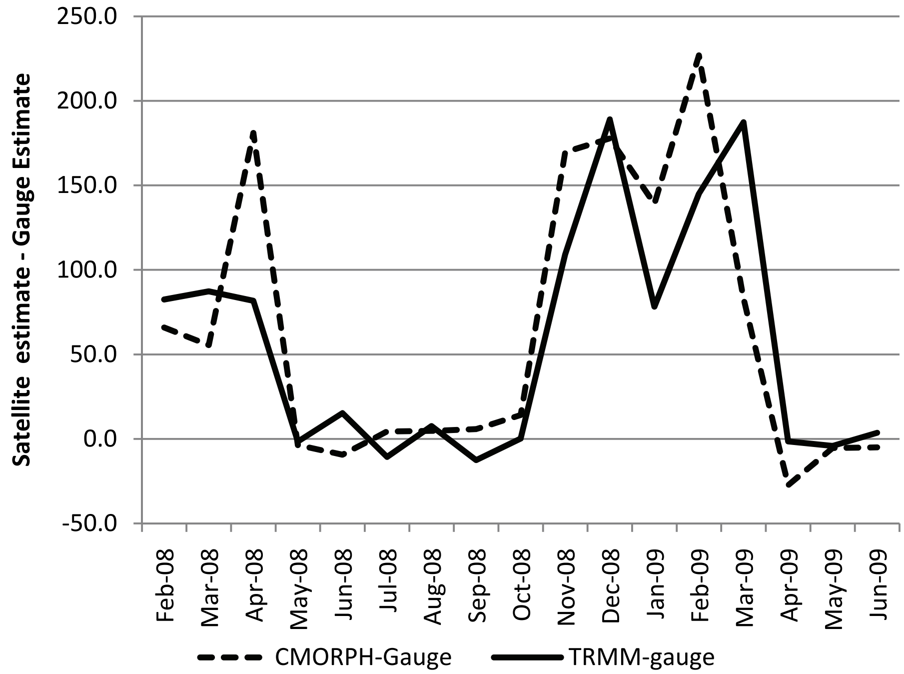



**Figure 4-5. Biases (differences) between satellite-derived monthly total precipitation and monthly precipitation observed at the Sapecho meteorological station.**

Gauge data exist for 2008 and 2009 for the months of February to June, so the bias correction factor for each of these months is calculated by combining data from both years. For the months of July to January, however, only one monthly gauge based estimate is available, so the bias correction factor is calculated from that single value. The monthly bias correction factors are shown in Figure 4-6. These bias correction factor estimates could be improved with more years of gauge-based data. ACDI/VOCA is currently embarking on a partnership that will result in the installation of several new gauges in the region. Future work will likely incorporate data from these stations for bias adjusting satellite-derived data. Figure 4-7 shows the bias between the bias-corrected CMORPH and TRMM-3B42 data (summed over each month) and the gauge-based monthly precipitation. On a monthly basis, the adjusted TRMM-3B42 precipitation tends to have a larger absolute bias than the adjusted CMORPH precipitation, except during the month of April 2008. April 2008 is not included in the calibration of the water balance model, which occurs between June 2009 and November 2009. Therefore, the bias-adjusted CMORPH data are deemed preferable for modeling in our case.

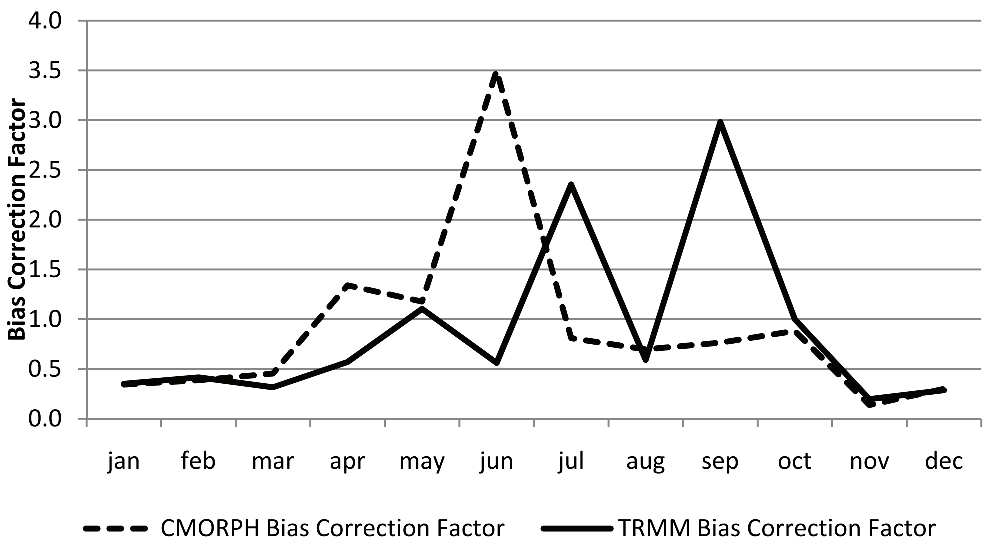



**Figure 4-6. Monthly bias correction factors for the CMORPH and TRMM-3B42 satellite-derived precipitation data. The bias correction factor is calculated as the ratio of the monthly gauge-based precipitation to the monthly satellite-derived precipitation.**

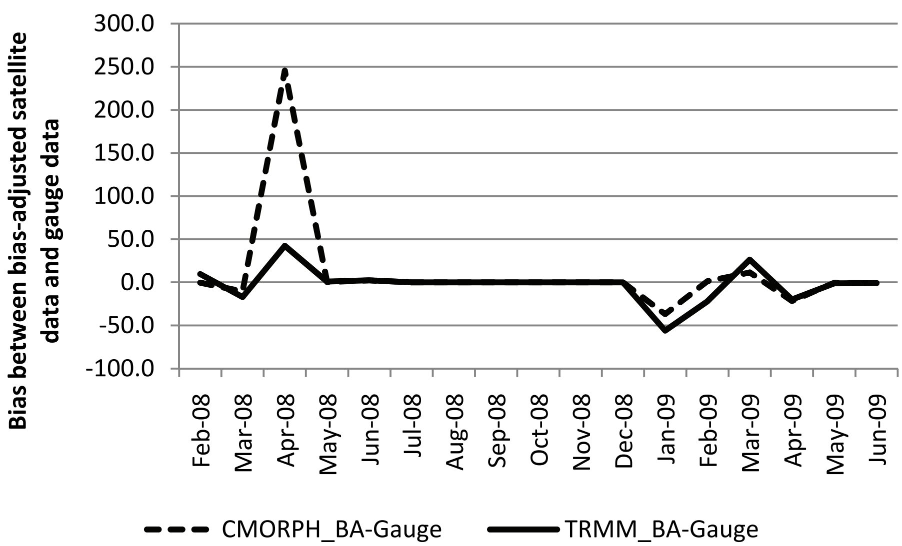



**Figure 4-7. Differences between adjusted satellite-derived monthly precipitation and gauge-based monthly precipitation.**

### 4.8.2 Calibration of the Water Balance Model

Runoff observations are available for 160 days at the IBTA watershed and for 80 days at the Mapuruchuqui watershed. There is little correlation between precipitation and runoff events on a daily time scale. Discrepancies are likely due to the larger scale of the satellite-derived data (729 $km^2$) compared to the watersheds (both about 25 $km^2$), as well as the fact that both watersheds have large elevation ranges, which could exacerbate bias. Because of the lack of correlation between daily runoff and precipitation events, the runoff curve number model was calibrated by minimizing the difference between the total modeled and observed runoff over the entire period rather than on a daily basis.

The curve numbers resulting from the best calibration of the water balance model (minimum difference between modeled and observed runoff) with each precipitation data set are shown in Table 4-3. In all instances, the curve numbers for agriculture are higher than the curve numbers for forest. Use of the unadjusted CMORPH precipitation resulted in the curve numbers being calibrated to their lower bounds, as a result of the large positive bias in the precipitation. The unadjusted TRMM-3B42 data have a slightly smaller positive bias, and so the calibration resulted in slightly higher curve numbers. Bias correction of the CMORPH data did not change the resulting curve numbers for the IBTA watershed, but did have an effect on the Mapuruchuqui watershed, where the composite curve number increased. Adjusting the TRMM-3B42 data for bias resulted in a slightly increased composite curve number for the IBTA watershed and the largest possible curve numbers for the Mapuruchqui watershed. The Mapuruchuqui composite curve numbers are much larger than the IBTA composite curve numbers (and the agriculture and forest curve numbers), which may be a result of bias in the discharge estimates.

**Table 4-3. Curve numbers resulting from calibration of the water balance model using unadjusted and bias-adjusted CMORPH and TRMM-3B42 data. Agricultral area accounts for 36.5% of land area in the IBTA watershed and 22% of land area in the Mapuruchuqui watershed.**

| | *CN (forest)* | | *CN (agriculture)* | | *CN (composite)* | |
|---|---|---|---|---|---|---|
| | IBTA | Mapuruchuqui | IBTA | Mapuruchuqui | IBTA | Mapuruchuqui |
| CMORPH (unadjusted) | 55 | 55 | 58 | 58 | 56.1 | 55.7 |
| CMORPH (bias-adjusted) | 55 | 67.7 | 58 | 68.4 | 56.1 | 67.8 |
| TRMM-3B42 (unadjusted) | 55.01 | 69.9 | 64.9 | 81.9 | 58.6 | 72.5 |
| TRMM-3B42 (bias-adjusted) | 55 | 77 | 58 | 82 | 56.1 | 78.1 |

An alternative method for calibrating the curve numbers may have been to calibrate the composite curve number for each watershed and then solve for the forest curve number and agriculture curve number following calibration. This was not feasible, however, because of the large difference between calibrated composite curve numbers of the two watersheds. Note that in in Table 4-3, the curve numbers for the Mapuruchuqui watershed are higher than those of the IBTA watershed, despite the fact that Mapuruchuqui has less agriculture than IBTA. This may be a result of bias in the measurement of discharge or bias in the rainfall estimates. The level sensor reports only the change in water level, so the discharge estimate depends highly on the initial measurement of water level and the characteristics required for Manning's equation (slope, cross-sectional area, and roughness), which all have accompanying uncertainties.

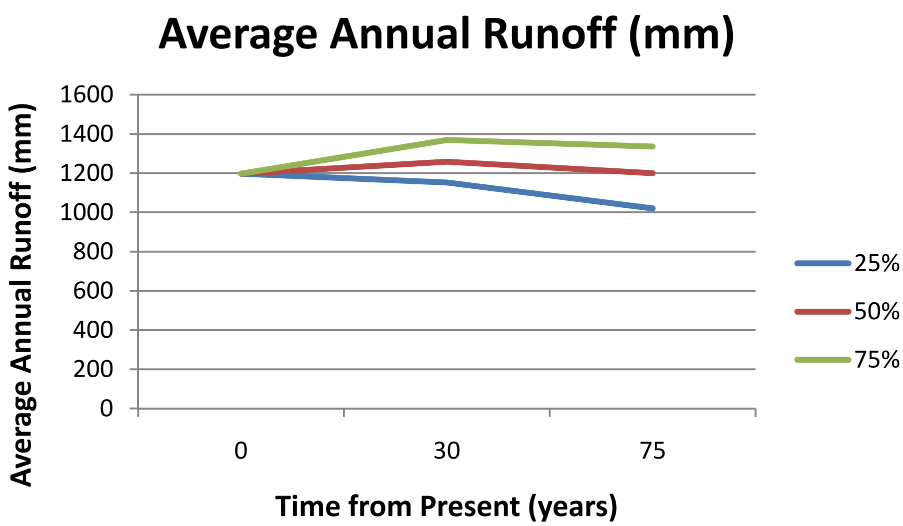
Because the CMORPH bias-adjusted precipitation shows the least bias from monthly gauge data, we use the curve numbers resulting from calibration with the CMORPH bias-adjusted data for further analysis. We assume that the curve numbers for forest and agriculture are the same in both watersheds, and estimate the value by averaging the curve numbers from the two watersheds. This results in curve numbers of 61.4 for forest and 63.2 for agriculture. The two curve numbers are very similar, and may be explained by the fact that much of the cacao and citrus farming is accomplished without the use of heavy machinery that could compact soils.

### 4.8.3 Application of the Water Balance Model

To investigate the potential effects of climate change on water availability in the region, the water balance model was run under scenarios of temperature and precipitation responses from the 21 multi-model data sets for the A1B scenario for the Amazon region, summarized in Table 4-1. The model was applied to all eleven watersheds in Figure 4-1. The model was then run again for all watersheds under the projected land use changes from forest to agriculture (described in Figure 4-2).

In the next 75 years, runoff over all eleven watersheds is predicted to change by -17% to +14%, whereas recharge is predicted to decrease by 14% to 27% over all eleven watersheds, as a result of the combined impact of land use change and climate change (Figure 4-8). As an example, Figure 4-9 and Figure 4-10 show modeled runoff and recharge rates under changes in climate (precipitation and temperature) and agricultural expansion for the Mapuruchuqui and IBTA watersheds.

Although runoff changes ranged from positive to negative, all scenarios resulted in decreased recharge. This decrease is primarily due to changes in climate, as the model predicts increases in potential evapotranspiration under all scenarios of climate change due to increased temperature. Runoff changes range from positive to negative, depending on what climate scenario is used, however, because precipitation increases under some climate scenarios and decreases under others. Despite perceptions that agricultural land use has resulted in reduced discharge from natural springs, the decrease in groundwater recharge was amplified only very slightly by effects of agricultural expansion because the calibrated curve numbers for orchards and forests were similar. Although better estimates of runoff may allow for more accurate calculation of the curve numbers, there is reason to believe these curve numbers are reasonable, because the cacao and citrus orchards in the region have a large amount of ground cover and are not tended by tractors or other heavy machinery. Due to the sensitivity of the results with climate inputs, a more significant improvement to the water balance model may come from better estimates of evapotranspiration from cacao and citrus orchards and from the tropical forest of the Alto Beni region.



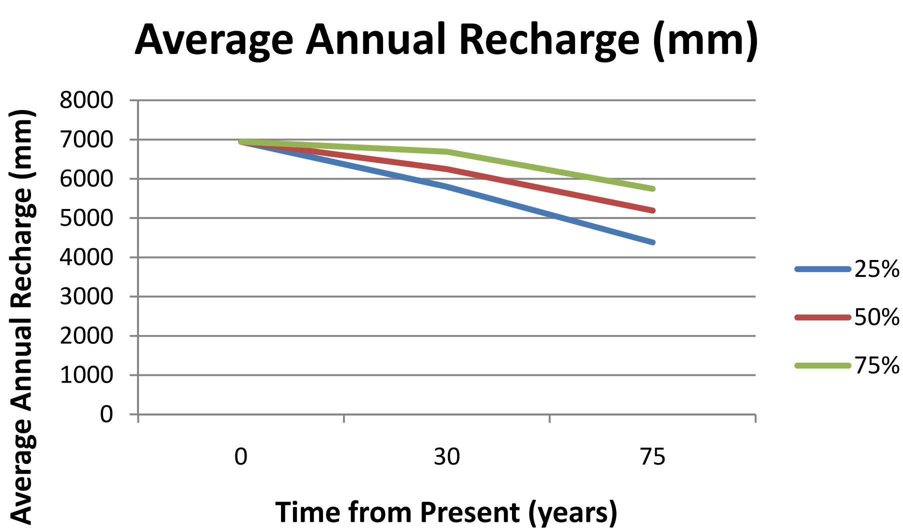




**Figure 4-8. Modeled average annual runoff and recharge over all eleven watersheds. Runoff and recharge were estimated at 30 years and 75 years from present, using the median, 25th and 75th quartile estimates from the regional averages of precipitation responses from 21 multi-model data sets reported by the IPCC. All are modeled using the median temperature response (Solomon et al. 2007).**

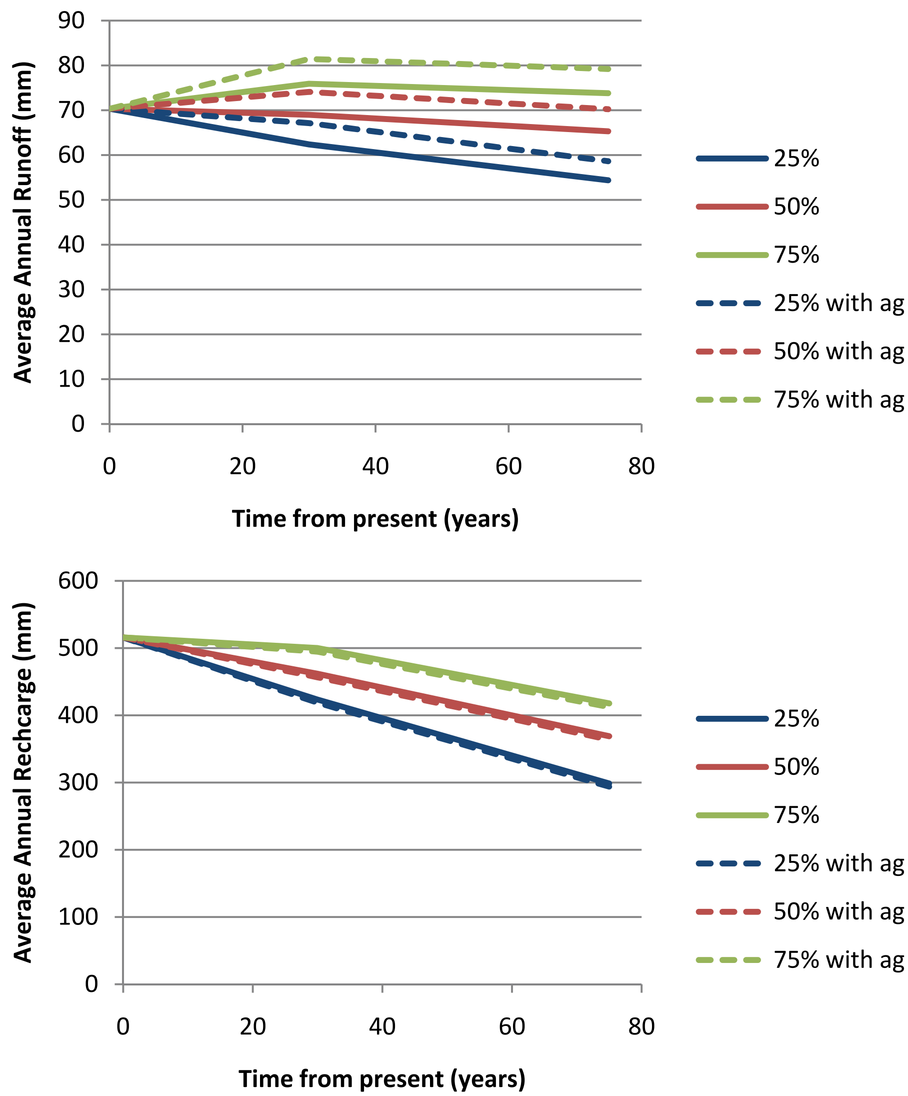



**Figure 4-9. Modeled runoff and recharge for the Mapuruchuqui watershed. Runoff and recharge were estimated at 30 years and 75 years from present, using the median, 25th and 75th quartile estimates from the regional averages of precipitation responses from 21 multi-model data sets reported by the IPCC. All are modeled using the median temperature response (Solomon et al. 2007).**

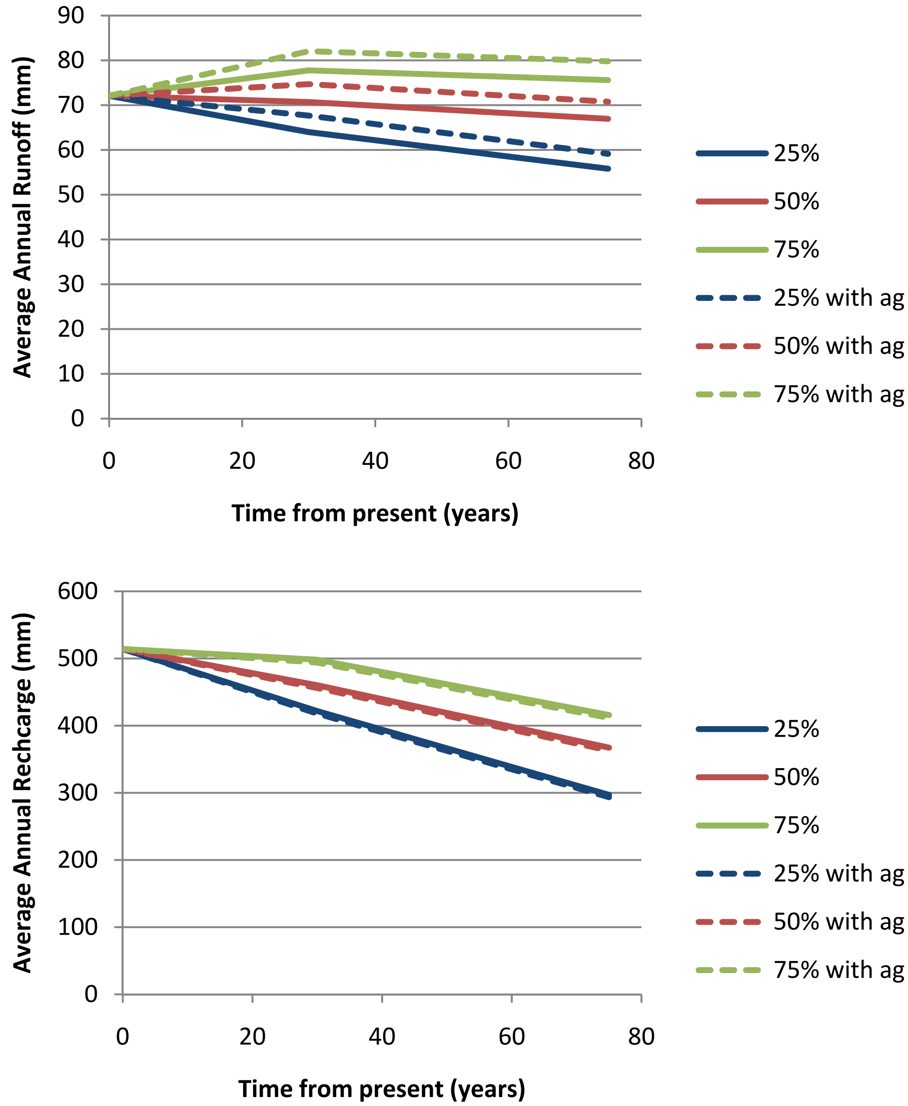



**Figure 4-10. Modeled runoff and recharge for the IBTA watershed. Runoff and recharge were estimated at 30 years and 75 years from present, using the median, 25th and 75th quartile estimates from the regional averages of precipitation responses from 21 multi-model data sets reported by the IPCC. All are modeled using the median temperature response (Solomon et al. 2007).**

### 4.8.4 Water Use and Sustainability

The projected water use under the 6 scenarios of water and sanitation service expansion (provided in Table 4-2) and the projected 3.64% annual population growth rate is shown in Figure 4-11. As Figure 4-11 shows, water and sanitation expansion will most likely follow that described in Scenario 1 (household water supply and sewer). This will result in the largest increase in water use.

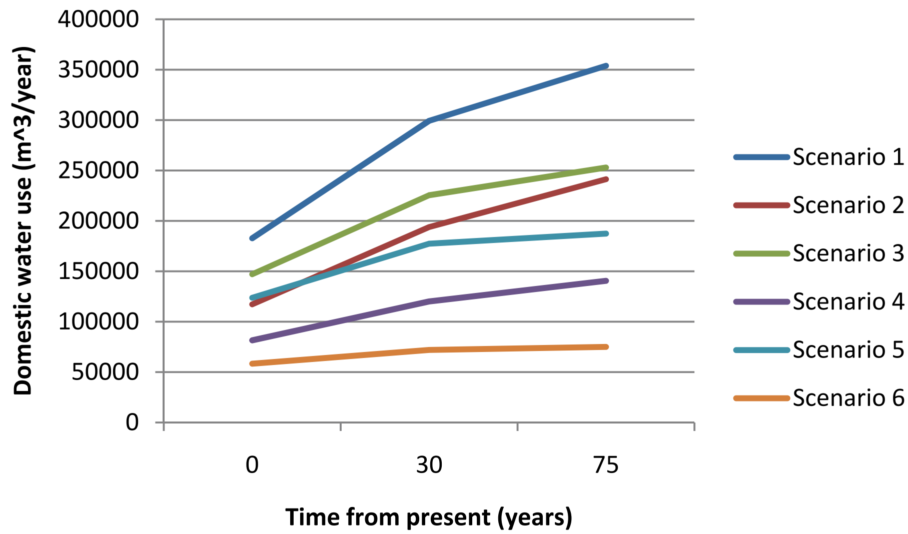



**Figure 4-11. Projected water use for the communities in the eleven watersheds of the Alto Beni Region under the 6 access-level scenarios described in Table 4-2. The growth in water and sanitation coverage rates were based on planned expansion cited by ACDI/VOCA (2007).**

Water stress, the ratio of water use to water availability, is often used as an indicator of water resource sustainability. Moderate water stress occurs when use accounts for more than 20% of available water resources, and severe stress occurs when use accounts for more than 40% of the resource. Because springs are the primary source of water and domestic use is the primary water use, in our study water stress is expressed as the ratio of domestic water use to recharge (equation 4-6). For example, at present time, if water and sanitation systems are consistent with Scenario 1, then water use is estimated to be about 183,000 $m^3$/year. At present, the recharge is estimated by the water balance model under the 25$^{th}$ percentile precipitation estimate to be $1.58 \times 10^8$ $m^3$/year. This means that the current water stress under water and sanitation service scenario 1 would be about 0.12%.

$$\text{Water Stress} = \frac{\text{Domestic Water Use } \left(m^3 / year\right)}{\text{Recharge } \left(m^3 / year\right)} \tag{4-6}$$

As shown in Table 4-4, if this indicator is used, then the suggested development plan is sustainable if all recharge is made available for the water systems. This estimate does not take into account the actual recharge areas of the springs however, which are likely a small portion of the total watershed area and would result in a much smaller water availability for gravity-fed distribution systems.

**Table 4-4. Water sustainability index under each climate and water/sanitation development scenario calculated as the ratio of domestic water use to groundwater recharge.**

| | | *Water and Sanitation Service Expansion Scenario* | | | | | |
|---|---|---|---|---|---|---|---|
| **Time from present** | **Climate Scenario** | **1** | **2** | **3** | **4** | **5** | **6** |
| 0 years | 25% | 0.12% | 0.07% | 0.09% | 0.05% | 0.08% | 0.04% |
| | 50% | 0.12% | 0.07% | 0.09% | 0.05% | 0.08% | 0.04% |
| | 75% | 0.12% | 0.07% | 0.09% | 0.05% | 0.08% | 0.04% |
| 30 years | 25% | 0.23% | 0.15% | 0.17% | 0.09% | 0.13% | 0.05% |
| | 50% | 0.21% | 0.14% | 0.16% | 0.08% | 0.12% | 0.05% |
| | 75% | 0.20% | 0.13% | 0.15% | 0.08% | 0.12% | 0.05% |
| 75 years | 25% | 0.35% | 0.24% | 0.25% | 0.14% | 0.19% | 0.07% |
| | 50% | 0.30% | 0.20% | 0.21% | 0.12% | 0.16% | 0.06% |
| | 75% | 0.27% | 0.18% | 0.19% | 0.11% | 0.14% | 0.06% |

Without specific information on spring discharge, a quantification of the water stress index is not possible. However, it is clear that recharge is expected to decrease because of climate change, while water use is expected to increase as a result of population growth and water and sanitation service expansion. Considering these predictions and the perceived reduction in springs' output, the sole use of natural springs for the provision of water supply may not be sustainable in the long term, but use of groundwater in the form of wells may be sustainable if the cost of drilling and pumping can be overcome. Alternatively, conservation strategies including implementation of less water-intensive sanitation would reduce stress on the springs' water resource, especially if combined with implementation of alternative water supply systems such as rainwater harvesting or pumping from a surface water intake (which would require significant treatment). These alternative water sources should be investigated for sustainability, however. For example, an analysis estimating the reliability of rainwater harvesting as described in Chapter 5 could provide insight into the sustainability of domestic rainwater harvesting, and the energy requirements and treatment requirements should be evaluated for feasibility of pumping from a surface water intake.

## 4.9 Discussion and Conclusions

Analysis of water resource availability can provide useful information for the planning and development of water supply and conservation strategies. In many developing communities, however, assessment of water availability has not been feasible because of constraints on time to complete a proposed system (resulting from grant requirements or duration of a development worker or agency's stay in a community), funds available for research to aid decision making, or lack of the significant amount of data that are usually required for hydrological models. The water balance model presented in this chapter provides a means of estimating the effects of climate change and agricultural expansion on daily runoff and groundwater recharge at the watershed scale, using data which are either freely available or simple to estimate from physical data that can be measured with limited time and resources. The data required for calibration of the water balance model include discharge, precipitation, temperature, and watershed characteristics including area and percent of land used for agriculture.

Discharge was estimated using Manning's equation, which has parameters that are easily measured or estimated in the field: slope, cross-sectional area and roughness. Precipitation data were obtained from the CMORPH satellite-derived precipitation data set and compared with gauge based data for a 17-month period from 2008 to 2009, and adjusted for bias accordingly. The TRMM-3B42 data set was also evaluated for use (unadjusted and adjusted for bias); however the CMORPH bias adjusted data was chosen for modeling purposes, because of its smaller overall bias during the calibration period.

Calibration of the NRCS curve number model to observed runoff resulted in curve numbers of 61.4 for forest and 63.2 for agriculture. The model was then applied to eleven watersheds with varying current and projected land use. As a result of the similar forest and agriculture curve numbers, the water balance model showed little impact of increased agriculture on future runoff and recharge in the region, contrary to perceptions that discharge from natural springs has decreased due to agricultural expansion. Climate change had a larger potential impact, however, and resulted in a reduction in recharge in all cases. This is a result of increased temperature in all climate scenarios, which increases evapotranspiration, whereas precipitation increases or decreases depending on the climate scenario.

The water availability (recharge) in the watersheds was then compared with water use resulting from planned expansion of water and sanitation services. The increase in water use was related to population growth as well as the type of water and sanitation services provided to meet target coverage. A likely scenario in which new sanitation services are sewers and new water supply is provided at the household results in the largest increase in water use. At the scale of the watersheds, water use appears sustainable (annual water use is much less than annual recharge) under even this most water intensive scenario; however, this analysis does not account for the actual recharge area of the springs, which is likely a small fraction of the total watershed area.

Interpretation of model results is limited by several sources of uncertainty. For example, the measurements required for Manning's equation each carry uncertainty. Additionally, recharge is highly dependent on the root zone depth, field capacity and the initial soil moisture, which all have considerable uncertainty. The potential evapotranspiration estimates could be improved by considering vegetation type and other meteorological information including wind speed, relative humidity, and net radiation. The gauge-based precipitation data record was much shorter than ideal for bias correcting the CMORPH data. Finally, land use was only divided into two gross categories:

agriculture and forest, whereas the curve numbers corresponding to specific types of agriculture and forest may be different from those calibrated for agriculture and forest. It is important to note that while we categorize all agriculture as citrus and cacao orchards, some areas have been subject to slash and burn style agriculture and may have a significantly different hydrological condition than the cacao and citrus orchards. These slash and burn agricultural plots are typically planted first with rice, followed by a variety of crops after one year. Determination of specific curve numbers would have involved more calibrated parameters, however, and would not have been feasible given the length of discharge record and number of monitored watersheds.

Despite uncertainties resulting from lack of gauge-based meteorological data, refined soil characteristics and PET estimates based on vegetation type, the model was useful for demonstrating the relative effects of climate change and agricultural expansion on groundwater recharge in the watersheds. This research was initiated because of concern that spring output has been decreasing with time. Although historical data are not available, model results suggest that spring output may have been decreasing over time due to climate change. Although the total annual recharge over the watershed appears to be a sustainable supply for the communities' future demand, the recharge areas of the springs are likely much smaller than the watershed area, and so recharge may be much smaller. Therefore the sole use of springs to meet the communities' water needs may not be sustainable. The potentially large reduction in recharge resulting from climate change, combined with the increase in water use from population growth and water and sanitation expansion, point to a need for new strategies for providing drinking water in the Alto Beni in the long term. These strategies may include conservation by implementing less water-intensive sanitation, or adding new sources of water such as rainwater harvesting, surface water intakes, and pumping from groundwater well, depending on cost and project feasibility.

If the communities continue to rely primarily on natural springs for their water supply, they may need to consider water conservation practices which may include consideration of less water intensive sanitation systems. For example, if compost toilets are an acceptable alternative, then developing water and sanitation services according to

Scenario 5 would result in much less stress on the water supply from springs. Composting toilets would have the added benefits of fertilizer and reduction of wastewater disposal into streams. Composting toilets require significant maintenance and operation, however, and are therefore only an appropriate alternative when communities are prepared and willing to accept additional responsibilities for sanitation at the household level. Additionally, composting toilets may not be feasible in urban areas where a system for using or disposing of the compost would be required.

An immediate next step for this research is to evaluate additional precipitation data sets for inclusion in the model, including data from the Global Precipitation Climatology Project. In the long term, future work to improve the results of the water balance model should include better characterization of the soil parameters including field capacity, root zone depth, and initial soil moisture. Additional improvements could result from better estimates of potential evapotranspiration if the meteorological data and vegetation data could be obtained. The installation of new meteorological stations in the regions will likely provide opportunities for improving both the PET estimates and the bias correction required for satellite data. Finally, in order to refine the water balance model to incorporate curve number estimates of specific types of agriculture, a more detailed study of the land use in the region, along with installation of stream gauges in other watersheds with different land use, would be necessary.

# 5 Quantifying Health Improvements from Water Quantity Enhancement: An Engineering Perspective Applied to Rainwater Harvesting in West Africa[1]

## 5.1 Abstract

Knowledge of potential benefits resulting from technological interventions informs decision making and planning of water, sanitation, and hygiene programs. The public health field has built a body of literature showing health benefits from improvements in water quality. However, the connection between improvements in water access and quantity and health is not well documented. Understanding the connection between technology and water use provides insight into this problem. We present a model to predict reductions in diarrhea disease burden when the water demands from hygiene and sanitation improvements are met by rainwater harvesting. The model is applied in a case study of West African cities. Similar predictions could be made for other interventions that improve water quantity in other locations where disease burden from diarrhea is known. Results varied by location in our case study, with the highest potential health impact in Tabou, Cote d'Ivoire, where about 25% of diarrhea disease burden could be prevented by domestic rainwater harvesting with a storage of 400 L combined with point of use treatment.

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1 The material contained in Chapter 5 has been submitted in a condensed form to *Environmental Science and Technology*.

## 5.2 Introduction

Sustainable development requires that technology used to meet the Millennium Development Goals (MDGs) be successful under the influence of stressors such as population growth, urbanization, land use and climate change (Zimmerman et al. 2008). Research in the water resources sector is commonly motivated by the need to evaluate the effectiveness of technologies and management strategies used to supply domestic water needs under varying environmental conditions (Luijten et al. 2001; Cowden et al. 2008; Lutz et al. 2008). As one example, recent research evaluated effectiveness of domestic rainwater harvesting (DRWH) technology for providing basic water requirements in West Africa considering seasonal variability, storage capacity, and roof size (Cowden et al. 2008). These previous studies relating environmental stressors to success of water supply technologies and management strategies have not incorporated quantitative ties to human health outcomes.

Health improvement, however, is one of the fundamental driving forces for improving water access, as is evident in MDG targets to reduce child mortality, eradicate hunger, and improve maternal health. Each of these health-related goals is significantly affected by access to safe and sufficient drinking water. As a result, the relationship to public health is important when policy makers and practitioners make decisions regarding technology choice for water provision. For example, estimates of expected health gains from rainwater harvesting with different design specifications such as roof area and storage size under different seasonal variations may aid decision makers in planning the implementation of rainwater harvesting programs.

Successful policies require the integration of water resources engineering, public health, and policy research. Figure 5-1 shows how these fields interact to guide implementation of policies for reducing water related diseases. Engineering analysis is needed to understand stressors on natural resources and human systems; engineering design provides technological solutions for mitigating these stresses; and public health research determines potential health outcomes resulting from both the stressors on the environment and the technological or social interventions used to implement public health policies. Figure 5-1 shows how these fields of research can work together to impact public health. In previous analyses, we used engineering design principles to estimate the potential for water quantity enhancement from rainwater harvesting (Cowden et al. 2008). In this analysis, we use results from these previous engineering analyses and draw on public health research to estimate the potential for changes in health from changes in provision of water quantity.

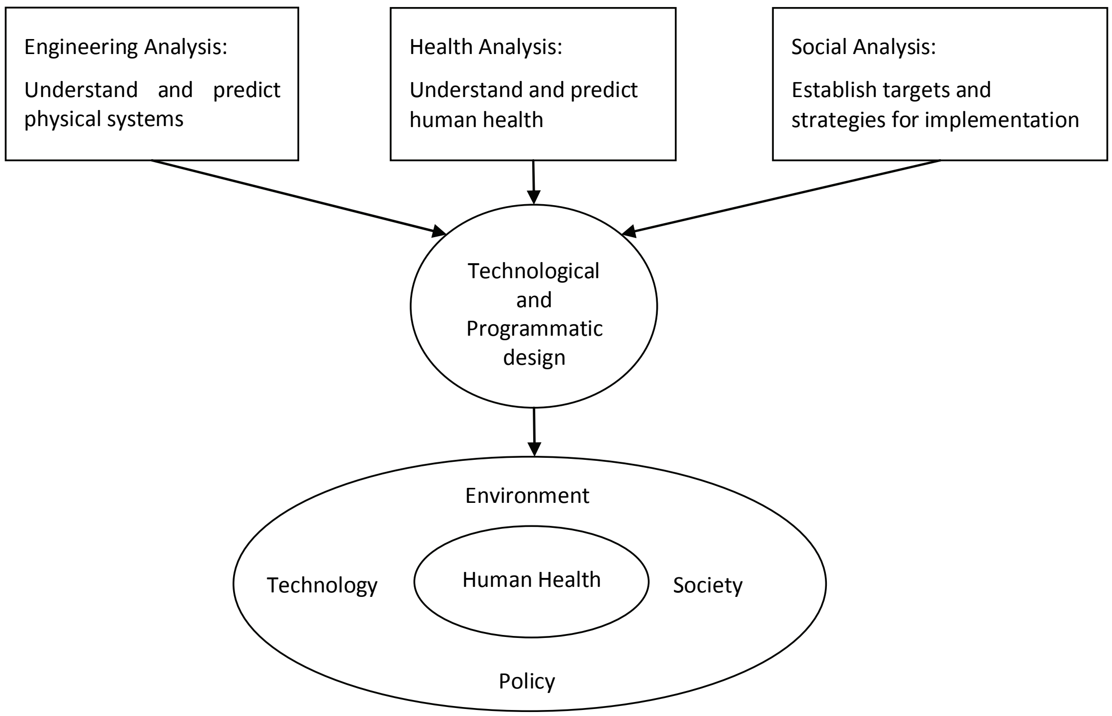



**Figure 5-1. Engineering Analysis, health analysis, and social analysis combine to improve public health. The inner circle represents human health. The outer circle represents categories of impacts affecting human health (environment, technology, society, and policy). Interventions to reduce the risks caused by this outer circle are represented in the "technological and programmatic design" circle, which is ideally a result of combined efforts in engineering analysis, health analysis, and social analysis.**

The effectiveness of interventions to remove pathogens and improve health has been well documented (Esrey et al. 1991; Fewtrell and Colford 2005; Clasen et al. 2007; Waddington and Snilstveit 2009), so public health policy decisions regarding *water* *quality* improvements such as point of use (POU) treatment can be well informed. In the case of technologies used to improve *water quantity* only, however, most studies assess general improvements in water quantity without consideration of the specific amount of water provided (e.g. those studies considered by Esrey (Esrey et al. 1985; Esrey et al. 1991) and Fewtrell (Fewtrell and Colford 2005; Fewtrell et al. 2005)). As a result, health improvements resulting from incremental improvements in water quantity may be less obvious to policy makers.

In this paper, we demonstrate an analysis incorporating public health considerations into evaluation of water quantity enhancement technologies, considering rainwater harvesting in West Africa as an example. Rainwater harvesting is a technology that can provide varying amounts of water, depending on roof materials and size, storage capacity, and seasonal precipitation patterns. It is also a technology that may become more or less effective where climate change or variability results in changes in precipitation amounts or frequency from historical records, which are short in many locations in the developing world. An engineering analysis procedure is introduced that provides quantitative estimates of potential health benefits from incremental improvements in water supply by considering how different water and sanitation technologies can become options when more water is available to a household. This analysis can be extended to evaluate other technologies or management plans that result in improvements in water quantity. Likewise, the analysis could investigate how decreases in water supply may impact human health (e.g., land use changes that adversely impact spring output).

## 5.3 Background

Worldwide, nearly 1 billion people lack access to safe drinking water and more than 2.5 billion people lack access to basic sanitation (United Nations 2008). Unsafe water, lack of sanitation, and poor hygiene contributed to 9.1% of global disease burden in 2002, and most of the 1.5 million deaths from diarrhea each year are children (Prüss-Üstün et al. 2008). Diseases that are entirely attributed to unsafe water, sanitation, and hygiene include schistosomiasis, trachoma, ascariasis, trichuriaisis, and hookworm

(World Health Organization 2002). Typhoid, hepatitis A, and hepatitis E are also water-related diseases attributable in large part to unsafe water, sanitation, and hygiene. In general, improvements in water quantity are thought to have the largest effect on so called "water-washed" diseases such as trachoma and scabies (Cairncross and Feachem 1993). This analysis focuses on reduction of diarrheal diseases, however, because diarrhea represents the single largest burden of disease attributable to unsafe water, sanitation, and hygiene, causing 1.5 million deaths annually (Prüss-Üstün et al. 2008).

According to the Millennium Development Goals Report of 2008 (United Nations 2008), about 1.6 billion more people will need to be served by sanitation by 2015. This will require a major acceleration in coverage, considering that in the past 18 years, only about 1.1 billion people have gained access to sanitation. The world is on track to meet the MDG Target for drinking water, although many countries in Sub-Saharan Africa and Oceania lag far behind their individual targets (World Health Organization 2008). As a result, accomplishing the water and sanitation target of the MDGs will require a major mobilization of political will, institutional support, financial resources, and natural resources. The underlying objective of the MDGs is to improve populations' well being; doing this efficiently requires an understanding of the health impact of specific interventions.

Epidemiological evidence links health to water quantity, water quality, sanitation, and hygiene. Such work, especially the multicountry studies relating diarrhea to water, sanitation, and hygiene (Esrey et al. 1985; Esrey and Habricht 1986; Esrey et al. 1991; Esrey 1996; Fewtrell and Colford 2005; Fewtrell et al. 2005; Waddington and Snilstveit 2009), has guided the implementation of water and sanitation engineering improvements in developing countries (Table 5-1). According to the results of the earlier analyses, providing increased quantities of water alone can reduce the risk of diarrhea by 20-25%. The most recent study by Waddington and Snilstveit (2009) contradicts these earlier studies, however, suggesting that water supply interventions are essentially ineffective for reducing childhood diarrhea and that sanitation hardware interventions are more effective than previously thought. No explanation is provided, however, for why water supply interventions result in no reduction in diarrhea. One possible explanation for this difference is that the increased household water availability that results from water quantity improvements may not be used in ways that benefit health (e.g. sanitation improvements, improved hygiene, etc.). In our analysis, we assume that additional water is used for these healthful purposes.

**Table 5-1. Estimated percent reduction in diarrheal disease from water, sanitation, and hygiene interventions.**

| *Intervention* | *(Esrey et al. 1985)* | *(Esrey et al. 1991)* | *(Fewtrell and Colford 2005)* | *(Fewtrell et al. 2005)* | *(Waddington and Snilstveit 2009)* |
|---|---|---|---|---|---|
| Multiple | 22% | 30% | 32% | 33% | 38% |
| Water quality | 16% | 15% | 22% | 31% | 42% |
| Water quantity | 25% | 20% | 23% | 25% | 2% |
| Water quality and quantity | 37% | 17% | No estimate | No estimate | No estimate |
| Excreta disposal (sanitation) | 22% | 36% | 24% | 32% | 37% |
| Hygiene | Not evaluated | 33% | 46% | 37% | 31% |

In addition to the work described in Table 5-1, Prüss-Üstün *et al.* (2002) have developed exposure scenarios associated with level of risk, based on the type of water and sanitation infrastructure and the fecal-oral pathogen load in the environment. These exposure scenarios were developed to incorporate existing knowledge on exposure-risk relationships and information from the *Global Water Supply and Sanitation Assessment 2000* (World Health Organization and United Nations Children's Fund 2000). The scenarios are such that risk decreases from scenario VI to scenario I as the fecal-oral pathogen load decreases from high to low (Table 5-2).

The WHO used these six scenarios in the 2002 Comparative Risk Assessment (Ezzati et al. 2002), and continues to use them to determine the disease burden of infectious diarrhea from the environmental risk factor *unsafe water, sanitation, and hygiene.* In order to estimate burden of disease, the WHO has assigned relative risk values (Table 5-2) to these exposure scenarios based on a literature review of major reviews, multi-country studies, and some intervention studies of "superior design" (Fewtrell et al. 2007). Relative risk is defined as the ratio of diarrhea incidence in a group exposed to a risk factor to diarrhea incidence in an unexposed group.

**Table 5-2. Relative risk estimates for each of the 6 scenarios used for the WHO's Comparative Risk Assessment (Ezzati, Lopez et al. 2002). Adapted from (Prüss-Üstün et al. 2002)**

| *Exposure Scenario*[a] | *Description of water and sanitation access*[a] | *RR of diarrheal disease (unitless)* |
|---|---|---|
| I | Ideal situation, corresponding to the absence of transmission of diarrheal diseases through poor water, sanitation, and hygiene. This situation does not exist in reality. | 1 |
| II | Population having access to improved water supply and sanitation services in countries where more than 98% of the population is served by those services; generally corresponds to regulated water supply and full sanitation coverage, with partial treatment of sewage, and is typical in developed countries. | 2.5 |
| III[b] | (a) IV plus improved water quality (point of use treatment)<br>(b) IV and improved personal hygiene; OR<br>(c) IV plus continuous piped water supply | 4.5<br>3.75<br>No estimate |
| IV | Population having access to improved water supply and improved sanitation in countries where less than 98% of the population is served by water supply and sanitation services, and where water supply is likely not to be routinely controlled. | 6.9 |
| V (a) | Population having access to improved sanitation but no improved water supply in countries where less than 98% of the population is served by water supply and sanitation services, and where water supply is likely not to be routinely controlled. | 6.9 |
| V (b) | Population having access to improved water supply, but not served with improved sanitation in countries which are not extensively covered by those services, and where water supply is not likely to be routinely controlled (less than 98% coverage). | 8.7 |
| VI | No improved water supply and no basic sanitation in a country where less than 98% of the population is served by those services and where water supply is not routinely controlled | 11 |

[a] From the Prüss-Üstün *et al.* methods for the Comparative Risk Assessment (Prüss-Üstün et al. 2002)

[b] Relative risk estimates for populations in Scenarios III(a) and III(b) in (Prüss-Üstün et al. 2002) were relative to Scenario II, so these estimates are obtained by multiplying by relative risk in Scenario II (2.5). Solid evidence is still lacking to provide estimates of risk reduction from piped water (Scenario III(c)) (Fewtrell et al. 2007).

Although it is clear that access to a sufficient quantity of water can reduce disease burden, the extent to which incremental improvements in water quantity can improve health is less clear. Some low-cost interventions have the ability to enhance the amount of water available to households without necessarily improving water quality (e.g. pumping from a surface water intake or open, shallow wells). Because of the inability to quantify health improvements due to specific quantities of water, an alternate method for estimating potential health gains from water supply interventions is needed. Review of literature relating to water requirements for health and sanitation and hygiene improvements can provide insight into connections between water quantity and health.

The World Health Organization defines basic water access, based on Howard and Bartram's 2003 review (Howard and Bartram 2003), as access to a source that provides 20 L/capita/day within 1 km of the household, ensuring use for consumption, hand washing, and basic food hygiene (Prüss-Üstün et al. 2008). Among other things, the Howard and Bartram study reviewed norms for minimum requirements of water, summarized in Table 5-3. As a result of the combined importance of water quantity and accessibility, Howard and Bartram defined water service levels based on level of health concern from no access to optimal access, as shown in Table 5-4. Note that these estimates do not consider water quality.

**Table 5-3. Norms for minimum water requirements, summarized by Howard and Bartram (2003).**

| *Study* | *Quantity* | *Comments* |
|---|---|---|
| (Sphere Project 2002) | 15 L/c/d | For disaster relief |
| (WELL 1998) | 20 L/c/d | Importance of reducing distance noted |
| (Gleick 1996) | 50 L/c/d | Basic requirement for domestic water supply (meeting all needs) |

**Table 5-4. Requirements for water service level to promote health, according to Howard and Bartram (2003).**

| *Service Level* | *Access Measure* | *Needs Met* | *Level of Health Concern* | *Quantity collected (L/capita/day)* |
|---|---|---|---|---|
| No access | More than 1,000 m or 30 minutes total collection time | Consumption – cannot be assured<br>Hygiene – not possible (unless practiced at source) | Very High | ≤ 5 |
| Basic access | Between 100 and 1,000 m or 5 to 30 minutes total collection time | Consumption – should be assured<br>Hygiene – handwashing and basic food hygiene possible; laundry/bathing difficult to assure unless carried out at source | High | ≤ 20 |
| Intermediate access | Water delivered through one tap on-plot (or within 100 m or 5 minutes total collection time) | Consumption – assured<br>Hygiene – all basic personal and food hygiene assured; laundry and bathing should also be assured | Low | 50 Average |
| Optimal access | Water supplied through multiple taps continuously | Consumption – all needs met<br>Hygiene – all needs should be met | Very low | ≥ 100 |

The WHO also discusses water access in emergencies in terms of a hierarchy of needs (World Health Organization 2005). According to this hierarchy (modeled after Maslow's Hierarchy of Needs), basic water requirements at the top of the pyramid are met first, and as more water is available, the needs toward the base of the pyramid can be met (Table 5-5). In general, water quality is more important at the top of the pyramid, but the quantity required increases toward the bottom of the pyramid. The WHO notes, however, that these requirements may change, depending on gender and culture. This pyramid suggests that water use for sanitation only becomes a priority when an individual has more than 60 L/day. According to the pyramid, the WHO recommendation of 20

L/capita/day for basic access is only sufficient for short term survival, and only provides water for drinking and cooking purposes.

**Table 5-5. Hierarchy of water needs, modeled after Maslow's Hierarchy of Needs (World Health Organization 2005).**

| *Household needs* | *Amount of water required* | *Short term survival* | *Medium term – maintaining* | *Long term – lasting solution* |
|---|---|---|---|---|
| Drinking | 10 L | X | X | X |
| Cooking | 20 L | X | X | X |
| Personal washing | 30 L | | X | X |
| Washing Clothes | 40 L | | X | X |
| Cleaning home | 50 L | | X | X |
| Growing food | 60 L | | X | X |
| Waste disposal | 70 L | | X | X |
| Business (crops production, livestock) | > 70 L | | | X |
| Gardens, recreation | > 70 L | | | X |

In reality, domestic water use for sanitation depends on the type of technology used, and can range from zero to more than 18 L per flush (McGarry 1982; Gleick 1996; United Nations Environment Programme 2002; United States Environmental Protection Agency 2007; WELL 2007). In previous research (Fry et al. 2008), we estimated the resulting domestic water use when populations with unmet sanitation needs acquired different sanitation technologies, summarized in Table 5-6.

**Table 5-6. Domestic water use as a function of sanitation technology for low to upper-middle income countries (Fry et al. 2008).**

| *Sanitation Technology* | *Household connection to drinking water* | *Basic access to drinking water* | *No drinking water access* |
|---|---|---|---|
| Sewer or septic system | 72.5 to 116.25 L/capita/day | 38 to 81.75 L/capita/day | 27.5 to 71.25 L/capita/day |
| Pour-flush latrine | 60 to 75 L/capita/day | 25.5 to 40.5 L/capita/day | 15 to 30 L/capita/day |
| No access or non-water consuming sanitation | 50 L/capita/day | 15.5 L/capita/day | 5 L/capita/day |

Hutton and Haller (2004) used the scenarios from the 2002 Comparative Risk Assessment (Prüss-Üstün et al. 2002) in their cost-benefit analysis of water and sanitation improvements. In their analysis, they included five intervention scenarios that essentially "moved" populations from one exposure scenario to a better one by providing different combinations of water and sanitation improvements. They then used the relative risk values from Table 5-2 to determine resulting reduction in diarrhea incidence and the reduction in mortality rates.

The analysis presented here estimates the potential public health improvement from increased water supply under the assumption that the added water would allow households to improve their level of sanitation and hygiene. We demonstrate the method by applying it to rainwater harvesting in West Africa, which has the potential to significantly enhance household water availability. Conversely, the method could be applied to scenarios where changes of climate and land use reduce water supply and lead to increase in disease. This analysis takes a similar approach to that used by Hutton and Haller (2004), in which new interventions move populations from one exposure scenario to another. The approach differs from that used by Hutton and Haller in that it includes engineering analysis to determine how the single intervention of increased water supply can enable populations to adopt new interventions water, sanitation, and hygiene interventions.

## 5.4 **Methods**

Our analysis estimates the potential reduction in diarrhea DALYs per month from enhancements in water supply from rainwater harvesting. To accomplish this, we estimated water requirements for the six exposure categories presented in Table 5-2, assuming that additional water collected from rainwater harvesting would improve health by “moving” people into a better exposure scenario. Determination of specific quantities of water used in each exposure scenario is based on the literature discussed above, and is described in (Table 5-7).

**Table 5-7. Water use estimates for the exposure scenarios used in this analysis. These exposure scenarios correspond to those described in Table 5-2.**

| *Exposure Scenario*[a] | *Daily per capita water use* | *Reasoning* |
|---|---|---|
| II | 110 L | Rainwater harvesting provides enough water to allow for indoor plumbing. We assume that water use is at least as much as the minimum water use of developed countries estimated by Gleick (1996). |
| III(c) | 110 L | Rainwater harvesting provides enough water to allow for indoor plumbing. We assume that water use is at least as much as the minimum water use of developed countries estimated by Gleick (1996). |
| III(b) | 70 L | Based on the WHO's hierarchy of water needs (World Health Organization 2005), meeting all water needs for consumption, hygiene, other household needs, and sanitation. |
| III(a) | 50 L | Same as Scenario IV, but with point of use treatment (POU). |
| IV | 50 L | 50 L/capita/day allows consumers to meet *basic* consumption, hygiene, and laundry needs (Gleick 1996). More than 50 L/capita/day would allow for better than basic hygiene and meet all household water needs, moving this population into Scenario III(b). |
| V (a) | 35 L | Middle value for pour-flush latrines, plus 10 L/capita/day for consumption (Table 5-5). |
| V (b) | 20 L | Minimum requirement for basic access defined by Howard and Bartram (Howard and Bartram 2003), confirmed by the amount required for consumption (drinking and cooking) in the WHO's hierarchy of water needs (World Health Organization 2005). |
| VI | 10 L | Minimum requirement for survival in the WHO's hierarcy of water needs (World Health Organization 2005). Note that it is above Howard and Bartram's estimate of 5 L/capita/day (Howard and Bartram 2003), but below their estimate for basic water access of 20 L/capita/day. |

[a] From the Prüss-Üstün *et al.* methods for the Comparative Risk Assessment (Prüss-Üstün et al. 2002)

We assume a population can move into a better exposure scenario if the required water can be provided reliably from rainwater harvesting. For example, a person in scenario VI uses 10 L/day, but would demand an additional 10 L/day to move up to scenario Vb, because scenario Vb requires 20 L/day. Therefore, if a demand of 10 L/capita/day can be met reliably (say, 95% of days), then the population in exposure scenario VI is moved into exposure scenario Vb. Likewise, if a demand of 25 L/capita/day can be met, the population in exposure scenario VI would instead move into exposure scenario Va. Because exposure scenario IV and IIIa are essentially the same, with the addition of point of use treatment in scenario IIIa, we run the analysis once under the assumption that point of use treatment is available and again under the assumption that point of use treatment is not available. We acknowledge that the use of waterless sanitation would allow populations to move from one scenario to the next with smaller water requirements. Such sanitation options, however, may not be considered feasible in urban or peri-urban areas by traditional urban planners, where water has been a traditional mechanism for moving disease-causing excreta away from populations.

The analysis starts with estimates of populations in each of the exposure categories. Our analysis was conducted for 37 cities in Benin, Togo, Ghana, Burkina Faso, and Cote d'Ivoire. Table 5-8 shows the distribution of the population among the exposure scenarios in the five countries in 2004 (Fewtrell et al. 2007).

**Table 5-8. Distribution of the population among the exposure scenarios (Fewtrell et al. 2007).**

| | *Percent of Population in Exposure Scenario* | | | |
|---|---|---|---|---|
| | **IV** | **Va** | **Vb** | **VI** |
| Benin | 33 | 0 | 34 | 33 |
| Burkina Faso | 13 | 0 | 48 | 39 |
| Cote d'Ivoire | 37 | 0 | 47 | 16 |
| Ghana | 18 | 0 | 57 | 25 |
| Togo | 35 | 0 | 17 | 48 |

The WHO provides guidelines for calculating burden of disease at national and local levels (Prüss-Üstün et al. 2003). The reduction in disease following an intervention is defined as the Impact Fraction (IF), also referred to as the attributable fraction (AF).

$$IF = \frac{\sum p_i RR_i - \sum p_i^{'} RR_i}{\sum p_i RR_i} \tag{5-1}$$

In Equation 1 $p_i$ is the proportion of the population in exposure scenario *i* prior to the intervention, $p_i'$ is the proportion of the population in the exposure scenario *i* following the intervention, and $RR_i$ is the relative risk for exposure scenario *i*. In our case, the intervention is an increase in water supply obtained from implementation of rainwater harvesting or some other water source (e.g, new spring or surface water). The initial proportion of the population under each exposure category in each city was assumed to be equal to the proportion of the population under each exposure category in the city's country (Fewtrell et al. 2007). The total DALYs avoided is determined as:

$$DALYs\ avoided = DALYs - \left(IF \times DALYs\right) \tag{5-2}$$

where *DALYs* is the original number of DALYs before the intervention. The World Health Organization provides its most recent national estimates (2004) of DALY rates (DALYs per 100,000 people) (World Health Organization 2009). We translate these rates to number of DALYs by assuming that the DALY rates are constant throughout the country and multiplying by the urban population and dividing by 100,000.

In this study, we apply our methodology to domestic rainwater harvesting (DRWH) in the 37 West African cities. Domestic DRWH is widely practiced throughout the world, and can range from collecting water from roof tops in open containers to permanent collection and storage systems (Cowden et al. 2008). Permanent DRWH systems consist of a roof where rain is collected, a gutter that transports water, and a storage system (Mihelcic et al. 2009). In many Sub-Saharan African countries, DRWH is promoted because of its relatively low cost, reliability, simplicity, and proximity for household use (Cowden et al. 2008).

In this study, populations are able to move from one exposure scenario to another depending on the reliability of DRWH to meet the demands shown in Table 5-7, where our model assumes the technology to be appropriate if the demand can be met at least 95% of the days in a month. Daily rainwater harvesting yield is calculated as the product of roof area, a runoff coefficient, and daily rainfall (Mihelcic et al. 2009). Estimates of monthly rainwater harvesting reliability, calcuated as the fraction of days that a specified water demand can be met, can be obtained using long precipitation records. As complete or long daily rainfall records are not available for many sub-Saharan Africa regions, a

1st-order Markov stochastic weather generator was used to produce continuous rainfall sequences for the rainwater harvesting calculations (Cowden et al. 2008). The 1st-order Markov model is a lag-one dependence model that uses maximum likelihood estimates of transition probabilities (dry to wet, or wet to dry) to produce sequences of wet and dry days statistically similar to the observed record. A mixed-exponential distribution is then used to model rainfall amounts of wet days. The analysis was conducted for 37 cities in West Africa where there were rain gages with sufficient data to predict reliability of rainwater harvesting (Cowden et al. 2008). Figure 5-2 shows the location of the rain gages. We assume an average household roof area of 10 $m^2$ and run the analysis for household water storage capacities of 400 and 1,000 L.

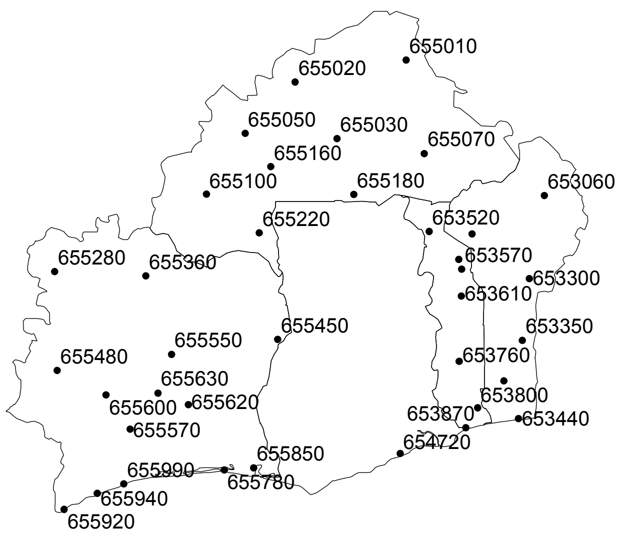



**Figure 5-2. Map of National Climate Data Center's rain gages used in this analysis. 37 gages in Benin, Togo, Ghana, Burkina Faso, and Cote d'Ivoire were considered.**

## 5.5 Results and Discussion

The first column in Figure 5-3 and Figure 5-4 shows the distribution of DALYs from diarrhea among these scenarios in Tabou, Cote d'Ivoire, the station where the rainwater harvesting could have the most impact on health in terms of DALYs avoided per capita. Before the introduction of DRWH or POU treatment, there are 702 DALYs per year in Tabou, under the assumption that disease burden from diarrhea in Tabou is consistent with disease burden in Cote d'Ivoire. This translates to about 0.04 DALYs per capita annually. In Tabou, domestic rainwater harvesting with a storage container of 400 L combined with point of use treatment could result in over 170 DALYs avoided annually (0.01 DALYs avoided per capita). This is roughly a 25% reduction in disease burden. Figure 5-3 and Figure 5-4 show how this distribution changes by month, following DRWH and/or POU treatment. The seasonal nature of precipitation means that the improvement from DRWH would mostly occur between May and December, although this is extended to January if storage is increased to 1,000 L.

The effectiveness of rainwater harvesting for reducing disease burden varied with different rainfall distributions, with the least impact in Accra, Ghana (station 654720), where DRWH and POU treatment with a 400 L storage capacity could result in only 0.001 DALYs avoided per capita. This variation is a result of the variable rainfall patterns as well as differences in the initial distribution of the population among the exposure scenarios.

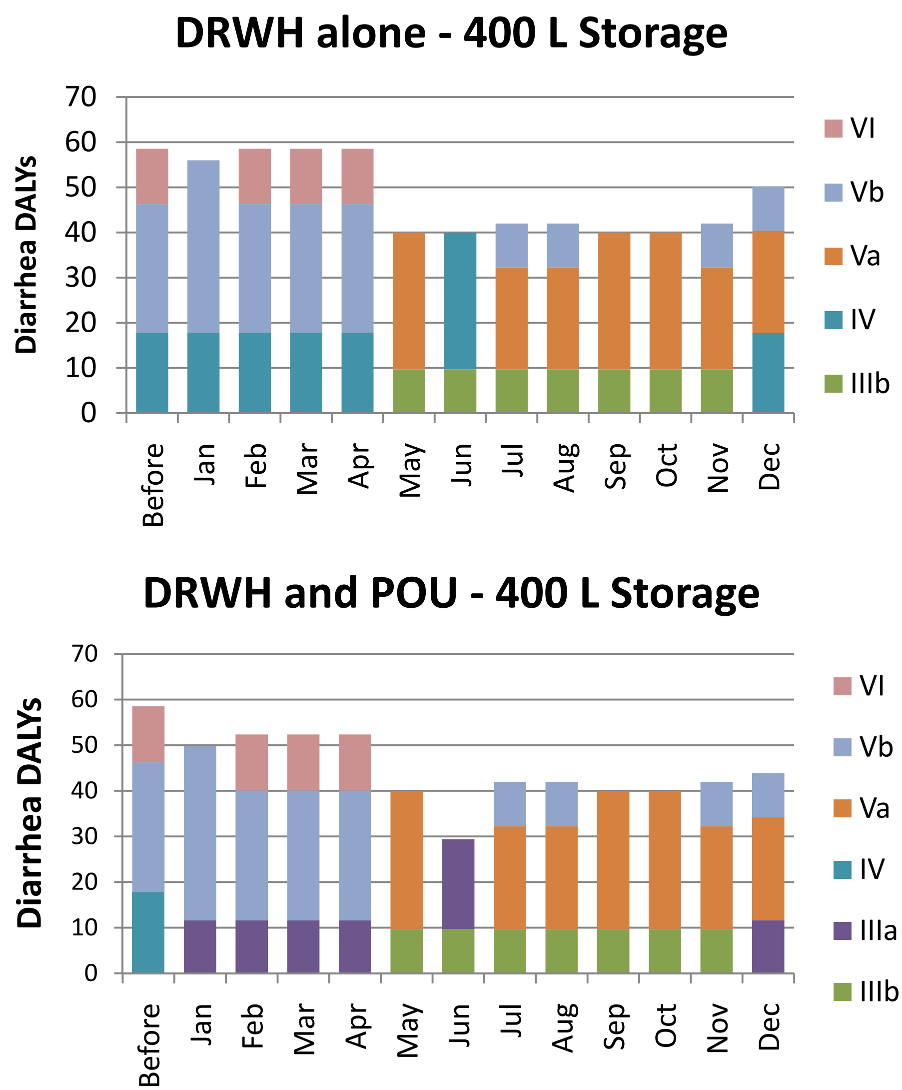
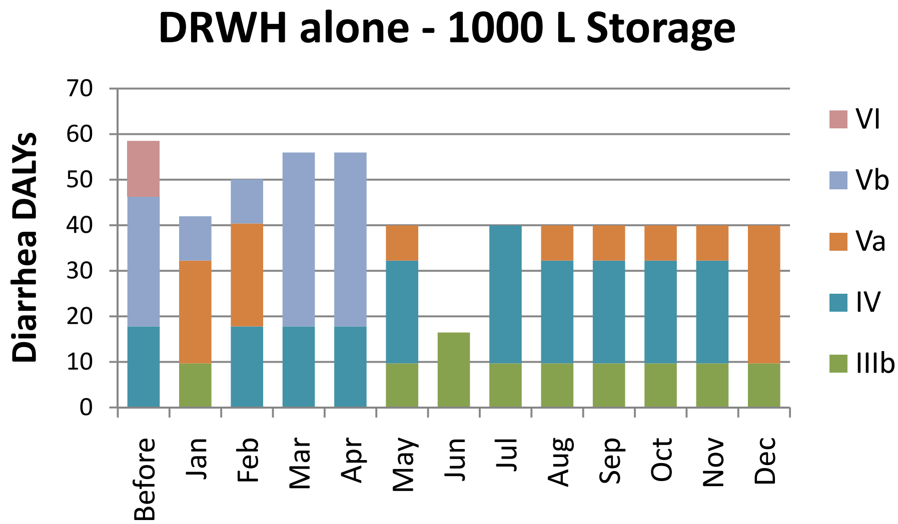



**Figure 5-3. DALYs resulting from diarrhea in each exposure scenario before DRWH or POU treatment and after the intervention with 400 L storage capacity at the station where the biggest impact is possible, measured by DALYs avoided per capita (gage 655920 in Tabou, Cote d'Ivoire). The exposure scenarios are described in Table 5-2. Note that we assume that the diarrhea DALYs before implementation of POU or DRWH is distributed evenly throughout the year (i.e. the bar showing DALYs before intervention in each of the charts is identical for every month of the year).**



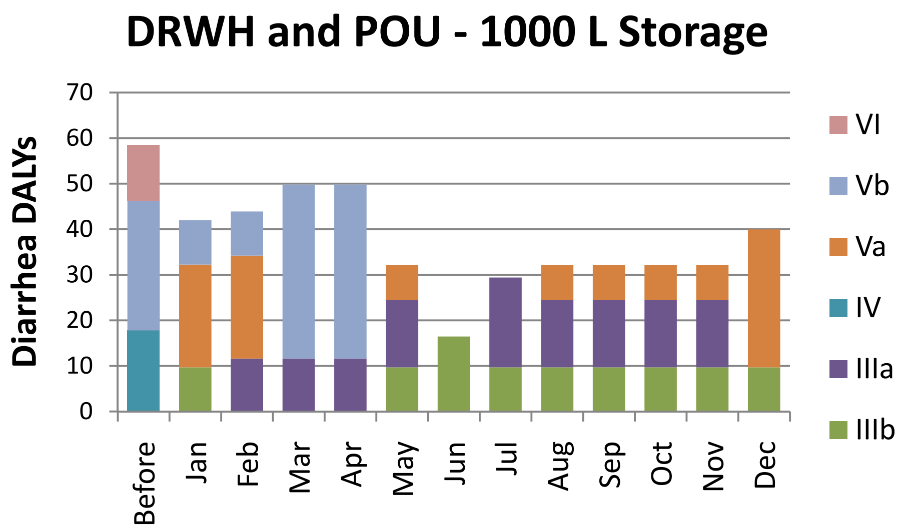




**Figure 5-4. DALYs resulting from diarrhea in each exposure scenario before DRWH or POU treatment and after the intervention with 1000 L storage at the station where the biggest impact is possible, measured by DALYs avoided per capita (gage 655920 in Tabou, Cote d'Ivoire). The exposure scenarios are described in Table 5-2. Note that we assume that the diarrhea DALYs before implementation of POU or DRWH is distributed evenly throughout the year (i.e. the bar showing DALYs before intervention in each of the charts is identical for every month of the year).**

For all the cities, with a total population of over 10 million, we estimate that there are about 420,630 DALYs per year from diarrhea, or about 0.042 DALYs per capita, under the assumption that disease burden in each city is consistent with its country's disease burden from diarrhea. Domestic rainwater harvesting with 400 L storage capacity could result in over 36,700 DALYs avoided (9% reduction). If domestic rainwater harvesting is combined with point of use treatment, this improvement is nearly doubled, with over 68,500 DALYs avoided (16% reduction) (Figure 5-5). If the storage capacity is increased to 1,000 L, then over 71,100 DALYs can be avoided by DRWH alone and over 97,200 DALYs could be avoided by implementing DRWH with POU treatment. The total number of DALYs that could be avoided by implementing DRWH alone in each city is shown in Figure 5-6.

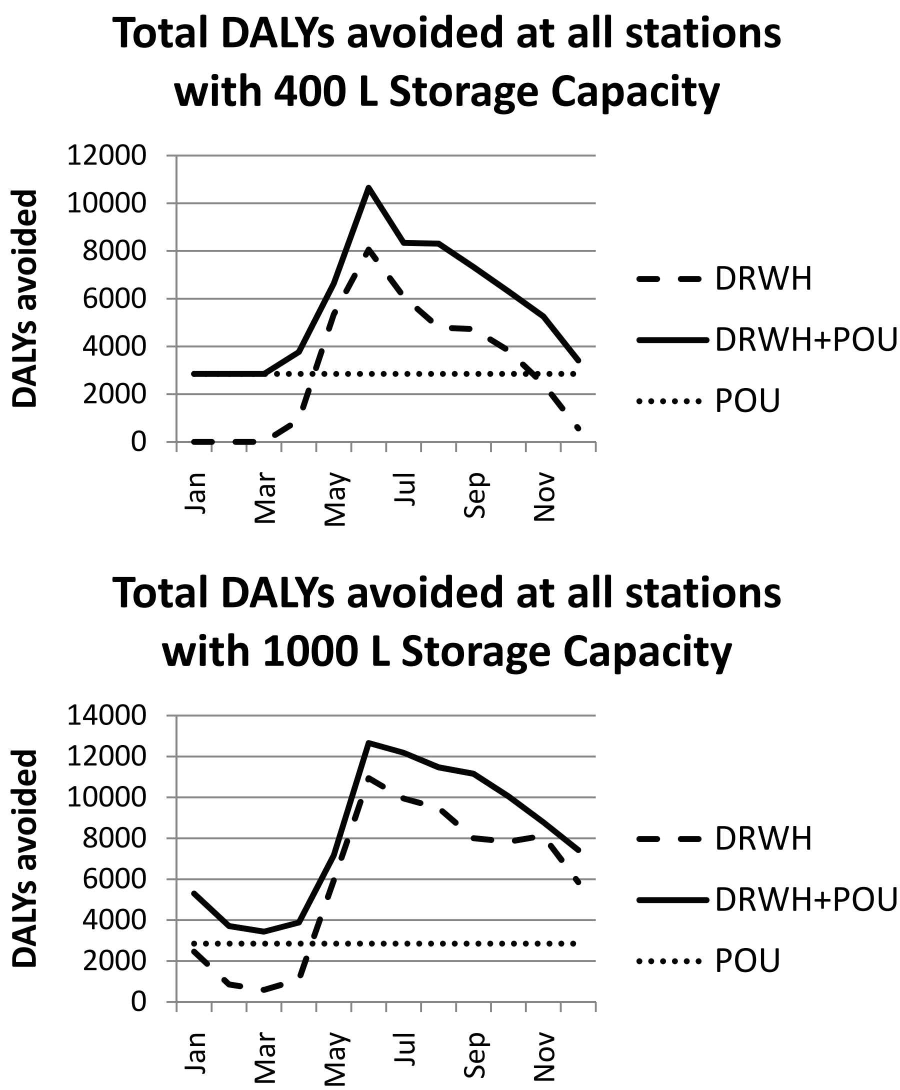



**Figure 5-5. DALYs that could be avoided by implementing DRWH and/or POU in 37 West African cities.**

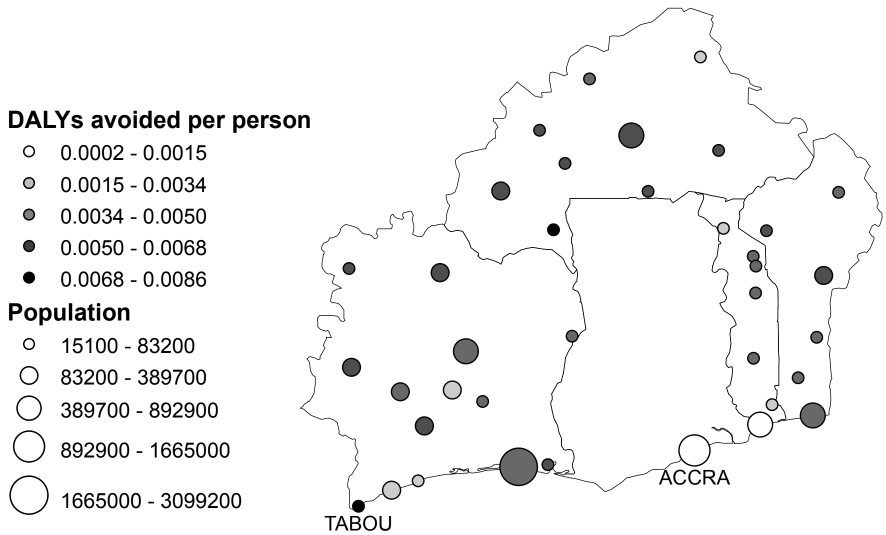



**Figure 5-6. DALYs that could be avoided by implementing DRWH alone with 400 L storage in 37 West African cities. The greatest impact could be attained by implementing DRWH where the population is large and there are many potential DALYs avoided per capita (large, dark circles).**

This analysis works under three important underlying assumptions about diarrhea and the effectiveness of interventions to prevent diarrhea. First, it was necessary to assume that the distribution of diarrhea DALYs among the exposure scenarios and the effects of water, sanitation, and hygiene interventions are the same throughout the study region. In reality, causes of diarrhea and the impact of diarrhea and interventions to prevent it are complicated and depend on environment, socioeconomic status, pathogen loading, and immunity, among other things.

Another approach to this analysis could be to study individual diarrhea-causing diseases in specific locations where the effects of diarrhea and the interventions to prevent diarrhea have been studied locally. Ascariasis and trachoma would be potential diseases to study, because they have been shown to be related to sanitation level (Esrey et al. 1991; Tshikuka et al. 1995; Prüss and Mariotti 2000; Assaolu et al. 2002). However, these relationships were observed in specific communities with characteristics that may not be similar to the cities in our analysis, and we are interested in a regional estimate of DALYs avoided. Therefore, the country estimates of DALYs from all-cause diarrhea

(World Health Organization 2009) and the global estimates of relative risk for the exposure scenarios (Prüss-Üstün et al. 2002) were used in this analysis.

A second important assumption in this analysis is that diarrhea does not vary seasonally. Seasonal variability in diarrheal incidence is a result of changes in temperature, relative humidity, and precipitation. Temperature and relative humidity directly affect pathogen replication rates, and precipitation can impact contamination of drinking water. Although extreme rainfall is associated with outbreaks of diarrhea, the relative contribution of these outbreaks to overall incidence is not clear (McMichael et al. 2004)

Although some individual diarrhea-causing diseases do vary seasonally or are related to extremes in weather (e.g. ascariasis (Gunawardena et al. 2004) and cholera (Kuhn et al. 2005)), and diarrhea incidence has been shown to change with temperature and precipitation for some specific locations (McMichael et al. 2004), all-cause diarrhea is difficult to relate to seasonality in a regional analysis because of the importance of other factors such as sanitation and human behaviors (Chambers 1981; Kuhn et al. 2005). A better understanding of seasonal variation of diarrhea-causing diseases as well as the seasonal performance of interventions to prevent disease would be necessary to incorporate these aspects into our analysis.

The third assumption necessary for this analysis was that the increased water supply would be used for purposes beneficial to health such as improved sanitation and hygiene. According to results from Waddington and Snilstveit's multicountry analysis (2009), improved water supply may have negligible impacts on childhood diarrhea. Although not mentioned in their analysis, this may be a result of beneficiaries not using new water supply for technologies or behaviors that improve sanitation or hygiene. Our analysis demonstrates the importance of ensuring that new water sources be used to improve sanitation and hygiene level of beneficiaries. This involves investment in appropriate sanitation technologies as well as promotion of household hygiene practices.

## 5.6 **Conclusions**

In this analysis, we estimate the potential for reduction in disease burden (as measured by DALYs avoided) from increased water supply resulting from domestic rainwater harvesting. The analysis was conducted for domestic rainwater harvesting alone and in combination with point of use treatment. By allowing populations to improve their water, sanitation, and hygiene status, the additional water provided by rainwater harvesting with a storage container of 400 L in the 37 West African cities would result in a potential 9% reduction in disease burden (DALYs) if it is implemented alone, and a 16% reduction if it is implemented in conjunction with point of use treatment. If the storage capacity is increased to 1000 L, then the potential reduction in disease burden from DRWH alone and DRWH with POU treatment would increase to about 17% and 23%, respectively.

The potential reduction in DALYs varied by location, depending on the rainfall distribution and the initial distribution of the population among the exposure scenarios. The city where domestic rainwater harvesting could have the most per capita impact on disease burden was Tabou, Cote d'Ivoire, where over 0.01 DALYs could be avoided per capita (25% reduction) annually if rainwater harvesting is implemented with 400 L storage containers and point of use treatment. The least impact would be achieved in Accra, Ghana, where only 0.001 DALYs could be avoided per capita if 400 L storage containers are used (6% reduction). These impacts were achieved primarily during the months with the highest rainfall.

At a local level, the analysis could be improved by incorporating specific diarrhea-causing diseases and a better understanding of seasonality of these diseases in the local setting. Additionally, an improved understanding of the local nature of disease transmission, effects of disease on the local population, and impacts of various water, sanitation, and hygiene improvements on these diseases for the local setting would improve this analysis. The analysis presented here does provide insight, however, into the potential for health improvement from increased water supply, as additional water allows populations to improve their water, sanitation, and hygiene status. The method is applicable for evaluating potential health effects of interventions that increase water quantity without necessarily improving water quality, and provides evidence that required for estimating cost-effectiveness of such environmental interventions.

# 6 Conclusions, Recommendations, and Future Work

## 6.1 Conclusions

The research described in this dissertation was initiated to address the overall question of sustainability of water and sanitation interventions for meeting the Millennium Development Goal 7: Environmental Sustainability. Sustainability aspects were related to interactions between engineering design and analyses, public health research and outcomes, and social and political aspects that must be considered to overcome the large gap in water and sanitation coverage in developing countries. The objectives outlined in Section 1.2 were met and resulted in the following conclusions and recommendations.

*Objective 1: Identify environmental engineers' role in public health and achieving the MDGs*

A compilation of public health statistics and review of literature from epidemiology and development organizations relating to water and sanitation demonstrated the importance of engineering activities in the world's efforts to eradicate extreme poverty as outlined by the Millennium Development Goals. Environmental engineers are particularly poised to address issues relating to water, sanitation, hygiene, and indoor air quality. The analyses investigating global challenges of sanitation coverage, sustainability of the water budget in watersheds in Bolivia, and potential health outcomes of interventions that increase water supply demonstrated that the appropriateness of technologies to meet water, sanitation, and hygiene needs in developing countries is affected by constraints related to water resource availability, effectiveness of technologies in achieving health outcomes, and reliability of social institutions to implement technological interventions. The analyses also showed that the sustainability of such technologies is affected by stresses resulting from rapid changes that are present in developing countries, including population dynamics, economic development (including rapid expansion of water and sanitation services), land use change, and potentially climate change. Accordingly, the role of the environmental engineer in public health and achieving the MDGs involves communication and two-way knowledge transfer with public health and social science researchers and practitioners, in addition to the traditional role of performing engineering analysis and design.

*Objective 2: Determine what are major challenges to achieving the MDG sanitation target*

The major challenges to achieving the MDG sanitation target worldwide were identified as inadequate investment, poor or nonexistent policies, corrupt governance, too few resources, and gender disparities. The importance of these challenges suggests that global sanitation coverage can only be achieved where there are strong institutions and economic commitment to reducing the gap in coverage. At a global scale, water availability was not found to be a significant challenge to sanitation coverage. However, a geospatial analysis at 0.5° scale showed water availability may be an important barrier to as many as 46 million people who are primarily living in urban areas where water quality is poor and populations are vulnerable because of dependence on environmental income associated with fish consumption.

The importance of water supply for achieving sanitation coverage was also examined at a local scale in eleven watersheds in Bolivia. Although the overall ratio of water use to availability (groundwater recharge) was found to be sustainable in these watersheds, limited accessibility of groundwater resources may result in difficulty in providing sewer coverage in the region. The communities in the watersheds rely primarily on natural springs for their water supply, and these springs likely have much smaller recharge zones than the watershed areas studied. Anecdotal evidence suggests that spring flow has been decreasing with time, and analysis of the water budget under scenarios of climate change suggested that recharge will decrease under all scenarios of climate change. As a result, water accessibility may become an important barrier to the planned increases in sewer coverage in communities in the region, if they continue to rely on spring discharge as their sole water supply.

*Objective 3: Examine the sustainability of a major increase in worldwide sanitation coverage in the context of water scarcity under different technology implementation scenarios*

According to the global analysis of challenges hindering sanitation coverage described in Chapter 3, increased sanitation coverage could have a significant effect on water resource sustainability in some localized settings. These settings are primarily urban areas where large numbers of people need new sanitation services and the populations depend on already degraded water resources for environmental income. In total, up to 46 million people could be newly affected severe water stress. This number depends on the sanitation technology used, with sewered systems causing the most water stress. In urban areas, sewers are often considered to be the only feasible sanitation option by traditional urban planners.

*Objective 4: Analyze the impacts of the following change drivers on gravity fed water supplies at a local (watershed) scale: land use change, population growth, water and sanitation service expansion, and climate change*

Chapter 4 describes an analysis of the water budget in eleven Bolivian watersheds that used low cost methods that take advantage of data that is either freely available or feasibly collected with the collaboration of a local counterpart with limited time and finances. The results demonstrated the potential importance of conducting hydrological analyses to understand sustainability of a water supply under influences of land use change, population growth, water and sanitation service expansion, and climate change. The water balance model showed that while runoff will either increase or decrease, depending on climate scenario, recharge will decrease under all scenarios of climate change as a result of increased evapotranspiration. These changes in runoff and recharge were much larger than potential changes resulting from increased agriculture, as a result of the low agricultural curve numbers that were estimated by calibration of the model.

Pressures related to population growth and water and sanitation service expansion were evaluated by estimating the amount of water demand that would result from using different technologies to meet the target coverage rates. The water use is expected to increase the most under the most likely scenario, which involves household water provision and sewer systems to accomplish new coverage. Although the water use of sanitation will be sustainable if the water budget of the entire watershed is considered, the increased water use from sewers may stress the currently *accessible* water resource (natural springs) beyond a sustainable level. A better definition of the recharge area of the springs would improve the understanding of the sustainability of this accessible resource.

*Objective 5: Estimate the improvements in health resulting from an intervention that increases household water availability.*

Chapter 5 describes a methodology for estimating public health impacts, in terms of disability adjusted life years avoided, resulting from increased water supply. The method provides a significant contribution for estimating cost-effectiveness of water supply technologies that do not necessarily improve water quality. The method was applied to domestic rainwater harvesting in 37 cities in West Africa. Rainwater harvesting has the potential to increase water supply seasonally, and the analysis showed that if the water is used for improvements in sanitation and hygiene, the installation of domestic rainwater harvesting systems could result in a significant reduction in disease burden. This reduction could be further enhanced if the installation incorporates point of use treatment, which reduces risk of diarrhea without increased water supply.

The methodology used for estimating the impact of water quantity enhancements on diarrheal disease burden was accomplished by incorporating engineering design principles for water supply (domestic rainwater harvesting) and sanitation technology (in terms of water requirements of sanitation technology). Without such an analysis, the potential impact of incremental water quantity improvements on diarrhea is not well understood. The analysis demonstrated the two-way transfer of knowledge between public health and engineering that is required for successful strategies to improve public health. Review of literature on water, sanitation, and health from public health and epidemiological research provided the required risk-related inputs for the method, while an engineering analysis was used to predict how new water supply could allow populations to adopt new sanitation and hygiene technologies and practices. The results from the engineering analysis will be useful, in turn, for decision-making regarding implementation strategies for reducing diarrhea disease burden in developing countries.

## 6.2 **Recommendations**

The following recommendations are drawn from the conclusions resulting from the literature review and analyses described in Chapters 2-5:

1. Engineers should feel called to serve developing countries' needs for water, sanitation, and hygiene.

Engineers play a critical role in reducing environmental disease burden. However, water and sanitation technologies are only appropriate when they can effectively reduce disease burden and can be implemented successfully by existing institutions. Accordingly, cost-effective and sustainable development of water resources and sanitation requires that engineers actively engage in communication and knowledge transfer with researchers and professionals from the fields of public health and social science.

2. Research should emphasize development of *appropriate* sanitation alternatives.

Engineering research should place emphasis on the development of sanitation technologies that will not result in increased water stress for urban populations in developing countries, especially where vulnerable populations depend on water resources for their environmental income. Research should result in alternatives to traditional water-consumptive sewer systems that often discharge directly to surface waters without treatment. The development of alternative technologies will require an understanding of appropriateness and sustainability in terms of cost, effectiveness, implementation strategies, and cultural acceptability. As a result, engineers should engage in partnerships with social scientists and public health professionals in the endeavor to meet sanitation needs.

3. Successful implementation of alternative water and sanitation technologies requires an understanding of the institutional and societal challenges that may hinder acceptability or effectiveness.

Chapters 3-5 showed that alternative water and sanitation technologies may assist the world in achieving sustainable water and sanitation coverage. It is important to note, however, that such alternative technologies may be accompanied by other challenges which should be understood for successful implementation. The impacts of sanitation coverage on water resources described in Chapter 3 suggest that alternatives to water intensive sanitation technologies in urban areas will reduce the potential for water stress in some locations. Less water-intensive technologies such as composting toilets could reduce stress on water resources; however, composting toilets may not be acceptable culturally, and in urban areas, implementation at a large scale would require significant institutional commitment to creating a market for the product or creating a system for transporting compost. Results in Chapter 4 showed that conservation by implementing less water-intensive sanitation technology (e.g. composting toilets) or the use of alternative water supply (e.g. wells or domestic rainwater harvesting) could improve the sustainability of water use in a region of Bolivia. Costs of drilling a well or treating surface water, along with the required pumping in a distribution system relying on wells or surface water, present significant economic challenges and require higher functioning institutions to operate and maintain the systems. In Chapter 5, it was shown that domestic rainwater harvesting has the potential to significantly reduce disease burden from diarrhea if additional water is applied toward sanitation and hygiene improvements. Although domestic rainwater harvesting is widely used as a back-up source of water, it is often considered to be unacceptable to beneficiaries who view distribution systems from surface or groundwater as a necessary step for community development. Institutional challenges often arise when implementing technologies at the household level (e.g. composting toilets or domestic rainwater harvesting), rather than community level (e.g. gravity-fed distribution systems). For example, during political campaigns promises of community water distribution systems tempt constituents as a significant step toward achieving economic and social status, even when future maintenance of the system is not guaranteed. Household level projects like domestic rainwater harvesting or decentralized sanitation require significant buy-in of beneficiaries and a commitment from institutions to work with individuals to ensure success. Future research should evaluate the magnitude of these challenges and investigate strategies for overcoming challenges to implementation of alternative water and sanitation technologies

4. Hydrological analysis should be applied to decision-making for development of new water supply and sanitation systems.

The availability of satellite precipitation products and low cost methods for monitoring parameters required for assessment of local water budgets can allow planners to increase the likelihood of sustainability of new water and sanitation projects in even the most data-scarce communities. Despite uncertainties resulting from data quality or lack of data, hydrological analysis provided evidence of changes in the water balance resulting from climate change and agricultural expansion. Such information can help decision-makers avoid future water stress resulting from implementation of inappropriate technology.

## 6.3 Future Work

The research presented in this dissertation would benefit from further research in the fields of hydrology, social science, economics, and public health. Future work should include the following:

1. Hydrological analyses should be improved with further research providing data necessary for water balance models. For example, installation of the low-cost water level sensor in additional watersheds in the Alto Beni region would contribute to a better estimate of curve numbers for agriculture and forest areas. Additionally, a better definition of the recharge areas of the springs would result in a better estimate of the sustainability of demands on the existing and planned gravity-fed water supply systems in the region.

2. Satellite data should be investigated for use in hydrological studies in developing countries as their associated biases are better understood in local and regional settings. This can be accomplished where there are meteorological data provided by ground-based stations. For example, in Bolivia, a better estimate of bias associated with the CMORPH and TRMM-3B42 data products will be possible when the new meteorological stations planned by ACDI/VOCA and its collaborators are installed and operating.
3. More research is needed to better define locally specific cultural appropriateness of alternative water and sanitation technologies that reduce the need for large amounts of water, such as sewers or take advantage of previously unused water resources, such as domestic rainwater harvesting. Additionally, implementation strategies for water and sanitation coverage should be developed that are feasible under challenges relating to the local social and political institutions.
4. The methodology for predicting reduction in disease burden from enhancements in water supply should be expanded to evaluate cost-effectiveness by relating costs of water supply systems to economic benefits from reduction in disease burden.
5. Improved knowledge of the seasonality of diarrhea or effects of sanitation interventions on specific diseases would aid in refining the estimated outcome from water quantity interventions. .

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**From:** Lauren Fry [mailto:lmfry@mtu.edu]
**Sent:** Wednesday, March 24, 2010 11:59 AM
**To:** Richter, Autumn
**Subject:** copyright question

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Thank you for your help,
Lauren

Lauren Fry
Ph.D. Candidate, Environmental Engineering
Department of Civil and Environmental Engineering
Michigan Technological University

4/5/2010

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# Appendix B: Chapter 2 Supplemental Information[1]

Table B 1. Principal component weights and percent variance explained.

| | *PC 1* | *PC 2* | *PC 3* | *PC 4* | *PC 5* |
|---|---|---|---|---|---|
| GDP(PPP) | **0.55** | 0.03 | -0.01 | -0.38 | **0.74** |
| SIC | 0.44 | -0.40 | -0.31 | **0.74** | 0.06 |
| FDI | 0.33 | **0.81** | -0.42 | 0.08 | -0.24 |
| GEM | 0.37 | 0.23 | **0.85** | 0.27 | -0.13 |
| CPI | **0.51** | -0.37 | -0.06 | -0.48 | -0.61 |
| % Variance | 49.44 | 17.60 | 15.96 | 10.97 | 6.03 |

[1] This material has been published online as supporting information for Fry, LM, Mihelcic, JR, Watkins, DW. 2008. Water and Nonwater-related Challenges of Achieving Global Sanitation Coverage. *Environmental Science and Technology* **42**(12): 4298–4304. It can be accessed free of charge at http://pubs.acs.org.

**Table B 2. Water use estimates used to determine domestic water use of populations within each grid cell. The total domestic water use in each cell resulted from adding the drinking water use and the sanitation use, as shown in Table 4 of the manuscript. Drinking water use includes all water uses except sanitation (i.e. drinking, cooking, hygiene, and household chores).**

| | *Water Use (L/capita/day)* | | |
|---|---|---|---|
| **Access Level** | **World Bank Income Group 1 and 2[a]** | **World Bank Income Group 3[b]** | **World Bank Income Group 4[c]** |
| Population with drinking water access at the home | 50 | 50 | 190 |
| Population with basic drinking water access | 15.5 | 15.5 | 15.5 |
| Population with no access to drinking water | 5 | 5 | 5 |
| Population with no sanitation or non water-based sanitation | 0 | 0 | 0 |
| Population with sewer or septic access[d] | 22.5-66.25 | 22.5-66.25 | 22.5-66.25 |
| Population with pour-flush latrines[d] | 10-25 | 10-25 | 10-25 |

[a] Use was estimated from Howard and Bartram, J. Domestic Water Quantity, Service Level and Health; WHO, 2003.

[b] Use for household access was estimated using lower estimate of water use for developed countries from Gleick, P. H. Basic Water Requirements for Human Activities: Meeting Basic Needs. Water International 1996, 21, 83-92. From that estimate, 60L/capita/day was subtracted for sanitation, assuming that households in Income Group 3 countries that have water within the home will also have flush toilets.

[c] Use for household access was estimated using the average per capita water use for developed countries from Gleick (1996). From that estimate, 60L/capita/day was subtracted for sanitation, assuming that households in Income Group 3 countries that have water within the home will also have flush toilets.

[d] Used minimum and maximum values from Table 3-4.

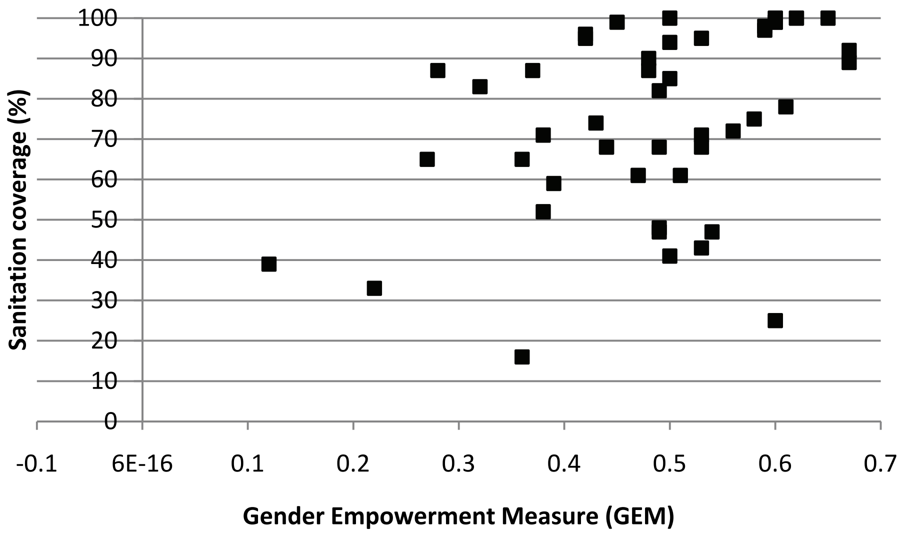


**Figure B 1. Sanitation coverage vs. Gender Empowerment Measure (GEM). Results show a positive correlation between gender empowerment and sanitation coverage for countries in World Bank Income Groups 1-3.**

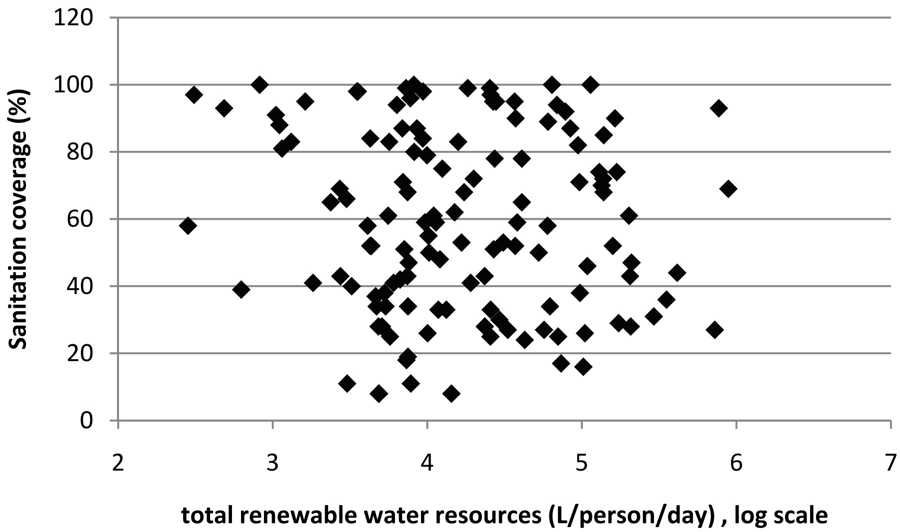


**Figure B 2 Sanitation coverage vs. total renewable water resources for Income Groups 1-3. At a national scale, our analysis showed that water availability was not correlated to sanitation coverage (UNEP The Geo Data Portal, compiled from FAO, AQUASTAT FAO's Information System on Water in Agriculture. http://geodata.grid.unep.ch (September 6, 2007). This is likely a problem of scale. An accurate study would require grid level data on sanitation coverage and water availability. In the following section we describe results from our grid scale analysis of sanitation impacts on water resources.**

**Table B 3. Populations estimated to live under moderate stress and severe stress calculated in this study for each of the six scenarios investigated. The minimum and maximum values for sanitation water use by the technology used to meet coverage targets under each scenario were used to determine a range of possible populations shifting into different water stress designations.**

| *Scenarios* | *Moderate Stress* | *Severe Stress* |
|---|---|---|
| 2000 min | $3.857x10^{8}$ | $2.020x10^{9}$ |
| 2000 max | $3.852x10^{8}$ | $2.030x10^{9}$ |
| 1 min | $4.542x10^{8}$ | $2.432x10^{9}$ |
| 1 max | $4.522x10^{8}$ | $2.444x10^{9}$ |
| 2 min | $4.539x10^{8}$ | $2.433x10^{9}$ |
| 2 max | $4.483x10^{8}$ | $2.448x10^{9}$ |
| 3 min | $4.535x10^{8}$ | $2.439x10^{9}$ |
| 3 max | $4.692x10^{8}$ | $2.453x10^{9}$ |
| 4 min | $4.923x10^{8}$ | $2.703x10^{9}$ |
| 4 max | $4.940x10^{8}$ | $2.723x10^{9}$ |
| 5 min | $4.914x10^{8}$ | $2.704x10^{9}$ |
| 5 max | $5.000x10^{8}$ | $2.728x10^{9}$ |
| 6 min | $5.007x10^{8}$ | $2.712x10^{9}$ |
| 6 max | $5.139x10^{8}$ | $2.769x10^{9}$ |

**Table B 4. Countries that have worse than average water quality and a significant number of fishers, and where more than 1 million people live under water stress.**

| *Country* | *Number of Fishers*[a] | *Water Quality Index*[b] | *Population under Water Stress in 2000* |
|---|---|---|---|
| Morocco | 106096 | -1.36 | $1.0x10^6$ |
| Egypt | 250000 | -0.15 | $1.1x10^6$ |
| Niger | 7983 | -1.04 | $1.3x10^6$ |
| Sudan | 27700 | -1.06 | $1.4x10^6$ |
| Pakistan | 272273 | -0.30 | $1.4x10^6$ |
| Libyan Arab Jamahiriya | 9500 | -0.33 | $1.7x10^6$ |
| India | 5958744 | -1.31 | $2.1x10^6$ |
| Algeria | 26161 | -0.64 | $2.8x10^6$ |
| Saudi Arabia | 25360 | -0.18 | $3.7x10^6$ |
| Mexico | 262401 | -0.69 | $3.7x10^6$ |
| Kazakhstan | 16000 | -0.33 | $4.5x10^6$ |
| China | 12233128 | -0.33 | $13.0x10^6$ |

[a] WRI; UNDP; UNEP; World Bank *World Resources 2005: The Wealth of the Poor – Managing Ecosystems to Fight Poverty*; WRI: Washington, D.C., 2005.

[b] Esty, D.; Cornelius, P. K., Environmental Performance Measurement: The Global Report 2001-2002. Yale Center for Environmental Law and Policy: New Haven, CT, 2002.

**Table B 5. Countries that have worse than average water quality where the population relies on fish for at least 20% of its protein, and where more than 1 million people live under water stress.**

| *Country* | *Protein from Fish*[a] | *Water Quality Index*[b] | *Population Under water Stress in 2000* |
|---|---|---|---|
| Egypt | 23 | -0.15 | $1.0x10^6$ |
| Peru | 25 | -0.08 | $3.9x10^6$ |
| United Republic of Tanzania | 27 | -0.22 | $2.8x10^6$ |
| Uganda | 23 | -0.42 | $2.0x10^6$ |
| Senegal | 44 | -0.42 | $1.3x10^6$ |
| Nigeria | 29 | -0.62 | $1.3x10^6$ |

[a] WRI; UNDP; UNEP; World Bank World Resources 2005: The Wealth of the Poor – Managing Ecosystems to Fight Poverty; WRI: Washington, D.C., 2005.

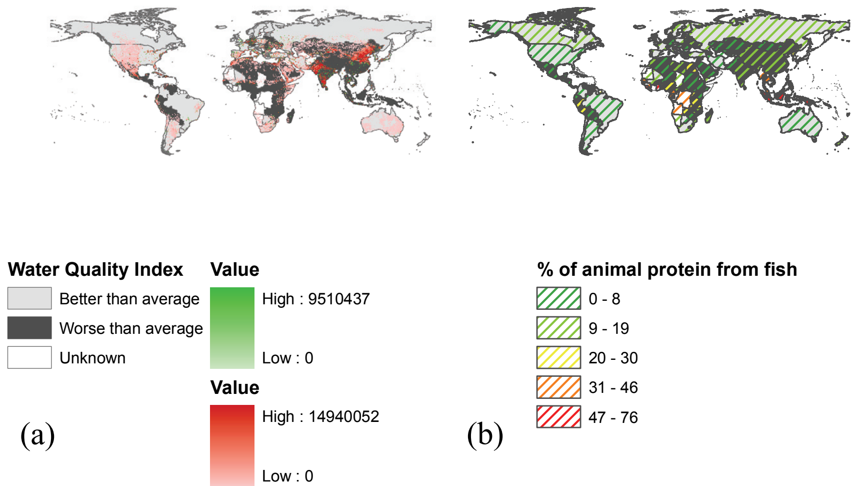


**Figure B 3. (a) Populations living under moderate and severe water stress in 2000, overlaid with the Environmental Sustainability Index's Water Quality Indicator (Esty, D.; Cornelius, P. K., Environmental Performance Measurement: The Global Report 2001-2002. Yale Center for Environmental Law and Policy: New Haven, CT, 2002).**

**(b) Percentage of the population's animal protein that comes from fish (WRI; UNDP; UNEP; World Bank *World Resources 2005: The Wealth of the Poor – Managing Ecosystems to Fight Poverty*; WRI: Washington, D.C., 2005) overlaid on the Water Quality Indicator. Note that, visually, the 2015 and 2025 scenarios do not change significantly from this 2000 map, so maps are not shown for 2015 and 2025.**

# Appendix C: Chapter 4 Supplemental Information

## Appendix C 1: Precipitation Data for the Alto Beni Watersheds

*Gauge data*

The only meteorological station in the study area is opperated by the cacao cooperative El Ceibo in Sapecho. Technician Justino Mamani obtained monthly preciptiation and temperature data from El Ceibo for the months of February 2008 to June 2009. Following June 2009, there was a change in leadership at the cooperative, and Mr. Mamani was unable to obtain further meteorological data. The precipitation and temperature data for February 2008 to June 2009 are shown in Table C 1.

**Table C 1. Precipitation and Temperature Data for the Sapecho Meteorological Station, provided by El Ceibo cacao cooperative.**

| | | *Ambient Temperature at Time* | | | | *Daily Temperature* | | *Precipitation* |
|---|---|---|---|---|---|---|---|---|
| **Month** | **Year** | **8:00** | **12:00** | **14:00** | **18:00** | **MAX.** | **MIN.** | **(mm)** |
| February | 2008 | 22.8 | 28.65 | 29.2 | 26.2 | 31.9 | 22.0 | 41.9 |
| March | 2008 | 22.1 | 28.786 | 29.8 | 25.7 | 32.6 | 21.6 | 65.2 |
| April | 2008 | 21.4 | 28.2 | 29.9 | 24.4 | 32.0 | 20.3 | 9.5 |
| May | 2008 | 19.4 | 25.613 | 27.6 | 22.0 | 29.2 | 18.9 | 25.8 |
| June | 2008 | 18.0 | 23.367 | 24.7 | 21.2 | 27.0 | 17.3 | 13.9 |
| July | 2008 | 18.8 | 25.952 | 28.2 | 23.0 | 30.1 | 18.2 | 18.5 |
| August | 2008 | 19.6 | 27.984 | 30.6 | 25.0 | 33.0 | 18.6 | 11.0 |
| September | 2008 | 20.8 | 28.5 | 30.2 | 25.7 | 33.4 | 17.7 | 19 |
| October | 2008 | 22 | 30.1 | 31.3 | 25.7 | 34 | 20.5 | 104 |
| November | 2008 | 23.1 | 31.5 | 33.1 | 27.7 | 36 | 21.3 | 26.7 |
| December | 2008 | 22.7 | 29.6 | 30.4 | 27 | 33.7 | 21.4 | 76 |
| January | 2009 | 22.2 | 28.9 | 30.3 | 26.9 | 33.3 | 21 | 128 |
| February | 2009 | 22.6 | 28.6 | 29.7 | 26.5 | 32.6 | 21.9 | 140 |
| March | 2009 | 21.8 | 29.4 | 30.5 | 26.5 | 33.6 | 21.5 | 48 |
| April | 2009 | 21.1 | 28 | 30.4 | 24.5 | 33.2 | 20.8 | 44 |
| May | 2009 | 20.3 | 27.5 | 29.9 | 23.9 | 31.9 | 19.8 | 33 |
| June | 2009 | 18.7 | 22.5 | 25.6 | 21.9 | 28.3 | 18.1 | 6.6 |

*Satellite Data*

Joyce et al. (2004) developed the CMORPH precipitation data set, which draws on thermal infrared (TIR) and passive microwave (PMW) instruments. Passive microwave data provide the most accurate satellite-based estimates of precipitation, so these data are used to estimate precipitation amounts and the TIR data are used to propagate raining pixels by deriving a cloud motion field. The CMORPH method does not estimate rainfall from PMW, but instead propagates rainfall estimates through space and time using the cloud motion data provided by TIR observations (Dinku et al. 2010). CMORPH is available at spatial and temporal resolutions of 0.25°×0.25° at 3 hourly or daily intervals and 8km × 8km at half hourly intervals from 2002 to present. It is important to note that the original satellite-derived estimates are at a resolution of about 12×15 km, so datasets of finer resolution provided by CMORPH are interpolated (Joyce et al. 2004).

The CMORPH data set is not corrected for bias, but Janowiak et al. (2007) have developed a methodology that corrects for bias by multiplying CMORPH hourly data by the ratio of the daily Climate Prediction Center (CPC) gauge analysis to the daily CMORPH value at each grid location. The resulting dataset is called RMORPH. This methodology was applied for a 35-day period in the North American Monsoon Experiment field campaign. A new method of correcting for bias using optimum interpolation is being developed which will provide precipitation estimates at 0.25° lat/long spatial and daily temporal resolution (Joyce et al. 2010).

TRMM-3B42 is another data set that combines data from TIR and PMW instruments. TRMM-3B42 comes at 0.25° spatial resolution and 3-hour temporal resolution. Estimates of rainfall are produced by (*i*) adjusting and combining PMW estimates from several sources, (*ii*) estimating TIR precipitation using PMW estimates for calibration, (*iii*) combining the PMW and TIR estimates, and (*iv*) rescaling the 3-hourly multi-satellite data to monthly precipitation from a satellite-gauge combination. Monthly gauge observations are combined with the monthly PMW and TIR estimates in a dataset called TRMM-3B43, which is used in step iv of the creation of TRMM-3B42 data. As a result, TRMM-3B42 estimates are already adjusted using gauge data. There is also a real time version that does not include step iv, called TRMM-3B42RT, which is not adjusted for gauge data. (Huffman et al. 2007)

Adler et al. (2000) analyzed the TRMM-3B43 merged satellite/gauge product by comparing it with surface datasets and the Global Precipitation Climatology Project (GPCP) merged data product (Huffman et al. 1997), which is a merged dataset using microwave and IR observations merged with gauge information. The GPCP dataset provides monthly estimates with 2.5° resolution. They found that the TRMM-3B43 estimates were 10% higher than the GPCP estimates over tropical oceans but that in the dry subtropics, TRMM values were smaller than GPCP estimates. Over land, the TRMM-3B43 estimates were significantly higher than surface estimates, which were observed at Houston, Texas, and Melbourne, Florida.

Vila et al. (2009) corrected the real-time TRMM Multisatellite Precipitation Analysis (3B42RT) using the CoSch technique over continental South America during summer 2004. In this method, the bias is determined using both an additive bias scheme and a multiplicative bias scheme. The additive bias and multiplicative bias is calculated for each gauge observation. Gauge observations are interpolated to create a gridded map of observed precipitation, masking out the grids that are more than five grid points from the closest observation. Each grid is assigned the bias correction scheme that results in the least difference from the grid resulting from interpolation of observations. Weights are assigned to each bias scheme at each grid location that represent the number of times a bias scheme (additive or multiplicative) is selected in a larger box centered at the grid location. For areas that were masked out in the interpolation, the original multisatellite estimate remains, with no bias correction. The selection of bias scheme is related to the rainfall regime, and changes accordingly. In cases where the satellite value is zero, but the observed precipitation is greater than zero, the additive scheme is more useful for bias adjustment. According to Vila et al., this would occur when there are warm clouds or clouds with no ice structure. When there are large discrepancies between observed and estimated values and the probability density function does not fit observed values, however, the multiplicative scheme is more useful. Vila et al. tested the CoSch bias removal technique by using a cross-correlation process with a South American gauge dataset. They compared the results from the CoSch method with estimates produced by only additive bias removal, only ratio bias removal, TRMM-3B42, and TRMM-3B42RT (without bias removal). The CoSch method performed better than all other estimates, according to the resulting bias, RMSE, and correlation coefficient. The method would require significant computation in order to create a bias-corrected precipitation data set for use in the daily water balance model in the Alto Beni.

A third satellite-derived precipitation data set is available from the Global Precipitation Climatology Project (GCPC). The GPCP has completed 30-year monthly and 5-day data sets covering 1979 to 2008 at a 2.5° grid, along with a daily product on a 1° grid from 1996. These products combine microwave and IR satellite data with the gauge analysis by the Global Precipitation Climatology Centre (GPCC). Version 2.1 is the most recent version, described by Huffman et al (2009). This data set was not evaluated for use in the daily water balance model, but will be evaluated in future work.

Tian et al. (2007) evaluated CMORPH and TRMM-3B42 precipitation estimates in the continental United States by comparing them with gauge-based estimates from the GPCC monthly gauge dataset and the National Centers for Environmental Prediction Climate Prediction Center (NCEP CPC) near-real-time daily precipitation analysis (Higgins et al. 2000). They found that TRMM-3B42 has much lower biases than CMORPH at a seasonal scale, but CMORPH performs better at a time scale of 5 days or less. CMORPH biases are highly seasonally dependent, with high positive bias in the summer and smaller negative bias in the winter. Both satellite estimates detect more high-intensity events than low-intensity events, which causes a shift in the "precipitation spectrum." This is problematic for hydrological modeling, and may result in overestimation of surface runoff. CMORPH performs slightly better at the time scale of rain events. Both CMORPH and TRMM-3B42 also both show higher RMSE, but also higher probability of detection and higher spatial correlation in summer than in winter. The authors recommend that CMPORPH be used for short-term applications and TRMM-3B42 be used for long-term, retrospective, and climatological studies.

There has not been much validation of satellite rainfall products over mountainous regions at a daily timescale, because of lack of gauge observations or lack of access to data (Dinku et al. 2010). Dinku et al. (2010) have compared CMORPH and TRMM data over mountainous regions in Ethiopia and Colombia. They found that the correlation between TRMM and CMORPH products was low, and that both products underestimated the amount of rainfall and frequency of rainfall in Ethiopia. In Colombia, however, they found that while both TRMM and CMORPH products underestimated frequency of rainfall, only TRMM-3B42 underestimated the amount. Overall, CMORPH had better validation statistics, and performance was better in Colombia than in Ethiopia, despite the fact that CMORPH has not been adjusted by gauge data. The authors recommend that rainfall estimates over mountainous regions could be improved by taking into account topography. If gauge data are available, this can be done by calibrating the satellite product with gauge data (Dinku et al. 2010).

Future improved precipitation products will include the Global Precipitation Measurement (Smith et al. 2007), which will provide measurements at about 10-km resolution, and the CMORPH dataset bias-adjusted with the optimum interpolation approach (Joyce et al. 2010).

Both CMORPH and TRMM-3B42 satellite precipitation data sets are available at $0.25° \times 0.25°$ resolution. Data for the 4 grid cell locations shown in Table C 2 were obtained from both data sets.

**Table C 2. Locations of the grid cells for which precipitation data were downloaded from the CMORPH and TRMM-3B42 datasets.**

| *Point Number* | *Latitude* | *Longitude* |
|---|---|---|
| 1 | -15.375 | -67.375 |
| 2 | -15.375 | -67.125 |
| 3 | -15.625 | -67.375 |
| 4 | -15.625 | -67.125 |

Steps for downloading the CMORPH and TRMM-3B42 data are shown below:

CMORPH

The mean daily precipitation CMORPH data are freely available for download from the International Research Institute for Climate and Society through their data library website at http://iridl.ldeo.columbia.edu/. Daily mean hourly precipitation data were downloaded as columnar tables for the four grid cells centered at the latitude and longitude coordinates in Table C 2. The daily precipitation was then calculated as 24 hours times the mean hourhly CMORPH precipitation.

TRMM-3B42

All TRMM data are freely available from the National Aeronautics and Space Administration's Goddard Earth Sciences Data and Information Services Center at http://mirador.gsfc.nasa.gov/.

1. Go to http://mirador.gsfc.nasa.gov/ and type TRMM-3B42 into the keyword search
2. Click the box for Daily TRMM and Others Rainfall Estimate (3B42 V6 derived) (TRMM_3B42_daily) and click "Add Selected Files to Cart."
3. The files can be automatically converted to netCDF files before downloading by clicking on "Convert to netCDF" under the "Available Services" Column. The netCDF files can be read by Matlab using tools described in later steps. Click "Convert to netCDF" and continue to shopping cart.
4. Click "Check Out"
5. To download the files using DownloadThemAll, click first in the checkbox that says "Keep items in the cart after selecting a download option." Then click on the "More Download Options" tab.
6. Use DownloadThemAll to download all files by clicking on the "URL Listing Page."
7. Newer versions of Matlab have the netCDF tool, however older versions do not. Instructions for downloading and using the he required tools are available at http://mexcdf.sourceforge.net/tutorial/.

## Appendix C 2: Soils Data for the Alto Beni Watersheds

Table C 1 compares three methods of determining soil texture: landscape, jar settling test, and feel. The classification by landscape came from the landscape map from ACDI/VOCA, along with a table in the ACDI/VOCA PDM document (page 27) showing typical soil types for various landscapes. This table gives a range of soil types for each landscape, for example sandy loam to silty clay loam.

Classification by jar was done by mixing the soil with water and allowing the soil to settle. This method has been compared with other texture analysis methods for use in the classroom by Yusten et al. (2003) and they found that it was comparable to a commercial test kit. The procedure is described at http://weather.nmsu.edu/teaching_Material/soil456/soiltexture/soiltext.htm.

Classification by feel was accomplished using standard field methods, described at http://soils.usda.gov/education/resources/lessons/texture/. This method relies on some "expert judgement", however, which results in uncertainty because of our lack of previous experience.

Based on the observations and data in Table C 3 and Figure C 1, soils in the region are predominantly sandy clay loam. Because soils were not sampled throughout the watersheds and the field observations and jar settling tests had significant uncertainty associated with the methods, we classify all soils in the model as sandy clay loam.

**Table C 3. Soil Classifications Resulting from Associated Landscape Type, Jar Settling Tests, and Field Observations (determined by feel in the field). The jar test agreed with the landscape test in about 30% of the cases and the feel test agreed with the landscape test in about 24% of the cases. Some of the jar or feel test results were close in proximity on the texture triangle to some of the landscape classification textures, highlighted in yellow. If these results are included as "good", then this results in the jar test agreeing with the landscape test in about 63% of the cases and the feel test agreeing with the landscape test in about 47% of the cases. All things considered, the jar test performed better than the test by feel in the field.**

| | Texture | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sample** | **Landscape (map gives a range of potential texture classifications)** | | | | | **Jar** | **Feel** |
| arroyotauro.10.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | sandy loam |
| arroyotauro.100.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | loamy sand | loamy sand |
| arroyotauro.50.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | loamy sand |
| brecha-h.10.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay | clay |
| brecha-h.100.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy loam | sandy loam |
| brecha-h.50.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay | clay |
| chivoy.10.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | |
| chivoy.100.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | clay | |
| chivoy.50.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | |
| ibta.10.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay | clay |
| ibta.100.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | clay |
| ibta.50.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | clay |
| losandes.10.17.06.09 | sandy clay loam | | | | | clay | sandy clay loam |
| losandes.100.17.06.09 | sandy clay loam | | | | | sandy clay loam | clay |
| losandes.50.17.06.09 | sandy clay loam | | | | | clay | clay |
| mapuruchuqui.10.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | sandy clay loam |
| mapuruchuqui.100.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | loamy sand | loamy sand |
| mapuruchuqui.50.20.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | sandy clay |
| parachoque.10.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | sandy loam |
| parachoque.100.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy loam | sandy clay loam |
| parachoque.50.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay | sandy loam |
| pulucani.10.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy clay loam | |
| pulucani.100.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | loamy sand | |
| pulucani.50.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy loam | |
| sapecho.10.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | | silty clay |
| sapecho.100.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | | |
| sapecho.50.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | | sandy loam |
| smhuachi.10.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sandy loam | |
| smhuachi.100.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | loamy sand | |
| smhuachi.50.19.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | | |
| tauro.10.17.06.09 | sandy loam | loam | | | | sandy loam | silty clay |
| tauro.100.17.06.09 | sandy loam | loam | | | | clay | silty clay |
| tauro.50.17.06.09 | sandy loam | loam | | | | sandy clay | sandy clay |
| triunfo.10.18.06.09 | sandy loam | loam | | | | sandy clay loam | silty clay |
| triunfo.100.18.06.09 | sandy loam | loam | | | | sandy clay loam | clay |
| triunfo.50.18.06.09 | sandy loam | loam | | | | sandy clay | clay |
| tucupi.10.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | sandy loam |
| tucupi.50.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | sand | sandy loam |
| tucupi.80.18.06.09 | sandy loam | loam | clay loam | sandy clay loam | silty clay loam | | sandy loam |
| viiacamacha.10.17.06.09 | sandy loam | loam | | | | sandy clay loam | silty clay |
| villacamacha.100.17.06.09 | sandy loam | loam | | | | sandy clay | sandy clay |
| villacamacha.50.17.06.09 | sandy loam | loam | | | | sandy clay loam | clay |
| villacamacha2.10.17.06.09 | sandy clay loam | | | | | sandy clay | sandy clay |
| villacamacha2.100.17.06.09 | sandy clay loam | | | | | sandy clay loam | sandy clay |
| villacamacha2.50.17.06.09 | sandy clay loam | | | | | sandy clay loam | sandy clay |
| villaelcarmen.10.17.06.09 | sandy clay loam | | | | | clay | clay |
| villaelcarmen.100.17.06.09 | sandy clay loam | | | | | sandy clay loam | sandy clay |
| villaelcarmen.50.17.06.09 | sandy clay loam | | | | | clay | clay |

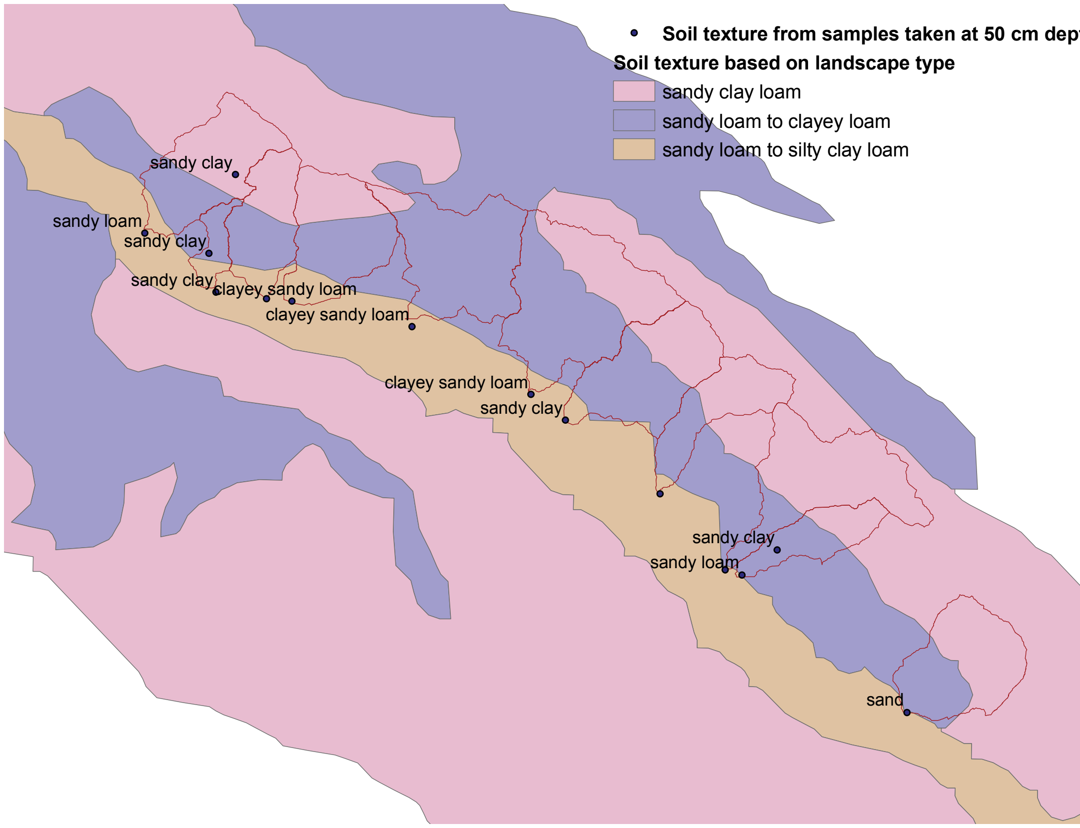


**Figure C 1. Soils determined by landscape type and by jar settling test. Soils determined based on landscape type were derived from a landscape shapefile and information on associations between landscape and soils (ACDI/VOCA 2007). Jar settling tests were conducted during field work in Summer 2009.**

## Appendix C 3: Discharge Data for the Alto Beni Watersheds

The following parameters were measured at each stream gauging location shown in Figure 4-1: depth at various locations across the stream for determining the cross sectional area and wetted perimeter, and slope of the stream channel. Discharge is calculated using Manning's equation:

$$Q = \frac{1}{n} A R^{2/3} S_0^{1/2}$$

where A is the cross sectional area ($m^2$), R is the hydraulic radius (A/P) (m), P is the wetted perimeter (m), $S_0$ is the longitudinal slope of channel (m/m), and n is Manning's roughness coefficient. The cross-sectional areas of thestream bed and flood plain beneath the bridges where they are monitored are shown in Figure C 2 and Figure C 3. In addition, we photographed each location to help in determining appropriate Manning's n values and found coordinates using a handheld GPS unit.

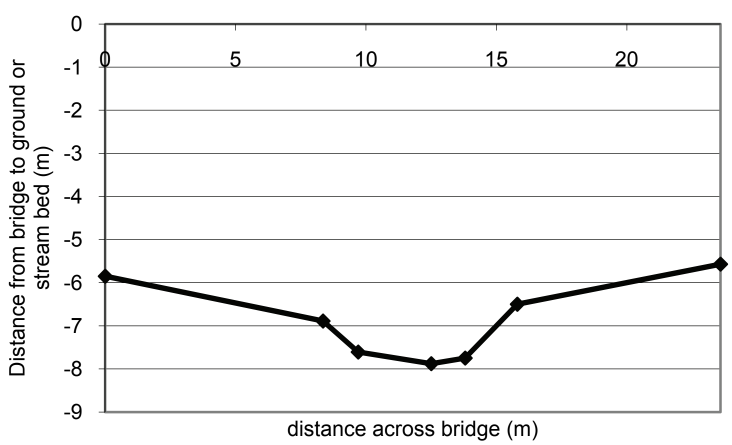


**Figure C 2. IBTA cross-sectional area underneath the bridge. The slope of the channel was 0.005° (estimated using a clinometer).**

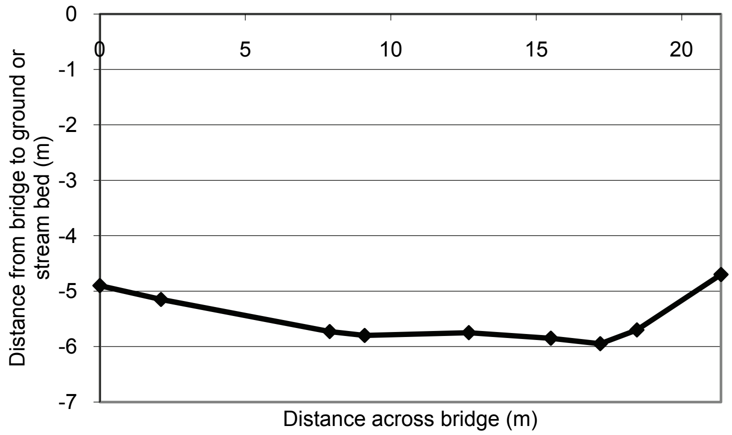


**Figure C 3. Mapuruchuqui cross-sectional area beneath the bridge. The slope of the stream bed was 0.01° (estimated using a clinometer).**

(a) (b)

**Figure C 4. The monitoring locaitons of (a) the Mapuruchuqui watershed and (b) the IBTA watershed. The roughness values for the Mapuruchqui watershed were determined as $n_{floodplain}$=0.0475 (scattered brush) and $n_{channel}$=0.04 (cobbles).The roughness values for the IBTA watershed were determined as $n_{floodplain}$=0.11 (dense brush) and $n_{channel}$=0.039 (clean, irregular). Photographs by author.**

## Appendix C 4: Land Use Data for the Alto Beni Watersheds

Shapefiles containing extent of area devoted to agriculture in 2007 and in the future were provided by ACDI/VOCA (ACDI/VOCA 2007), shown in Figure C 5. The percent of watershed area used for agriculture was determined using ArcMap.

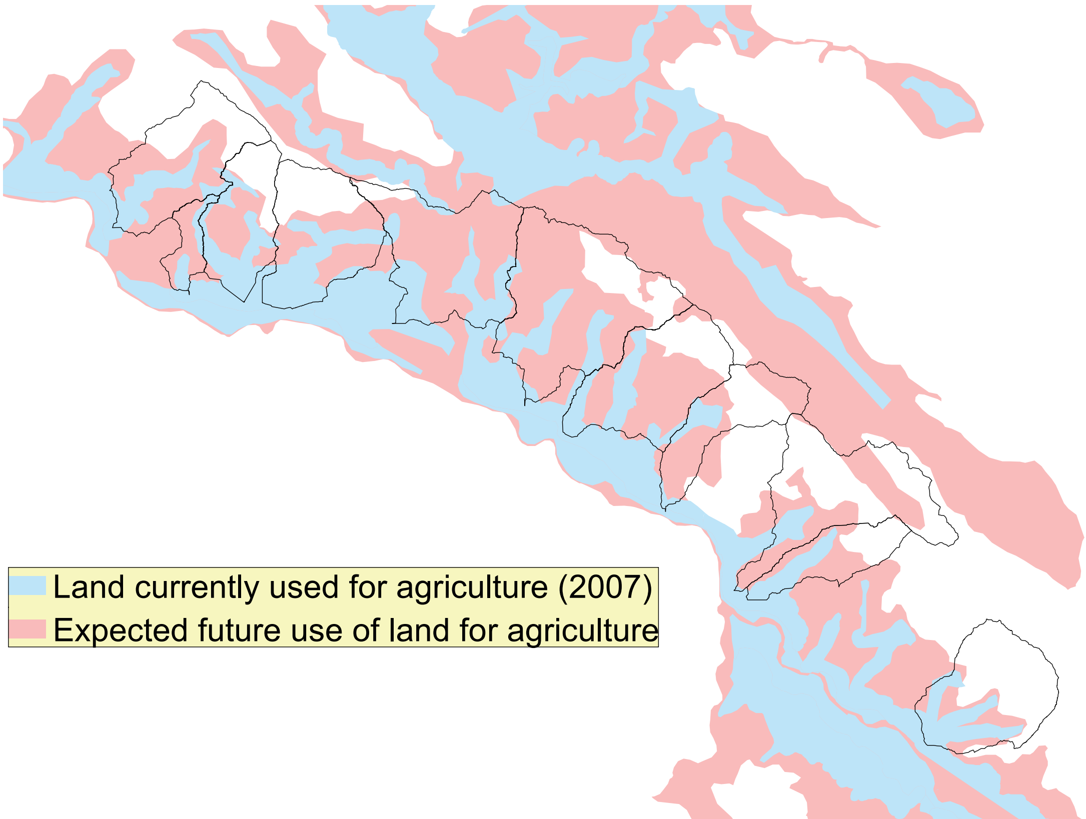


**Figure C 5. Agricultural area data provided by ACDI/VOCA (ACDI/VOCA 2007).**

## Appendix C 5: Population Data for the Alto Beni Watersheds

ACDI/VOCA provided population estimates for the *centrales* of the region, which were then used to calculate the population density for each *centrale* (Figure C 6). These population densities were then attributed to the watersheds. If a watershed overlapped more than one *centrale*, then the population of the watershed was first calculated by summing the products of the population density of the each *centrale* and the area of that *centrale* contained in the watershed. In the case of the Tucupi watershed, where population data are not available outside the Tucupi *centrale*, the population of the watershed was assumed to be equal to the population of the town of Tucupi, because the majority of the population is in the town.

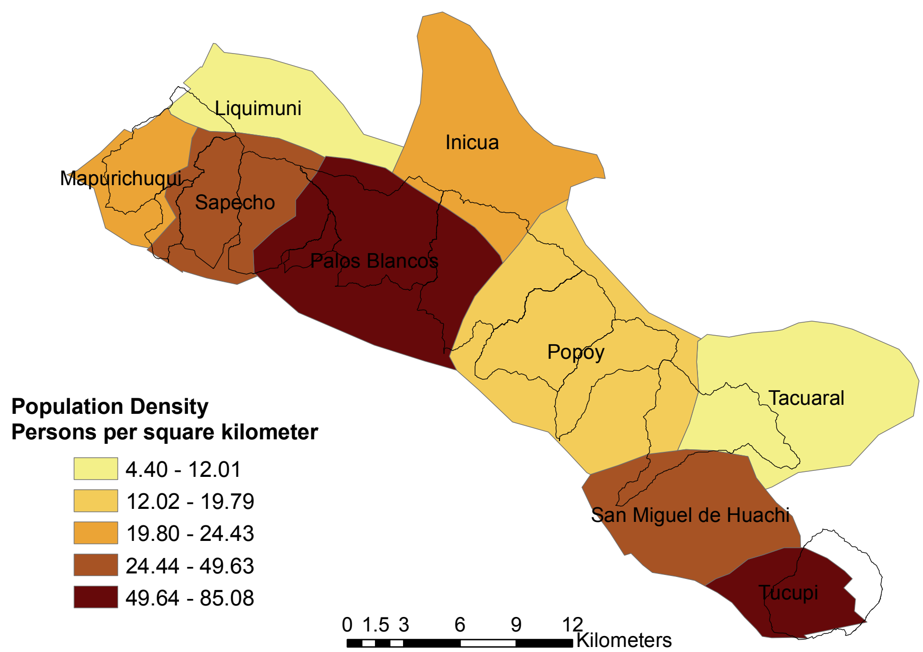


**Figure C 6. Population densities of the *centrales* of the region. Population densities of these *centrales* were estimated by dividing the *centrale* population provided by ACDI/VOCA by the area of the *centrale* estimated from a *centrale* shapefile provided by ACDI/VOCA (ACDI/VOCA 2007).**