

Sustainable Control of Water-Associated Diseases – A Systems Approach

A discussion paper for the Graham Environmental Sustainability Institute

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1. Introduction

1.1. Purpose

The motivation for this “think piece” paper (now in an early, incomplete and draft form²) is the need to define the short- to mid-term research agenda for the design, monitoring and assessment of sustainable strategies aimed at reducing the burden of infectious water-associated disease. As will be discussed, the existing health burden is huge, providing clear evidence of deficiencies in current practices, and further, most stressors have unfavorable trends, which will exacerbate problems regarding water, hygiene, sanitation and ultimately health. Many disciplines are attempting to respond, the complexity of the factors affecting environmental and water-related diseases is increasingly recognized, and the analysis, understanding, and interventions are growing more sophisticated. Still, tremendous gaps remain, and current approaches seem unlikely to solve many problems in a sustainable manner—even with impossibly vast increases in funding for water supply and sanitation. We believe that a *systems approach* is the best strategy, taking the best contributions from multiple fields, with the ability to integrate and communicate among disciplines, and to achieve synergies. In this context, we need to define the research agenda that can make sustainable solutions possible. The aims of this paper are limited to providing background information that:

- (1) Reviews the approaches used to evaluate and manage, hopefully in a sustainable manner, water-associated diseases. The review identifies some of the patterns and themes in the field, including unanticipated problems, complexity, and knowledge gaps;
- (2) Frames some of the issues, defines several key terms, and highlights some new approaches. Ultimately, we hope to provide a rigorous framework and methodology that is broadly applicable to the problem given its complexity and dynamics; and
- (3) Encourages discussions and interactions among a multidisciplinary group to allow forward movement.

1.2. A research agenda for sustainability

To the authors, sustainability implies the following: a long, intergenerational time horizon for activities; a broad and holistic scope of analysis and intervention; and movement toward the goal of improving health and the quality of life of populations. For water-related diseases, a decade or two – or maybe more – may be needed to complete a cycle of analysis, intervention and evaluation, during which some or many factors are likely or certain to change. Thus, we define the research agenda for sustainable research as those activities that should be undertaken over the short- to mid-term time frame. A nominal time horizon of 20 years is suggested.

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² This paper represents an early and incomplete draft. It is designed to collect ideas from a diverse team, with the intention of leading to greater integration and synergy. At this point, these ideas remain incompletely refined.

1.3. Motivation

Water and disease-related issues represent major roadblocks on the path to sustainable development (Toepfer in Shiffries & Brewster 2004). As examples: 80% of illness and death in the developing world is water-related; half the world's hospital beds are occupied by people with water-related diseases; water-related illness (diarrhea and malaria alone) are by far the largest cause of under-five mortality (34%) in Africa in the 2000-03 period; preventable deaths from water-related disease are estimated to range up to 5 million people per year, most of them children; and infant mortality in low-income countries is more than 13 times higher than in wealthier countries. Roughly 1.1 billion people worldwide are without access to safe and reliable drinking water, and 2.4 billion people are without access to sanitation services. The Millennium Development Goals (MDG) adopted at the 2002 World Summit on Sustainable Development commit to halving the proportions without clean water or sanitation by the year 2015, with an estimated annual cost of \$30 billion, representing at least a doubling of current expenditures. (Also see footnote 4 for issues associated with the MDGs).

Many factors exacerbate the water crisis and represent stressors that increase the prevalence of water-associated diseases, e.g., diarrheal disease, malaria, dengue fever, schistosomiasis, hookworm, filariasis, and guinea worm. Key stressors include: (1) *Population growth and urbanization*, increasing population densities in areas that typically lack infrastructure including housing, water supply and sanitation, e.g., the sub-Saharan Africa (SSA) rate of urbanization was 4.6% between 1990 and 2001, while the slum population expanded by 4.5% annually; (2) *Climate variability and change* with pernicious impacts on human welfare due to the erosion of food production capacity, impacts on water availability and quality, and increased flooding and drought due to inadequate drainage and storage (in part due to the increased episodic nature of rainfall); (3) *Growing water demand* by cities, industry and agriculture, often with very limited opportunities for reservoir development or aquifer utilization; (4) *Increased vulnerability* of populations to disease, a result of crowding, poverty, inadequate education, resources, greater mobility, etc.; and (5) other factors including *changes in agriculture, housing, deforestation, species diversity and migration*, etc. These factors are interactive and synergistic in ways that have increased the vulnerability of many communities and the likelihood of adverse health outcomes.

1.4. Scope

This paper focuses on water-associated diseases, which are broken into two categories. First, we classify *water-borne infectious diseases* as those adverse health outcomes primarily associated with unsafe water (including ingestion and contact), poor sanitation, and inadequate hygiene—which are often linked to the lack of access to water. As noted earlier, infectious diarrhea makes the largest single contribution to the burden of water-borne disease. The second category is *water-associated vector-borne diseases*, which require water for the propagation of the vector, which transmit pathogenic microbes when taking a blood meal from a human. Prime examples of vector-borne diseases include malaria and dengue fever. Standing water can become a breeding ground for the mosquitoes that transmit these diseases. Different vectors have different water habitat requirements, which include both large and small water bodies and channel (e.g., lakes, lagoons, rivers, ditches, culverts, sewers), poorly drained soils, manmade containers (e.g., flower pots, tires), and natural containers (leaves, tree stumps).

It is important to address the spatial scales that are involved in the patterns of disease, in the water-associated factors that affect disease occurrence, as well as in the data available to understand the system. These range in scale from local to regional, continental and global. For example, disease incidence may be affected by such local factors as sewage outflows, regional factors such as reduced river flows or water quality, continental factors such as changes in precipitation patterns, and global factors such as climatic change and sea level rise. In a parallel manner, data can range from point data in the form of an individual water sample, to regional/continental data available from intensive field campaigns and/or remote sensing instruments, to global observations tracking the occurrence and impacts of climatic variations.

2. Characterizing “the problem” - a brief literature review

2.1. Brief history of approaches

The incidence of water associated diseases—including epidemics and pandemics of cholera, malaria, yellow fever—can be successfully countered with lessons learned 164 years ago from John Snow and Henry Whitehead, if not thousands of years ago with water supply, hygiene and sanitation practices of the Egyptians, Romans and

others. While the full paper will provide salient historical aspects, we next turn to a brief review of the nexus of water-disease-environment problems and discuss recent activity from several perspectives.

2.2. Current approaches

2.2.1 Social/cultural approaches

Anthropological studies of water in relation to disease and the environment have focused on several themes, including studies of *local understandings* of water-associated vector-borne diseases such as dengue fever (Kendall et al., 1991; Whiteford, 1997) and diarrheal diseases (Nichter, 1988); *conceptualizations of water*—as pure, unclean, scarce, or healing (Arar, 1998; Wellin 1955)—and its use in treatments such as oral rehydration therapy (ORT) for diarrheal diseases (Bentley, 1988; Burghart, 1996); water, sanitation, and the *political ecology/economy* of health care (Ecks, 2008; Obrist, 2004); and *health development/education and community participation* (Nichter, 1985; Yasumaro et al., 1998). For example, several anthropologists have noted distinctive local interpretations of water and the implications of these interpretations for public health initiatives. In an early (1955) study in Peru, Wellin found that instructions to boil water were largely ignored, often due to preferences for “uncooked” water. While this study was conducted among mainly those with little Western education, a later study by Nichter (1985; 1988) in Sri Lanka of individuals, many of whom had Western education, found a similar dynamic, although the specifics of their views about water differed. In a subsequent study of instructions to use “boiled water” in preparing ORT mixes, Burghart (1996) found that women in southern Nepal boiled water according to their own understandings of the effects of heat on water. Yet in Tanzania, Obrist (2004) found that for women who accepted public health messages about using clean water, difficulties involved in obtaining piped water led some to take a more pragmatic approach.

These themes also reflect theoretical shifts within medical anthropology: from *interpretive analyses of the cultural understandings* of illness and local classification of diseases; to *ethnoecological studies* which examine environmental, biological and social aspects of disease; and more recently, to the *political-economic approaches* of critical medical anthropology, which place public health care within a larger global nexus of power and knowledge (Whiteford and Whiteford, 2005). Using interpretive and ecological approaches, anthropologists have worked with public health practitioners to formulate and evaluate interventions, including examination of the national and international forces that have contributed to health inequalities.

2.2.2 Ecological approaches

Water-associated disease has strong links to ecological processes, some of which are depicted in Figure 1. Exploitation of the natural ecology has led to decreased food production resulting in famines and malnutrition. Changing climates and water flow patterns have led to increasingly variable patterns of water and its availability, which in turn has influenced the emergence and reemergence of infectious diseases, e.g., malaria, cholera and schistosomiasis.

In response to the increasing appreciation that emerging and re-emerging pathogens have their origin in environmental change, the field of *disease ecology* has grown in prominence. Indeed, research of water-related infectious disease has long used an ecological perspective to understand how best to control transmission. Research on vector-

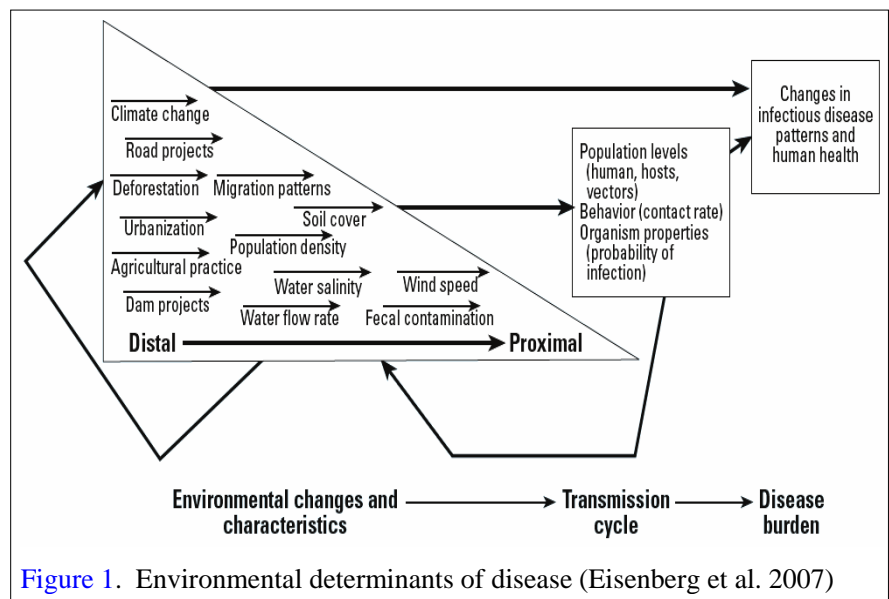


Figure 1. Environmental determinants of disease (Eisenberg et al. 2007)

borne diseases, e.g., malaria and yellow fever, has focused on mosquito ecology as a primary means to design interventions. Likewise, waterborne disease research has focused on *microbial ecology* to understand transmission and to develop appropriate interventions.

2.2.3 Engineering approaches

For millennium, physical and scientific principles have been used to engineer both the flow and quality of water for drinking, irrigation, recreation and other purposes, to handle solid and liquid wastes, to drain (and more recently) restore wetlands, and to provide for flood control. The *water-related infrastructure*, including water distribution systems (e.g., reservoirs, wells, treatment systems, pipelines) and drainage facilities (e.g., bridges, dams, channels, culverts, levees, storm sewers) was designed to provide a sufficient supply of healthy water, and to remove physical, chemical and biological (pathogen) contaminants that can adversely affect health and the environment. All of these aspects are intimately linked with water-related disease. Improvements in drinking water and sanitation systems have provided outstanding reductions in the risks of infectious disease. It is notable that *environmental engineering* (formerly called sanitary engineering) is multidisciplinary in order to address the environmental, economic, social and institutional elements of large scale water systems.

In developed countries, much of the civil engineering infrastructure is designed, built and operated according to prescriptive codes, practices, regulations, and standards, although there is a trend to use more flexible performance-oriented approaches. For example, water quality standards, which prescribe maximum levels of contaminants that can be present in drinking water, are designed to minimize adverse health impacts. For virus, bacteria and other waterborne pathogens, these standards impose treatment standards for their removal (by filtration) and inactivation (by disinfection), and protection of source waters. City or community water systems stay continuously pressurized to avoid infiltration of potentially contaminated water, and frequent water testing (e.g., heterotrophic plate counts, total coliforms, turbidity) ensure water quality by rapid detection and correction of problems. In North America and Europe, engineered water systems provide drinking water that is safe and abundant (at least for most individuals and in most areas). However, a large fraction (35 to 45%, EPA 1998) of rivers, streams, lakes, reservoirs and ponds are considered impaired, much of which is due to the presence of pathogens (along with other pollutants and stressors). Dams, impoundments, and other alterations to surface water systems have altered aquatic and sometimes terrestrial ecology, sometimes with human health consequences. Moreover, growing urban populations, the lack of integration of energy, water and waste systems, inadequate funding and repair of aging and failing infrastructure, and climate and other changes are leading to serious issues. As an example, a recent evaluation of US infrastructure (ASCE, 2005) gave the drinking water a grade of “D-” due to an annual shortfall of \$11 billion to replace aging facilities and comply with water quality standards; the wastewater system received the same grade due to untreated waste discharges, and the need to invest \$390 billion over the next 20 years to replace existing and construct new systems to meet increasing demand.

In developing countries, water distribution infrastructures range from the simplest of water containers to the complex systems mentioned above. Mostly the situation is problematic, and grossly deficient infrastructure and management systems for water flow and quality are intimately linked to the prevalence of infectious disease. Key problems include unreliable and unsustainable water supplies, water contamination, inadequate distribution, and high prices. Poor drainage and other problems lead to a proliferation of habitats suitable for mosquitoes and other vectors. These problems result from the stressors mentioned earlier including: urbanization and megacities that increasingly concentrate people without proper sanitation and lead to self-pollution of water resources; seasonal and annual variability of precipitation and stream flow; longer-term climatic changes that exacerbate acute water shortages and further increase pollution; financial and other resource limitations; lack of engineering expertise and management capability; and conflicts that lead to further infrastructure failings.

2.2.4 Economic/political

This section highlights a few key contributions on the extensive literature on the economic and political dimensions of the interface between water, health and the environment. As discussed, there has been a lack of water and sanitation improvements in the poorest regions of the world. While the reasons are complex, the literature places *economic and political factors* among the core causal elements. Especially salient is the lack of political will and resources among the government agencies charged with the water and sanitation tasks.

Chaplin (1999) ties the neglect of sanitary conditions of the poor in India's urban areas to the lack of pressure from the middle classes who have little confidence in local municipalities to deal with problems and alternatives that do not rely on local governments. In contrast, the poor have little or no voice, pay few taxes and are excluded from the resources and services the state provides. Sanitation is particularly unattractive given the cultural and socially sensitive nature of the subject and the broad range of faecophobic and faceophilic societies (Rosenquist, 2005). Nuna and Satterwaite (1999) point to other dimensions, e.g., the poor availability of data that illustrates the link between environmental conditions and poverty in urban areas with its associated health problems. Others tie the lack of political will to the lack of clear responsibility when competing agencies are responsible for sanitation and water (Njoh, 1999). Colt (2002) shows this was a clear impediment in dealing with the environmental and health challenges of a cholera outbreak in Madagascar in 1999.

Moreover, water-related projects have been heavily influenced by the health and environmental agendas of donors rather than by the priorities set by local governments. The early focus on water supply was broadened in the 1980s to include sanitation and health education, proclaimed the "United Nations International Drinking Water Supply and Sanitation Decade (1981–1990)". However, the agenda was also driven by the World Bank's adjustment policies that deemphasized government-related social projects while pushing market-driven options like the privatization of water supply. Donor project approaches continued to be phased out in the 1990s, and bilateral aid moved toward the pooling of resources to aid economies through sector-wide action programs (SWAPs). For example, the phasing out of the large scale Swedish International Development Cooperation Agency (SIDA) Health, Sanitation and Water project around Lake Victoria was driven by the decision of SIDA, not the central or local governments of Tanzania (Weeks et al., 2002). By 2005, there were real problems with the sustainability of the effort. Only 24% of the water user groups, which were organized by SIDA to run the projects as it was pulling out, had spare parts needed for maintenance. Fee collection mechanisms were weak with only 25% collecting water charges on a regular basis, and only 50% of water users willing to pay. Only a third of the water user groups (WUGs) had active financial plans and 15% had alternative sources of income to support their activities (Rautanen et al., 2006). Clearly, new ways must be explored to make these systems self-sustaining. One approach might be to tie them more systematically into micro-credit schemes or health related clubs that help institutionalize clean water and sanitation habits (Waterkeyn and Cairncross, 2005).

Priorities on health issues continue to be set by the global aid community. Interviews with officials in the Tanzanian National Institute for Medical Research in July, 2007 indicated that donor disease priorities were focusing on what they referred to as "ATMs" (AIDS, TB and malaria), rather than diarrhea which was the number two cause of morbidity and mortality in the country³. The remaining focus on water and sanitation was being shaped by the priorities set by the global aid community via the MDGs. As has been pointed out, these have been poorly conceptualized and raise the question of whether the MDGs are more an exercise in public relations rather than an avenue for transformation for poverty reduction.⁴ Thus, the political will continues to be circumscribed by the power asymmetry embedded in the international aid apparatus. Policy spaces need to be generated so that developing countries can set priorities that transcend political fashions from the developed world. A process that genuinely *empowers* the historically marginalized might be one important mechanism to change the nexus between water, the environment and health.

³ The interview by Howard Stein was part of a broader project on health and socioeconomic development in Mwanza undertaken by a group of U. of Michigan SPH and SNRE grad students during the summer of 2007.

⁴ For example, Goal 7, Target 11, the aim is to achieve significant improvement in the lives of 100 million slum dwellers by 2020. Indicator 31 is related to this Target and is focused on the proportion with access to improved sanitation. How do they measure sanitation? In Nairobi WHO/UNICEF statistics indicate 96% have access to sanitation and in Dar Es Salaam it is 98%. How is this possible? They do it through household surveys which ask questions like "Do you have access to a latrine". This says nothing about the quality or number of people using a latrine. In Nairobi with half the population in informal settlements there can be more than 200 people per open pit. In Dar, the pits frequently overflow in the rainy season flooding streets with raw sewage. Do they really have access to sanitation facilities (Satherwaite, 2003)?

2.3. Critique and themes

If nothing else, the enormous human toll from water-associated diseases illustrates the inadequacies of current practices and the urgent need for new analyses and approaches. This section highlights a few aspects of the problem.

2.3.1 Complexity & interactions

Although much of what we know about the relationship between water and health comes from the various disciplinary approaches discussed above, the reality is that the social, ecological, engineered, economic, and political domains consist of a *complex and highly interactive system of nonlinear dynamic processes* that as a whole act to influence water and health. This realization is growing in most disciplines, which are shifting to a more holistic, ecosystem-type mode. Meaningful representations of these interactions in either statistical analyses or physically-based simulation models seem daunting, not only in terms of accounting for the potentially high-dimensionality of the model but also the typical limitation in sample sizes, prohibiting investigation of higher order interactions. Another consequence of complexity is the problem of unintended consequences to environmental changes (also see below), resulting in short-term effects that are drastically different than long-term ones, or local effects that are drastically different than regional ones. These environmental effects, ranging from climate change to dislocation and war, can have far ranging impact on water and health.

2.3.2 Unanticipated consequences

The literature is rife with unanticipated consequences of projects and interventions, e.g., flood control programs that lead to flooding, flood control programs that reduce flooding but lead to increased risk of vector-borne diseases, creation of bore-wells aimed at providing water free of microbes that has high concentrations of arsenic, and use of improperly treated water to irrigate crops that then transmit infections. In the environmental impact assessment literature, problems associated with water supply and other projects are classified as *primary impacts* that are directly associated with the project (e.g., river diversions, displacement of communities, channelization), and much more difficult-to-predict and often ultimately more significant *secondary impacts* (e.g., siltation, ecological changes, parasite infestation, community restructuring). Several such impacts are illustrated in the case studies, following. Similarly, public health researchers might consider *direct* impacts of water-related health problems as those that affect pathogens or poisons in water or food that are ingested, and the *indirect* effects involving agriculture and nutrition, floods or drought, and other more remote (distal) water-associated factors that affect human well-being. All of these represent concerns involving sustainability in the context of water and health.

2.3.3 Lack of data and widely ranging and variable time and physical scales

A challenge in assessing impacts of water quality and quantify, interventions, and policies on the incidence of disease is the high cost associated with *environmental monitoring*. As a result, exhaustive information on relevant water-related parameters is never available, and information must be gleaned from multiple sparse datasets. An additional complication arises from the spatial and temporal scales of available data, which can be incompatible across data types, as well as incompatible with the scales relevant to epidemiology. For example, surface water quality data are typically available from a small number of point locations within a watershed, which are sampled only sporadically. Footnote 4 raises further issues regarding the quality and relevance of existing data. These data may be supplemented with remote sensing measurements of other parameters, e.g., water temperature, chlorophyll concentration, which are only secondarily related to the main parameters of interest. Innovative *data fusion* techniques are needed to quantify the information content of all available data sources with respect to the parameters that are needed in the context of risk assessment and mitigation policy planning.

2.3.4 Lack of sustainability

Many or most interventions have not had the lasting improvements desired, many operate only with donor support, and few would be considered sustainable. While there have been improvements in a number of health outcomes, generally, infectious diseases have not been eradicated.

Sustainability implies forever, but “things change,” thus the relevance and usefulness of an intervention approach—or a research agenda—is contextual. At the onset, we discussed the issue of time horizon. Some of these dynamics, which must be addressed in the systems framework, are highlighted in the following case studies.

2.4. Case study of water-associated disease

To illustrate a systems perspective, we present two short case studies. The first examines *causal linkages* between road development; water, sanitation and hygiene, and diarrheal disease. In 1996, the Ecuadorian government began a 100 km road construction project to link the southern Colombian border with the Ecuadorian coast. The road was completed in 2001, but secondary roads continued to be built, linking additional villages to the paved road. These roads provided a faster and cheaper mode of transportation compared with rivers, and led to major changes in the ecology and social structure of the region (Sierra, 1999). While there is evidence that road construction affects the incidence of vector-borne and sexually transmitted diseases (Birley, 1995), the impacts of environmental changes from road construction on diarrheal disease remain largely unexplored. There is strong evidence showing the relationship between the *proximal factors* of water quality, as well as sanitation and hygiene levels, on transmission of enteric pathogens. There are fewer studies demonstrating a relationship between *distal social factors*, such as crowding or general social infrastructure, and *distal ecological factors*, such as regional scale water patterns, with diarrheal disease (Curriero et al., 2001).

Road development represents a comparatively distal environmental change that can impact both ecological processes, such as deforestation, biodiversity and hydroecology, as well as social processes, such as migration, demographics, and infrastructure. Deforestation can cause major changes in watershed characteristics and potential local climate change, which can affect the transmission of enteric pathogens (Curriero et al., 2001). Perhaps more important than ecological processes, social processes, e.g., migration that is facilitated by roads, can increase the rate of pathogen introduction into a region. Road proximity affects short-term travel patterns, thereby resulting in continual reintroduction of new pathogen strains into communities. New communities created along roads and existing communities can rapidly increase in density. Changes in social structures of communities often create or are accompanied by inadequate infrastructure, which affects hygiene and sanitation levels, and in turn the likelihood of transmission of enteric pathogens. Roads also can increase flows of consumer goods, such as processed food, material goods and medicines, and may also provide communities with increased access to health care, health facilities, and health information. Figure 2 illustrates a mapping of the distal environmental change, due to road proximity, to the proximal environmental factors associated with water sanitation and hygiene that directly influences disease transmission. Often, it is unknown whether these relationships act to increase or decrease the disease burden.

To study environmental impacts of road development on diarrheal disease transmission in this Ecuadorian

landscape requires a design that examines and integrates processes at multiple spatial and temporal scales using regional, village-wide, individual, and molecular-level data, and system-level models to integrate these data. Epidemiological study designs are complemented by hydrology and water quality studies, remote sensing and geographic information system technologies, social network analysis, ethnography, and molecular strain typing to elucidate pathogen flows across the landscape. The scale and inherent dimensionality of the problem requires such a systems-based approach for examining the relationships between environmental, social, and biological changes, including, for example, the relationship between road access and infection.

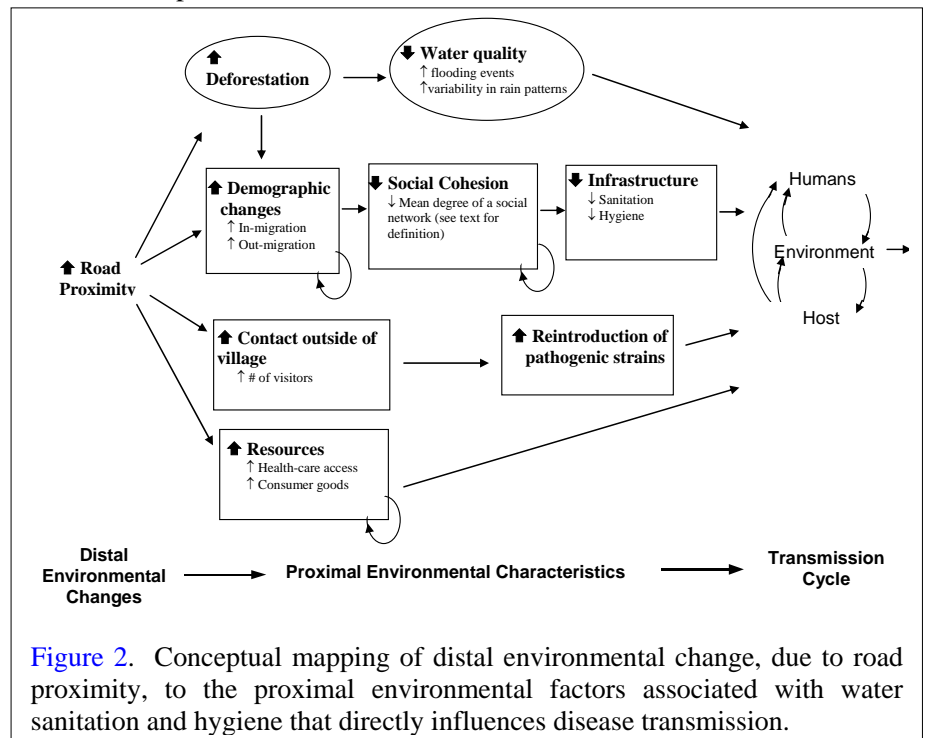


Figure 2. Conceptual mapping of distal environmental change, due to road proximity, to the proximal environmental factors associated with water sanitation and hygiene that directly influences disease transmission.

2.5. Case studies of vector-borne disease

Many important infectious diseases throughout the world are transmitted by arthropod vectors (mosquitoes, sand flies, black flies, ticks, etc.), and the abundance of each of these vectors is related in sometimes complex ways to water and the environment. As examples: Precipitation increases habitats for larval stages of mosquitoes, even occasionally reducing abundance in extreme events. Fast-flowing river water is critical for the larval stages of black flies, which passively filter-feed and capture oxygen while attached to objects on the river bottom. Seasonal rains produce temporary pools that determine hatching and development of certain mosquito species. Irrigation schemes can create standing water that permits abundant snail populations that are necessary for transmission of schistosomiasis. Winter precipitation in temperate regions influences survival and spring abundance of ground-dwelling ticks. Tropical deforestation and agricultural practices can permit sunlight to reach newly created pools of water that support development of larvae of various vector species. Dams alter the flow, depth and nutrient content of rivers, and can either increase or decrease abundance of various vectors.

An example of the complex effects of dams occurred in 1987 along the Senegal River, which is the boundary between northern Senegal and southern Mauritania. The Diama Dam, at the mouth of the river near the Atlantic Ocean, was designed to prevent saltwater incursion during the long dry season when water flow was diminished. In addition, it was expected that the more stable water availability would allow rice production along the fertile river banks. The dam effectively controlled water flow and encouraged people to move to the areas near the river in search of work. However, the vast areas where shallow water accumulated, especially during the rainy season, created previously non-existent breeding sites required by *Aedes* mosquito species. Human population density increased considerably, but the herding agriculturalists who moved to the area also brought with them tens of thousands of sheep and goats. Rift Valley Fever (RVF) is a viral disease that occurs throughout most of sub-Saharan Africa, and is transmitted by various mosquitoes, particularly in the *Aedes* genus. Previous studies had demonstrated low-level transmission in this area (southern Mauritania/northern Senegal). The normal transmission cycle of the RVF virus involves domestic ungulates (cattle, sheep, goats, camels) which serve as the natural reservoirs that infect the mosquito vectors, which then in turn infect other ungulates. RVF can be mild or inapparent in adult animals, but is highly fatal to young animals and causes abortion in pregnant animals. However, the mosquito vectors do not feed exclusively on these domestic ungulates, and can bite people, particularly those living nearby these animals. People, thereby, can be infected by RVF virus, producing mild to fatal human disease. Despite the desirable development goals of the Diama Dam project, it unintentionally produced environmental changes that brought together many susceptible people, large herds of domestic ungulates, and highly abundant *Aedes* mosquito vectors. The result was an epidemic of RVF in a large area around the Senegal river that produced morbidity and mortality in both animals and humans. One estimate indicated that thousands of animals and at least 200 people died as the result of the epidemic. This is but one of many examples of how environmental change and water interact to produce health risks.

3. Framing the issues

3.1. Lessons learned and what do we need to correct the deficiencies?

This (incomplete) review shows that analysis and interventions require designs that consider the ecologic and social context in which they are implemented, and thus necessitate a multidisciplinary and systems approach that considers the ecological, social/cultural, economic, and political realities. We recognize that many of these disciplines have made contributions to water and health. For example:

- From environmental science and ecology, projects like the UNESCO's Ecohydrology Program consider the functional interrelations between hydrology, aquatic ecosystem processes and their biota, with the objective of using ecological and hydrological processes to enhance the overall integrity of aquatic ecosystems in the face of human-mediated alterations (Zalewski 2006).
- From public health and disease ecology, individual-level and environment–disease models that capture many of the ecologic and social factors that affect disease burden – including environmental changes, ecological and social factors, and transmission dynamics of infectious pathogens – have rapidly evolved and are beginning to inform policy (Eisenberg et al., 2007).
- From social science, we are now beginning to consider and manipulate adaptive capacity – including that of

social/governance, engineered, and ecological systems – to accommodate climate variability and other stressors. We also have growing understanding of the beliefs and actions of individuals that influence or determine the responses of communities, health personnel, and government officials with respect to water-related diseases and water resources, and the need to broadly frame the problem boundaries – and solutions – to encompass ecologic, hydrological, socio-political processes in community with responses that integrate water, sanitation and hygiene intervention strategies (Lemos et al., 2007).

3.2. *Essential and interacting frames*

There are a many prerequisites for relevant research that addresses the interface between water, health and the environment, and that can lead to successful analysis and sustainable interventions. Multidisciplinary teaming and a *systems framework* are suggested that can capture these complex dynamics by conceptualizing the interconnectivity of different processes at *multiple temporal and spatial scales*.

- Social/cultural – Factors that impede or improve access to safe drinking water, improved sanitation and other actions affecting disease transmission, including individual beliefs, possible vulnerabilities, and incompatibilities of groups/communities within the population with current policy initiatives.
- Ecological – Causal transmission pathways (water, sanitation, hygiene, vectors), as well as water quality & disease forecasting. [Figure 2](#) (shown earlier) illustrates *environmental determinants of disease*, grouped into distal and proximal causes, and important *feedback loops*.
- Engineering – The science and technology to design and deliver safe water, sanitation and hygiene and provide adequate drainage, as well as forecasting, operations, and management skill sets needed optimize and maintain systems for a suitably long period.
- Economic/Political/Policy/Management – Actions/interests/instruments of individuals and organizations including corporations and governments, the role of institutions and markets shaping these actions and interests, the production and distribution of goods and services, and capacity-building that may affect the sustainability of interventions and the susceptibility to water-associated disease.
- Evaluation – Modern statistical data mining and variable selection techniques using tree-based searches through the model space (Breiman, 2001) may be useful tools given the complexity of water associated disease models. Latent variable models under a structural equation framework may also provide an option for looking into the causal pathways leading to disease transmission and for relating the interacting factors that contribute to disease transmission. As noted above, the study of water-associated diseases will involve various spatio-temporal covariates with the spatial variables often measured at different scales and with a nested interface. The effects of spatial scale and different levels of aggregation on disease-mapping are well-known. There are several approaches to handle multiscale spatial models, including wavelet based methods and spatial process models. A hierarchical or multilevel modeling framework is natural in such situations, and Bayesian inferential methods have become popular choices from both theoretical and practical perspectives (Banerjee, Carlin, Gelfand, 2004; Louie and Kolaczyk, 2006).

4. **Setting the research agenda.**

4.1. *Systems framework*

The proposed systems framework provides opportunities to address important issues and to foster multidisciplinary research. To develop successful and sustainable strategies, we should consider a wide variety of disciplines as noted earlier, each providing crucial input. Thus, the framework should encompass and link the interacting subframes involved in water associated diseases, such as social factors and transmission dynamics, and it should be linked to the stressors described earlier, e.g., urbanization and climate change. Informed decisions can only be made by integrating across disciplines and the science-community-policy nexus ([Figure 3](#) on the following page). We suggest that a systems perspective on water and health provides the most amenable framework for the challenge of improving public health with respect to infectious disease.

The framework will encompass multiple time and spatial scales. It is inherently highly multidisciplinary, e.g., bridging scientific mechanisms and stressors, individual and social systems, health care systems, and economic and policy institutions. The proposed systems framework, and indeed, the overall strategy, is driven by the need to

improve public health by promoting means to address water-associated diseases, vectors and stressors, with *health outcomes being the principal indicators*. It should encompass elements that affect the appropriateness, robustness, and sustainability of interventions vis-à-vis multiple stressors and existing constraints and opportunities, including, among others: climate variability and change, water resource systems; infrastructure; education, culture, behavior and resources; technology/interventions; health care delivery systems; implementation and evaluation of interventions; surveillance; income support and equity.

4.2. Opportunities

As the demand and uses of water increase worldwide, new forms of management are emerging that promise to increase the capacity of existing water systems to meet demands while responding to growing stresses on water availability (addressing both quantity and quality needs). A dominant and emerging paradigm is Integrated Water Management (IWM), which is informed by three main principles:

- The *ecological principle* for integrating water management around river basins, rather than independent institutional users, with the integration of land and water governance for environmental reasons.
- The *institutional principle* for basing resource management on dialogue among all stakeholders through transparent and accountable institutions governed by the principle of subsidiarity—the devolution of authority to the lowest appropriate level, from user groups at the base to local government and river basin bodies.
- The *economic principle* for making more use of incentives and market-based principles to improve the efficiency of water as an increasingly scarce resource (UNEP, 2006)

In facing the challenges of higher demand and resources increasingly depleted by overuse and environmental change, water managers have struggled with the question of how to continue to meet demand in a way that guarantees future supplies. While different water management regimes adopt different ways to “value” water so as to encourage efficient and sustainable use, the delicate balance between the implementation of regulation and compliance needs better understanding. The new paradigm for water management—heavily promoted by agencies such as the World Bank and the United Nations—prescribes *decentralization, societal participation, integration and sustainable use* as desirable elements to include in reforms. In principle, while most experts and policymakers would be hard pressed to find fault with the new paradigm, its implementation has proven complex (Formiga et al., 2007; Wester et al., 2004).

One particularly contested aspect of the IWP paradigm is the reframing of water as a public good with economic value, that is, a commodity for which users should pay. While tariffs have long existed for piped water and waste water, the new reforms advocate bulk water charges in different formats, ranging from cost recovery of operation and management (O&M) for bulk water supply to fully private water rights markets.⁵ This is a crucial departure from the public perception in many countries that water is a basic right—a ‘gift from God’ for which consumers should not have to pay. The rationale for bulk water charges is that, by having to pay, water users will be induced to utilize water efficiently, i.e., conserve it. Such water charges may have important implications in consumption that in turn may affect health-related issues. For example, stakeholders in the Paraíba do Sul river basin in Brazil elected to include charges on pollution discharges. Although the charges do not meet the true costs

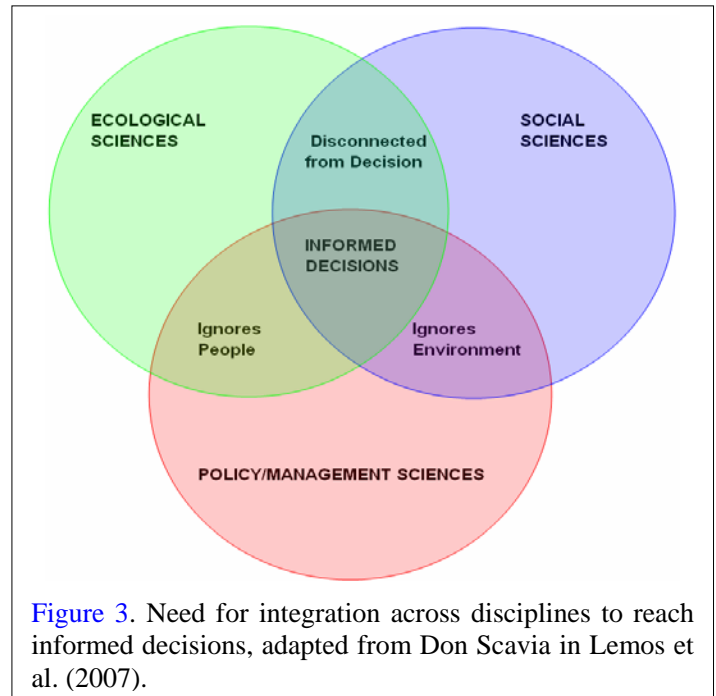


Figure 3. Need for integration across disciplines to reach informed decisions, adapted from Don Scavia in Lemos et al. (2007).

⁵ See, for instance, Asad, Azevedo, Kemper and Simpson (1999) who make an important distinction between the price of water as a resource and the price of providing the resource to users, i.e., the water supply and sanitation services.

of water environmental services, they have provided an incentive for sanitation companies to improve their water treatment rates (Formiga et al., 2007).

The IWM framework has applications in many significant and cross-cutting activities aimed at water supply, water quantity and human health. This framework might be applied to any of the opportunities (in part from Schiffries and Brewster, 2004):

- Multibarrier protection in a watershed and groundwater basin approach that will integrate environmental and public health issues.
- Enhanced monitoring, surveillance, assessment, research, and risk assessment.
- Cost-effective methods to significantly improve drinking water quality and reduce disease transmission.
- Education efforts targeted to all levels of society, including local communities and key local constituencies, including women regarding source water protection and natural water purification.
- Research on local knowledge about water, hygiene, and water-borne diseases.
- Programs for developing low cost hygiene technologies.
- Research and development efforts to develop technologies and practices to reduce pollutants and improve source water protection.
- Enhancement of adaptive capacity of human and water systems.
- Enhanced public participation, communication, policy making, as well as an analysis of political factors which inhibit this participation.
- Understanding and addressing tensions between local/individual/community views on water, health, and the environment and epidemiological/economic/environmental views (Sen, 2006).
- Integrated assessment, including dams (McCully, 2001).

5. Conclusions

This review paper has described the need for fundamental changes in water and sanitation policy, management, and use in order to meet basic human and ecological needs for water, improve water quality, eliminate overdraft of groundwater, reduce the risks of political conflict over shared water, and prevent the transmission of infectious disease. There are many unanswered questions, but a key problem is our poor understanding of how to design, implement and evaluate interventions that will be appropriate and sustainable over long periods. Here we suggest a research agenda that utilizes a systems-oriented multidisciplinary approach with a health outcomes focus, and one that encompasses the social/cultural, ecological, engineering, economic/policy, and policy/management frames. For the University of Michigan to promote and excel in research using IWM or other systems-oriented framework, we need to integrate our unique areas of expertise and institutional capabilities, promote partnerships including both traditional and non-traditional partners, encourage innovation and multidisciplinary work, demonstrate synergies, and obtain resources. We welcome your feedback.

6. References

- Anand, Sudhir, Fabienne Peter, Amartya Sen, eds. 2004. Public Health, Ethics and Equity. Oxford University Press, New York.
- Arar, Nedal H. 1998. Cultural responses to water shortage among Palestinians in Jordan: The water crisis and its impact on child health. *Human Org* 57, 3, 284-91.
- Asad, M; L.G. Azevedo; K.E. Kemper; L.D. Simpson, Management of water resources: Bulk water pricing in Brazil. Technical Paper No. 432, World Bank, Washington, D.C.
- Bentley, M.E. 1988. The household management of childhood diarrhea in rural North India. *Soc Sci & Med* 27, 1, 75-85.
- Birley, Martin H, 1995. The health impact assessment of development projects. HMSO, London.
- Burghart, Richard. 1996. The purity of water at hospital and at home as a problem of intercultural understanding. *Med Anthro Quar*, 10, 1, 63-74.
- Chaplin, Susan, 1999. Cities, Sewers and Poverty: India's Politics of Sanitation. *Environment and Urbanization*, 11, 1.
- Colt, Katherine, 2002. The Mismatch Between Politics, Aid and Environmental Health with Particular Reference to Cholera in Madagascar. *Environ and Urbanization*, 14, 1.

- Coreil, Jeannine, and J. Dennis Mull. 1988. Introduction: Anthropological studies of diarrheal illness. *Soc Sci Med*, 27, 1, 1-3.
- Curriero F.C., JA Patz, JB Rose, S Lele, 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *Am J Public Health*, 91, 8, 1195-1199.
- Ecks, Stefan. 2004. Bodily sovereignty as political sovereignty: "Self-care" in Kolkata, India. *Anthro and Med*, 11, 1, 75-89.
- Eisenberg J, Desai MA, Levy K, Bates SJ, Liang S, Naumoff K, Scott JC. 2007. Environmental Determinants of Infectious Disease: A Framework for Tracking Causal Links and Guiding Public Health Research. *Env Health Persp*. 115, 1216-23.
- Ennis-McMillan, Michael C. 2001. Suffering from water: Social origins of bodily distress in a Mexican community. *Med Anthro Quart*, 15, 3, 368-390.
- Formiga-Johnson, Rosa Maria, Lori Kumlerb, Maria Carmen Lemos, 2007. The politics of bulk water pricing in Brazil: lessons from the Paraíba do Sul basin. *Water Policy*, 9, 1, 87-104.
- Gibbal JM. 1994. Genii of the River Niger. Chicago, University of Chicago Press.
- Hardiman. 2006. Healing Bodies, Saving Souls: Medical Missions in Asia and Africa (edited collection with introductory essay by D.H.), Rodopi, Amsterdam and New York.
- Harms R. 1999. Games Against Nature: an ecocultural history of the Nunu of equatorial Africa. Cambridge University Press; New Ed edition.
- Kendall, Carl, Patricia Hudelson, Elli Leontsini, Peter Winch, Linda Lloyd, and Fernando Cruz. 1991. Urbanization, dengue, and the health transition: Anthropological contributions to international health. *Med Anthro Quart* (NS) 5, 3, 257-268.
- Kunitz, Stephen. 2006. The Health of Populations: General Theories and Particular Realities. New York: Oxford University Press.
- Lemos MC, Recharte J, Chang CT. 2007. Integration of Social Science in the UNESCO's Ecohydrology Programme. A report submitted by the UNESCO's Ecohydrology Programme Social Science Task Force, April.
- Mccully P. 2001. Silenced Rivers, Zed Books; Updated edition.
- Nichter, Mark. 1985. Drink boiled water: A cultural analysis of a health education message. *Soc Sci & Med*, 21, 667-669.
- Nichter, Mark. 1988. From Aralu to ORS: Sinhalese perceptions of digestion, diarrhea, and dehydration. *Soc Sci & Med*, 27, 1, 39-52.
- Njoh, Ambe. 1999. The state, urban development and policy and society in Cameroon. *Cities*, 16, 2, April.
- Nunan, Fiona and David Satterthwaite. 1999. The Urban Environment, School of Public Policy, University of Birmingham.
- Obrist, Brigit. 2004. Medicalization and morality in a weak state: Health, hygiene and water in Dar es Salaam, Tanzania. *Anthro and Med*, 11, 1, 43-57.
- Rautanen, Sanna-Leena, Osmo Seppälä and Tauno Skyttä (2006) Health through Sanitation and Water Programme(HESAWA), Tanzania: Ex-post (Retrospective) Evaluation Study Report No. 06/36, Department of Natural Resources and Environment (Stockholm: SIDA)
- Rosenquist, Louise. 2005. A psychosocial analysis of the human-sanitation nexus. *J Environ Psych*, 25, 3.
- Satterthwaite, David. 2003. The Millennium Development Goals and urban poverty reduction: Great expectations and nonsense statistics. *Environ and Urban*, 15, 2.
- Schiffries C, Brewster A, 2004. Water For A Sustainable And Secure Future - A Report of the Fourth National Conference on Science, Policy and the Environment, January 29-30, Washington, DC.
- Sheridan TE, 1988. Where the dove calls-the political ecology of a peasant corporate community in northwestern Mexico, University of Arizona Press.
- Sierra, R., 1999. Traditional resource-use systems and tropical deforestation in a multi-ethnic region in North-west Ecuador. *Environ Conser*, 26, 2, 136-145.
- Treitler, Inga and Douglas Midgett. 2007. It's about water: Anthropological perspectives on water and policy. *Human Org*, 66, 2, 140-149.
- US EPA, EPA National Water Quality Inventory: 1998 Report to Congress, Washington, DC.
- UNDP 2006: 170. Maria?
- Waterkeyn, Juliet and Sandy Cairncross. 2005. Creating demand for sanitation and hygiene through community health clubs: A cost-effective intervention in two districts in Zimbabwe. *Soc Sci & Med*, 61.
- Weeks, John, David Anderson, Chris Cramer, Alemayehu Geda, Degol Hailu, G., Frank Muhereza, Mateo Rizzo, M., Eric Ronge, and Howard Stein. 2003. Supporting Ownership: Swedish Development Cooperation with Kenya, Tanzania and Uganda Stockholm: SIDA, Volume 2.
- Wellin, Edward. 1955. Water boiling in a Peruvian town. In: Health, Culture, and Community: Case Studies of Public Reactions to Health Programs, B. Paul, ed. New York: Russell Sage Foundation, pp. 71-103.
- Wester et al. 2004, MARIA?
- Whiteford, Linda M. 1997. The ethnoecology of dengue fever. *Med Anthro Quart*, 11, 202-223.
- Whiteford, Linda M., and Scott Whiteford, eds. 2005. Globalization, Water, and Health: Resource Management in Times of Scarcity. Santa Fe: School of American Research Advanced Seminar Series.
- Yasumaro, Sueli, Maria Silva, Maria Andrighetti, et al. 1998. Community involvement in a dengue prevention projection in Marília, São Paulo, Brazil. *Human Org*, 7, 2, 209-214.
- Zalewski M. 2006. "Flood pulses and river ecosystem robustness." *Frontiers in Flood Research/ Le Point de la Recherche sur Les Crues*. International Association of Hydrological Sciences (IAHS) Publication No. 305:143-154.