Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Conference White Papers and Abstracts

Faculty White Papers and Student Abstracts from the Graham Institute's 2008 Annual Conference

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Table of Contents

Preface

Introduction

I. Faculty White Papers

Human Health

Sustainable Control of Water-Related Infectious Diseases: A Review and Proposal for Interdisciplinary Health-Based Systems Research
S. Batterman, J. Eisenberg, R. Hardin, M. E. Kruk, M. Carmen Lemos, A. Michalak, B. Mukherjee, E. Renne, H. Stein, C. Watkins, and M. L. Wilson………………………………………………...Conference Paper A

Spread of Antibiotic Resistance in the Water Environment Impacts on Human Health
O. Jolliet, P. Adriaens, J. Eisenberg, B. Foxman, K. Hayes, J. LiPuma, N. Love, C.F. Marrs, M. Milbrath, C. Picioreanu, L. Raskin, R. Riolo, C.P. Simon, B.F. Smets, M.L. Wilson, and C. Xi………………………………………………………….Conference Paper B

Development of a Sustainable Water Resource Policy For Bolivia, South America
C. Poulsen, T. Ehlers, M. C. Lemos, and A. Steiner…………………………………………………………….Conference Paper C

Emerging Contaminants in Rural Water Systems: Establishing the Research Needs
Xagoraraki, T. Harrigan, H. Li, T. Voice, and J. Rose……………………………………...…………..……..Conference Paper D

Aquatic Ecosystems and Energy

Cyberinfrastructure for Risk Forecasting and Communication: Application to the Great Lakes Observatory System
P. Adriaens, A. Michalak, N. Love, M. Liu, E. Parker, T. Finholt, J. DePinto, T. Slawecki, S. Ruberg, D. Schwab
……...Conference Paper E

Complex Interactions among Land, Water, and Harmful Algal Blooms
J. Dyble, M. Evans, D. Hyndman, E. Litchman, M. Phanikumar, O. Sarnelle, R. Stevenson……………………..Conference Paper F

Impact of Watershed Changes on Estuarine Morphology and Aquatic Life
N. Katapodes, V. Ivanov, P. Webb………………………………………………………..Conference Paper G

The Energy-Water Nexus: Climate Change Impacts on Energy Production and Water Allocation
C. Lastoskie, P. Adriaens, J. Wolfe, L. Weintraub, R. Rood, G. Helfand, A. Demond, T. Olson,
D. Scavia …………………………………………………………………………………………………......….Conference Paper H

A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater
J . Guest, S. Skerlos, J. Barnard, M. B. Beck, G. Daigger, H. Hilger, S. Jackson, K. Karvazy, L. Kelly, L. MacPherson, J. Mihelcic, A. Pramanik, L. Raskin, M. Van Loosdrecht, F. Yeh, N. Love…………………………………………………...Conference Paper I

Harmful Algal Blooms in the Great Lakes
C. Xi, W. Guo, K. Bush, J. Lehman, J. Nriagu, D. Sherman……………………………………...……………Conference Paper J

II. Student Abstracts

Anaerobic Membrane Bioreactors for Treatment of Domestic Wastewater: Fouling and Fouling Control
T. Borrell, C. Donahue, J. C. Cho, E. Morgenroth, J. Kim, L. Raskin, S. Skerlos……………………………...Student Abstract A

Applying Geospatial Decision Support Tools to Assess Water Quality and Human Health Risk in the Great Lakes Region
R. Shuchman, G. Meadows, C. Brooks, L. Liversedge, B. Koziol, C.Hatt, C. Ide, C. Roussi………………… …Student Abstract B

Detection of Ammonia-oxidizing Bacteria and Archaea in a Recirculating Shrimp Aquaculture System Biofilter
M. Brown, A. Briones, J. Diana, L. Raskin…..………..……... ……………………………………………….Student Abstract C

FeS-Coated Sand for Removal of Arsenic (III) under Anaerobic Conditions Coating Method and Characterization
Y-S. Han, T. Gallegos, A. Demond, K. Hayes ………..……... ……………………………………………..Student Abstract D

Biological Mediated Simultaneous Removal of Arsenic, Perchlorate, and Nitrate from Drinking Water
G. Upadhyaya, K. Hayes, L. Raskin …………………………………………………………..………………Student Abstract E

Microorganisms Responsible for Anaerobic Biodegradation of Benzene under Nitrate-Reducing Conditions
R. Gitiafroz, C. Washer, M. Nandi, A. Ulrich, L. Raskin, E. Edwards…………………………………………… Student Abstract F

Remediation of Groundwater with Iron Sulfide and Zero-Valent Iron: Interaction with Calcium Carbonate and Implications for System Longevity
A. Henderson, A. Demond ………………………………….....……………………………………...…… Student Abstract G

Development of a Spectrophotometry-Based Method for Evaluating Disinfection Kinetics
D. Holder, D. Dai, D. Berry, L. Williams, L. Raskin, C. Xi ……………………………………………………. Student Abstract H

Comparative Assessment of Waterborne Toxic Impacts on Aquatic Ecosystems and Human Health Using the USEtox Model
O. Jolliet……………………...……………………………………………………………………………. Student Abstract I

Environmental Fate of Brominated Flame Retardants in Lake Huron and Lake Erie Sediments and Aquatic Organisms
D-H. Lim, C. Lastoskie ………………………………………………………………………………………Student Abstract J

Describing a Chlorinated Phenol-Dependent Antibiotic Resistance Mechanism in the Opportunistic Pathogen Pseudomonas aeruginosa: Consequences for the Water/Human Health Interface
J. Muller, A. Stevens, N. Love……………………………………………………………………………….Student Abstract K

Neglected Toxic Metals in the Great Lakes
J. Nriagu ……………………………………………………………….………………………………….Student Abstract L

Arsenic Uptake and Release on Sulfide Nanoparticles
D. Renock, T. Gallegos, S. Utsunomiya, K. Hayes, R. Ewing, U. Becker……………………………………..…..Student Abstract M

Fate Factors and Emission Flux Estimates for Emerging Contaminants in SurfaceWater
H. Trinh……………………………………………………………...……………………... ………………….Student Abstract N

Microbial Community Analysis of Biofilms in Drinking Water Distribution Systems
L. Williams, D. Berry, D. Dai, D. Holder, C. Xi, L. Raskin…………...…………………………………………Student Abstract O

Effects of Culture Conditions on Mixed Species Biofilm Development
D. Dai, D. Holder, D. Berry, L. Williams, L. Raskin, C. Xi,.....…………………………...………………………… ..Student Abstract P

Profile of Antibiotic Resistance of *Acinetobacter* spp. and Antibiotic Resistant Genes in the Wastewater Treatment Process and Its Receiving Water
Y. Zhang, C. Marrs, C. Simon, C. Xi ……………………………….. ………………………………………..Student Abstract Q

Survival Mechanisms of Bacterial Pathogens in Biofilms in Drinking Water Distribution System
C. Xi, D. Holder, D. Berry, D. Dai, L. Williams, L. Raskin……………………………………………………Student Abstract R

Effects of Phosphorus Addition on Microbial Communities in Biologically Active Carbon Reactors
W. Yuen, X. Li, J. Brown, E. Morgenroth, L. Raskin……………………………………………………………….. Student Abstract S

GRAHAM ENVIRONMENTAL SUSTAINABILITY INSTITUTE

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Preface

The Graham Environmental Sustainability Institute brings together and leverages University of Michigan (U-M) strengths to pursue solutions to complex sustainability challenges. While the bulk of our efforts focus on student-facing educational opportunities and faculty-oriented research and assessment programs, we recognize the need to reach beyond the U-M community to achieve meaningful impacts. In support of our broader outreach mission, the Graham Institute organizes and hosts annual interdisciplinary conferences focused on important sustainability issues. We do so not only to facilitate new knowledge and understanding on critical topics, but also to foster a truly interactive dialog among different disciplines and stakeholders, because solving complex sustainability problems requires embracing a wide range of perspectives and approaches. By convening researchers from multiple disciplines, leaders from non-profit organizations, industry experts, community members, government officials, and others, our annual conferences serve as valuable catalysts. I hope that the following pages – highlighting ideas developed at our 2008 conference on water and health– prove helpful to you. We invite you to consider joining us for future conferences

Donald

Donald Scavia, Ph.D.
Graham Family Professor of Environmental Sustainability
Professor of Natural Resources and Environment
Professor of Civil and Environmental Engineering
Director, Graham Environmental Sustainability Institute

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Introduction

On March 26 and 27, 2008, the Graham Environmental Sustainability Institute organized and sponsored a major conference, "Water, Health, and the Environment: Establishing the Research Agenda" to identify research and assessment needs and opportunities in support of regional, national, and international sustainable water-human systems. As it is well-known, and increasingly becoming apparent to policy makers and the general public, the relationships between water and human health are becoming more complex and the problems associated with them more urgent. On a daily basis, newspapers document issues ranging from beach closures due to combined sewer overflows, persistent organic pollutants in drinking water, increasing surface and ground water pollution from industrial and agricultural practices, intensified demand, competition, and conflict for water amongst different communities, as well as concerns how global warming will affect future water availability.

These and other issues span multiple spatial and temporal scales, and solutions require interdisciplinary approaches. To foster discussion and collaboration between traditional academic disciplines (e.g., engineering, public health, natural resources, etc.), as well with industry and governmental agencies, the Graham Institute sponsored this conference to create a forum whereby these diverse groups could craft intensive, interdisciplinary responses necessary to successfully address these problems.

Over 150 people attended, including participants from Europe, Canada, as well as across the United States. Representatives from governmental and non-governmental agencies engaged academic and industrial researchers to discuss how best to integrate engineering, environmental sciences, public health, and public policy to develop systems-wide approaches that effectively address the complex, multi-faceted, and inter-related water-health issues we face. As a result of these discussions, several of the white papers presented here have been published in prestigious peer-reviewed journals and I am proud to say that collaborations are ongoing between conference participants.

I would like to close by thanking the numerous sponsors that provided financial support: NSF International, Shell Group and the following groups at The University of Michigan - the College of Engineering, Department of Civil and Environmental Engineering, School of Public Health, Environmental Law and Public Policy Program, and the Erb Institute for Global Sustainable Enterprise. With their support, we have started the long, yet crucial process to develop interdisciplinary approaches that create sustainable water systems that protect and provide for human and environmental health.

Sincerely,

Jeremy D. Semrau PhD
Associate Professor, Civil & Environmental Engineering
Associate Professor, School of Natural Resources and Environment
Head, Conference Organizing Committee, Graham Environmental Sustainability Institute

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Faculty
White Papers:

Human Health

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Sustainable Control of Water-Related Infectious Diseases: A Review and Proposal for Interdisciplinary Health-Based Systems Research

Stuart Batterman, Joseph Eisenberg, Mark Wilson, Elisha Renne, Rebecca Hardin, Maria Carmen Lemos, Lutgarde Raskin, Anna M. Michalak, Howard Stein, Bhramar Mukherjee

Water and disease-related issues represent major roadblocks on the path to sustainable development. 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. Eighty percent of illness and death in the developing world is water-related.

Many factors exacerbate the water crisis and represent stressors that increase the prevalence of water-associated diseases. Fundamental changes in water and sanitation policy, management, and use are needed. A key problem, addressed in the white paper, is that our understanding of how to design and implement appropriate interventions that will be sustainable over long periods of time remains poor.

The white paper presented at the conference has since been revised and published in the July 2009 edition of the journal Environmental Health Perspectives. The published version of this paper is presented on the following pages of this document.

Sustainable Control of Water-Related Infectious Diseases: A Review and Proposal for Interdisciplinary Health-Based Systems Research

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Objective: Even when initially successful, many interventions aimed at reducing the toll of water-related infectious disease have not been sustainable over longer periods of time. Here we review historical practices in water-related infectious disease research and propose an interdisciplinary public health–oriented systems approach to research and intervention design.

Data sources: On the basis of the literature and the authors' experiences, we summarize contributions from key disciplines and identify common problems and trends. Practices in developing countries, where the disease burden is the most severe, are emphasized.

Data extraction: We define waterborne and water-associated vectorborne diseases and identify disciplinary themes and conceptual needs by drawing from ecologic, anthropologic, engineering, political/economic, and public health fields. A case study examines one of the classes of water-related infectious disease.

Data synthesis: The limited success in designing sustainable interventions is attributable to factors that include the complexity and interactions among the social, ecologic, engineering, political/economic, and public health domains; incomplete data; a lack of relevant indicators; and most important, an inadequate understanding of the proximal and distal factors that cause water-related infectious disease. Fundamental change is needed for research on water-related infectious diseases, and we advocate a systems approach framework using an ongoing evidence-based health outcomes focus with an extended time horizon. The examples and case study in the review show many opportunities for interdisciplinary collaborations, data fusion techniques, and other advances.

Conclusions: The proposed framework will facilitate research by addressing the complexity and divergent scales of problems and by engaging scientists in the disciplines needed to tackle these difficult problems. Such research can enhance the prevention and control of water-related infectious diseases in a manner that is sustainable and focused on public health outcomes.

Key words: infectious disease, interdisciplinary, malaria, research, systems approach, water. *Environ Health Perspect* 117:1023–1032 (2009). doi:10.1289/ehp.0800423 available via *http://dx.doi.org/* [Online 17 April 2009]

Why have interventions against infectious diseases often proven to be less successful than anticipated? Even when initially successful, many are not sustainable over longer periods of time. During the past 30 or 40 years, we have observed many and diverse examples where infectious disease reduction efforts have failed to meet expectations, with diseases reemerging to preintervention levels or worse. Dengue fever, for example, was eliminated from the Americas for many years only to reemerge with a more virulent form of the disease, including dengue hemorrhagic fever. Schistosomiasis and malaria both have shown that they can quickly reemerge after intervention efforts are loosened. Waterborne zoonotic agents such as *Escherichia coli* O157:H7, *Campylobacter jejuni*, and *Cryptosporidium parvum* have emerged in recent years (Cotruvo et al. 2004). Many other water-associated human pathogens, including *Vibrio cholerae* O139, hepatitis viruses, cyclospora, microsporidia, *Yersinia enterocolitica*, and environmental bacteria (e.g., *Legionella pneumophila*), have been associated with waterborne illnesses over the past few decades (Sharma et al. 2003). Thus, sustainability has become an important criterion for gauging the success of disease reduction efforts.

The nature and impact of water-related infectious diseases are mediated by both ecologic and socioeconomic processes [Eisenberg et al. 2007; United Nations Environment Programme (UNEP) 2007]. Although the complexity of these processes is being increasingly realized, current research and management approaches include only a subset of the considerations and interdisciplinary exchanges needed to approach and realize sustainable solutions. These issues represent major gaps that cannot be resolved by simply boosting funding for water supply and sanitation facilities. The need for new approaches to address the challenges of water-related infectious disease research motivates this review and assessment. In particular, we argue that one problem with interventions to reduce infectious disease incidence and emergence, particularly those that are water-associated, is that efforts are generally directed against proximal causes of infection transmission, paying less (and often insufficient) attention to the more distal causal factors. This proximal focus comes from an individual-based approach to etiology and epidemiology that emphasizes the immediate and short-term risk factors. We suggest that incorporating more distal processes into analyses and designs of interventions will result in more sustainable interventions. This new approach requires both systems-level thinking and an interdisciplinary approach to research and intervention design.

Here we review the different disciplinary approaches to infectious disease research and interventions and argue for an expanded interdisciplinary approach. We focus on water-related diseases (such as waterborne and vectorborne) and their more distal causes, which involve both social and ecologic processes. We summarize traditional and recent approaches, identify the main disciplinary themes, and discuss their strengths and weaknesses. We then propose an interdisciplinary, public health–oriented systems approach to research aimed at providing a comprehensive means to prioritize water-related health outcomes using evidence-based interventions (Ezzati et al. 2005). Finally, the suggested approach is illustrated using a case study that focuses on diseases associated with water and sanitation management practices in developing countries where the disease burden is the most severe.

Background and motivation. Water- and disease-related issues are major roadblocks to sustainable development. As noted by Toepfer (2004), disease statistics are stark and tragic: 80% of illness and death in the developing world is water-related; half of the world's hospital beds are occupied by people with water-related diseases; diarrhea and malaria are by far

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The contribution of C.W. was supported by a grant from the Graham Environmental Sustainability Institute at the University of Michigan.

The authors declare they have no competing financial interests.

Received 24 November 2008; accepted 17 April 2009.

the largest causes of mortality in children < 5 years of age (34%) in Africa; and the number of deaths from water-related disease approaches 5 million annually, most of them children. These deaths, most of which are preventable, largely occur among the estimated 1.2 billion people worldwide without access to safe and reliable drinking water and the 2.5 billion without access to sanitation services. Despite ongoing efforts, the 2002 Millennium Development Goal of halving the population without clean water or sanitation by 2015 is unlikely to be achieved (United Nations 2008).

Many stressors affect water hygiene and sanitation. These include *a*) population growth, urbanization, and increasing population density that increases vulnerability to waterborne diseases; *b*) growing water demand by cities, industry, and agriculture, often coupled with limited opportunities for reservoir or aquifer development; *c*) climate variability and change that together erode food production capacity, diminish water availability and water quality, and increase flooding and drought due to inadequate drainage and storage; and *d*) "advancements" associated with development, such as dams, roads, deforestation, and agricultural irrigation, that lead to increased prevalence of water-associated disease (Patz et al. 2004). These factors can interact in ways that adversely affect water quantity, quality, sanitation, and health.

We group water-related infectious diseases into two categories. Waterborne infectious diseases, such as diarrhea, are linked to poor sanitation, inadequate hygiene, ingestion of and contact with unsafe water, and lack of access to adequate amounts of safe water [World Health Organization (WHO) 2008]. Water-associated vector-borne diseases, such as malaria and dengue fever, require water to propagate insect vectors (e.g., mosquitoes, black flies) that transmit pathogenic microbes when taking a blood meal from a human (WHO 2008). Another kind of water-associated disease, schistosomiasis, is caused by a worm or blood fluke whose life cycle involves particular aquatic snails and human contact with infected water. Habitat requirements of such insect and snail vectors are species-specific and can include large and small water bodies and channels (e.g., lakes, lagoons, rivers, ditches, culverts, sewers), poorly drained soils, and containers (e.g., pots, tires, leaves, tree stumps) (Figure 1). Many water-related infectious diseases have been referred to as the "neglected diseases of neglected populations," because they receive little attention and disproportionately affect poor people in developing nations (Ehrenberg and Ault 2005).

Figure 1. A drainage canal constructed by local community efforts in Zaria City, Nigeria, a malaria region. Dr. Samaila U. Dakyes, of the Department of Industrial Design, Ahmadu Bello University–Zaria, is a local chief who has organized people in his community to maintain sewers and waste control. Such efforts can improve conditions, but the stagnant water shown in the photo indicates the need for additional work and infrastructure. Photo by S. Batterman.

Sustainability and research. We adopt a definition of sustainable water use as the "use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrologic cycle of the ecologic systems that depend on it" (Gleick et al. 1995). This broad definition is necessary to appropriately address the more distal factors associated with disease burden, and it suggests a research agenda for sustainable water management that represents a profound change from focusing on specific human uses—for example, water treatment plants, wells, and sewage systems—to considering a more holistic system that encompasses both human and ecologic systems and infrastructure components. Furthermore, in this context, sustainability must be approached using interdisciplinary tools that span social, physical, and ecologic sciences, including health sciences. In practice, indicators of sustainability are context- or problem-specific, and programs that seek to advance sustainability must be flexible. To complete a cycle of planning, analysis, intervention, and evaluation, time frames must span one or preferably two decades, appropriate for economic discounting and forecasting, climate and other ecologic changes, and sociocultural trends. As discussed below, many disciplines have contributed to an understanding of water-related disease. We present these disciplinary approaches, which help to motivate the need to move toward more integrated interdisciplinary approaches.

Approaches to Water-Related Infectious Disease Research

As early as the Hippocratic writings, scholars recognized the connection between food, water, and the environment, along with the direct and changeable influence of human behavior on disease prevalence (Franco and Williams 2000). The Egyptians, Romans, Greeks, and other ancients had perfected many water supply, hygiene, and sanitation practices (el Gamili et al. 2001; Koutsoyiannis et al. 2008). In modern times, John Snow (the "father of epidemiology") and Henry Whitehead pioneered the understanding of the causes of water-related disease transmission (Newsom 2006). Many disciplines have significant interests in water management and disease control, including those concerned with natural and physical processes (e.g., ecology and engineering), human dimensions (sociocultural and economic/political); and health outcomes (e.g., biology, ecology, epidemiology, parasitology).

Such disciplines provide complementary frames that together can provide a comprehensive approach to understanding water-related infectious diseases. The following section highlights key themes from critical disciplines.

Ecologic approaches. Water-related infectious disease research has long used an ecologic perspective to understand how best to control transmission (Eisenberg et al. 2007). Ecologic approaches to water-related diseases have drawn from biology, epidemiology, and genetics, among other fields, to focus on environmental determinants of disease via natural and increasingly anthropogenic changes to the physical environment, which frequently result from shifts in (human) population, consumption, and technologic growth (UNEP 2007). Often vectors, stressors, and disease can be mechanistically linked to these changes from micro (e.g., ponds, rivers, wells) to global scales (e.g., effects of climate change on water flow patterns and biomes).

Disease and microbial ecology research has identified multiple modes of transmission for both vectorborne and waterborne pathogens that depend on environmental, climatic, infrastructural, and sociocultural conditions (Wright et al. 2004). Many pathogens move about the environment via human feces (Curtis et al. 2000), and both humans and animals can act as hosts. Exposure to fecal pathogens occurs in both private (e.g., domestic living spaces, private yards, and fields) and public spaces (e.g., workplaces, transportation hubs, markets; Kosek et al. 2003) and is most often linked to poverty, poor education, and underdevelopment. Knowledge of the interactions between bacterial, viral, and parasitic enteric pathogens and the microbial system of the human gut can shed light on population differences in susceptibility (Mathew et al. 1991), whereas vector ecology can inform the design of interventions—for example, mosquito behavioral flexibility (Huang et al. 2006), flight range, and spatial distribution (Pope et al. 2005; Sirot et al. 2008). Disease ecology, however, cannot be seen as independent of social behavior and political economy.

Motivated by unsuitable and poorly targeted vector control programs, as well as diseases that are drug-resistant or for which there are no vaccines, the WHO has promoted integrated vector management (IVM) (WHO 2004), an ecologic approach that includes both vector ecology (promoting minimal use of insecticides) and public health initiatives (including community dialogue and participation). The need for increased community education, management integration, monitoring, and evaluation in such programs has been recognized (Mukabana et al. 2006; Townson et al. 2005; Van den Berg et al. 2007).

Engineering approaches. Engineering approaches offer the science and technology for the design of safe (and adequate) water, sanitation, hygiene, and drainage systems, as well as the forecasting, operations, and management skills needed to maintain and optimize systems for a suitably long period. For millennia, 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 flood control. Water-related infrastructure, including distribution systems (e.g., reservoirs, wells, treatment systems, pipelines) and drainage facilities (e.g., bridges, dams, channels, culverts, levees, storm sewers) is designed to provide a sufficient supply of healthy water and to remove physical, chemical, and biological (pathogen) contaminants. When any of these aspects is ignored, water-related disease can emerge; thus, both design and maintenance are crucial to the sustainability of water-related infrastructure.

Much of the water-related infrastructure in developed countries has been designed, built, and operated according to prescriptive codes, standards, regulations, and practices (Neumann et al. 2005). In contrast, infrastructure in developing countries ranges from simple water catchment systems (containers of any sort to harvest and store rain, river, run-off water, etc.) to those rivaling the complexity of those anywhere. Most often, however, much of the water-related infrastructure and management systems in developing countries is grossly deficient because of unreliable and unsustainable water supplies, contamination, inadequate distribution, the high cost of water in some areas, and numerous other reasons (UNEP 2008). Obvious examples of deficient infrastructure include poor drainage or water catchment, which may result in habitats suitable for certain mosquitoes, and inadequate or intermittent pressure/operation of potable water distribution networks, which permits the entry of pathogens and other contaminants. Such factors unquestionably increase the prevalence of infectious disease. From an engineering perspective, innovative although not necessarily complex infrastructure is essential to reduce water-related diseases in poor countries (Mara 2006), especially in urban areas where population density, financial, institutional, and other constraints can preclude elaborate systems. In arid areas, technologies such as dry or low-water-use toilets can help to decouple water supplies from sanitation, thus extending limited water supplies.

Multidisciplinary engineering perspectives have long addressed environmental, economic, social, and institutional elements inherent to large-scale water systems in developed countries. Environmental engineering (formerly called sanitary engineering) addresses, as examples, urbanization and inadequate sanitation that can lead to water pollution; seasonal and annual variability of precipitation and stream flow; climate change that exacerbates water shortages and increases pollution; financial and other resource limitations; and engineering and management expertise (Liu et al. 2007; Medd and Chappells 2007). Economic engineering and risk/cost-benefit analyses recognize the multiple values (e.g., monetary costs and benefits) of water projects, and systems approaches have been used to determine cost-effective designs and operation (e.g., Lund et al. 2006). The natural and social sciences inherently overlap in this work.

Anthropological approaches. Anthropological studies of water-related disease have focused on several themes including local understandings of water-associated diseases such as dengue fever (Kendall et al. 1991) and diarrheal diseases (Nichter 1988); conceptualizations of water—as pure, unclean, scarce, or having healing properties (Arar 1998; Wellin 1955); water use in treatments such as oral rehydration therapy (ORT) for diarrheal diseases (Burghart 1996); the political economy of health care and access to proper sanitation (Ecks 2004; Obrist 2004); community participation and health education (Yasumaro et al. 1998); and gender, occupational, and cultural inequalities in disease burden (Ramaiah et al. 2000; Vlassoff 1994). Many of these themes are interconnected and overlapping.

Local interpretations and use of water, which appear independent of Western influences, may have important implications for public health. There are many examples: Peruvians with little Western education ignored instructions to boil water and instead preferred "uncooked" water (Wellin 1955); in contrast, many well-educated Sri Lankans also failed to follow boiling instructions (Nichter 1988), whereas women in southern Nepal, when preparing ORT mixes, boiled water according to their own understandings of the effects of heat on water, using traditional procedures for sterilizing milk (Burghart 1996). In Tanzania, among women who accepted public health messages about using clean water, infrastructure deficiencies made it difficult to obtain piped water and created emotional stress on those who wanted but did not have access to it (Obrist 2004); others knew the importance of boiling water, but could not afford the fuel. Thus, water-associated disease risk and prevention is not only economically and politically framed, but often is also socially and behaviorally constrained.

In the absence of adequate and usually state-provided knowledge and resources, social science approaches increasingly recognize adaptive capacity—that is, the ability to cope with change—of individuals, institutions, and even entire social systems. Adaptive capacity considers resilience and, instead of devising interventions that replace old behavior and technology with novel behavior and technology, explores the development of interventions that incrementally alter existing systems (Yacoob and Whiteford 1994). This approach has been offered as a means to improve integrative water management programs in UNESCO's (United Nations Educational, Scientific and Cultural Organization) Ecohydrology Program (Lemos et al. 2007). Adaptive capacity integrates local knowledge, skills, and traditions at all levels and illustrates that although "disease is a biological condition … it exists within a human and social context" (Yacoob and Whiteford 1995). While admittedly controversial in the sustainability context, adaptation is also a response to climate change.

The anthropological approach also encompasses a shift within medical anthropology from interpretive analyses of the cultural understandings of illness and local classification of diseases to ethnoecologic studies that examine environmental, biological, and social aspects of disease, as well as political/economic approaches in which public health is placed within a larger nexus of power and knowledge (Whiteford and Whiteford 2005). Using interdisciplinary approaches, anthropologists and public health practitioners have worked together to formulate and evaluate appropriate interventions. At the same time, they have examined distal factors, such as national and international aid and loan schemes that contribute to health inequalities, a theme examined next. Rapid ethnographic analyses may prove advantageous in these investigations.

Economic/political approaches. An essential determinant of water availability and quality is the extent to which political will and economic resources exist among water management agencies (Coit 2002). Further, political approaches must overlap with sociocultural research to address issues of trust and empowerment. For example, the neglect of sanitary conditions of India's poor urban areas has been tied to the mistrust of the government: The poor have little or no voice, pay few taxes, and thus are excluded from state-provided resources and services, whereas middle-class residents, who have little confidence in local municipalities to deal with problems, create alternatives (albeit subpar) that do not rely on local governments (Chaplin 1999). Such mistrust is compounded by the culturally sensitive nature of sanitation in India (Rosenquist 2005).

The relevance and validity of indicators and underlying data availability and quality are important concerns. For example, Target 11 of Millennium Development Goal 7 aims to significantly improve lives of 100 million slum dwellers by 2020 (United Nations 2008), as measured, in part, by access to sanitation and the response to the question "Do you have access to a latrine?" WHO (2000) statistics report that 96% of Nairobi's (Kenya) and 98% of Dar Es Salaam's (Tanzania) inhabitants have access to sanitation. However, in Nairobi, with half the population in informal settlements, there can be more than 200 people using a single open pit; in Dar, pits frequently overflow in the rainy season and flood the streets with raw sewage (Satterthwaite 2003).

The concentration of poverty implied in the previous discussions of deficient water supply and sanitation infrastructure is a key force behind the spread of water-related (and other) diseases (Massey 2009). Poor people often have greater exposure to pathogens (e.g., crowding may promote disease transmission and vector growth), higher prevalence of underlying diseases, and less access to adequate health services (discussed later). Such social determinants of health, which include both proximal factors (e.g., homelessness, crowding, water supply, and nutrition) and distal factors (employment and development policy), are integrally linked to poverty and act to increase susceptibility to disease.

Another dominant theme for water-related development projects is the influence of donor agendas rather than priorities set by local governments. The structural adjustment policies of the World Bank have deemphasized government-related social projects while promoting market-driven options, for example, privatization of water supply (Stein 2008). Donor project approaches were phased out in the 1990s, and bilateral aid moved toward the pooling of resources to aid economies through sectorwide action programs. However, there are rarely mechanisms (financial, institutional, capacity-related) in place to continue the project when donor contributions end (Rautanen et al. 2006). For example, the termination of the large 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, and without consideration of the sustainability of the project (Weeks et al. 2003) The continued donor-coordinated focus on AIDS, tuberculosis, and malaria rather than diarrhea, which is the second leading cause of morbidity and mortality in the country, may also be seen as evidence of a donor-controlled health agenda. Policy spaces need to be generated that empower the historically marginalized and that change the nexus between water, environment, and health. Recent and self-sustaining systems that can help to institutionalize clean water and sanitation habits include microcredit schemes and health-related clubs (Waterkeyn and Cairncross 2005). These economics-driven plans depend on interdisciplinary insights from ecology, engineering, and the social sciences if they are to be technically effective and culturally appropriate.

Public health approaches. From its beginnings with Snow and Whitehead, public health research has shown the need to address all possible points of water contamination, including sources and storage (Wright et al. 2004), sanitation systems (Cairncross 2003), and hygiene processes (Curtis et al. 2000; Curtis and Cairncross 2003). Public health research areas most germane to water-related infectious disease include surveillance/forecasting, environmental health, epidemiology, interventions, and health education, and the methods to strengthen the relevance and impact of findings in each of these areas. These areas themselves are multidisciplinary and overlapping. Surveillance is critically important and sometimes quite poor, especially in developing countries. For example, although declines in diarrheal mortality have been reported in some settings, true rates may be greater because of reliance on verbal autopsy reports or confounding by other health conditions, such as HIV/AIDS and malaria (Parashar et al. 2003). In addition to health indicators, surveillance can be of water quality and quantity parameters that provide fundamental data for predicting and possibly preventing disease outbreaks by anticipating, for example, impacts of seasonal changes and weather patterns (Fisman 2007).

Many public health interventions have been conducted to evaluate insecticides and vector control techniques (Edman 2005), vaccines (Tetteh and Polley 2007), immunizations, rehydration therapies, and ORT supplements (Bhutta et al. 2000). Such interventions do not always account for sociocultural traditions and norms and pathogen and human ecology and behavior. Moreover, interventions should be aimed at the incremental reduction of disease rather than eradication (Koren and Crawford-Brown 2004). Another trend is a move beyond risk analysis and risk reduction strategies toward more holistic health-impact assessments, which use ongoing community-oriented evaluations and a broad set of techniques (Patz et al. 2008; Veerman et al. 2005). Such approaches promote the use of preventative measures and early warning systems and can help to close the gap between research and policy (Eisenberg et al. 2002).

Health systems, which are responsible for both curative and preventive care, offer many public health opportunities for provision of clean water and improved sanitation through surveillance, education, and interventions. Yet developing country health posts, clinics, and even referral hospitals themselves suffer from a range of water-related problems. Often, operating and delivery rooms in developing countries dispose of infectious waste in pits and open sewers, and the water supply is neither clean nor reliable. For example, in Uganda, 77% of primary care clinics and 46% of hospitals lacked running water, and only 40% of all facilities had a functioning latrine, an acceptable level of cleanliness, and a protected waiting area (Uganda Service Provision Assessment Survey 2008). Such deficiencies in water and sanitation create opportunities for serious breaches of hygiene that increase the rate of postoperative and other iatrogenic infections.

Despite increasing cross-disciplinary activities, an important disconnect remains between public health research and the social/behavioral and economic/political approaches discussed earlier. Development goals often only indirectly address public health goals (Satterthwaite 2003), while most public health programs notably exclude issues such as political will, economic livelihoods, and resource availability. Still, public health research has led to many successful policies and interventions. The literature shows some agreement about prioritizing interventions; for example, safe and sanitary fecal disposal is of utmost importance; routine hand washing and access to potable drinking water are important, but secondary (Curtis et al. 2000).

Other interdisciplinary approaches. There have been many earlier efforts to synthesize and integrate disciplinary contributions to water- and health-related research. These include the renowned and groundbreaking science–community–policy nexus (e.g., Brundtland 1997; Lemos et al. 2007), a largely conceptual model useful for recognizing omissions in analyses and motivating interdisciplinarity, but not necessarily one that provides a framework suitable for research and analysis. Another example is integrated water management (IWM), promoted by the World Bank and United Nations and also guided by multidisciplinary (ecologic, institutional, and economic) principles. However, IWM intends to provide a universal solution to very complex problems, rather than a framework for understanding and controlling potential outcomes. It also has been criticized for compartmentalized management and, in the case of flood control, a focus on postdisaster responses rather than predisaster prevention and protection (UNEP 2004). Additional examples of interdisciplinary approaches, mentioned earlier, include WHO's IVM, UNESCO's ecohydrology program, and many large-scale research projects emerging from public health.

Common Problems and Conceptual Needs

Although the disciplinary approaches discussed above have reached out to other disciplines and have provided valuable insight into many aspects of water and health, a systems approach requires more integration. Here, we highlight several common issues associated with water-related research and suggest how interdisciplinary approaches might be used to enhance understanding and improve the effectiveness of interventions.

Complexity and interactions. The social, ecologic, engineering, economic/political, and public health domains that together determine water and health outcomes are complex, interactive, nonlinear, and dynamic. These processes are difficult to represent using statistical or physically based simulation because of their high-dimensionality, sample-size limitations, which prohibit investigation of most interactions, and unmeasured or unknown spatial and temporal variables (Fleming et al. 2007). Ideally, models should represent a balance between simplicity, which may increase robustness, and complexity, which should enhance realism (Soller and Eisenberg 2008).

Multiple outcomes. Impacts of water-related projects can be classified using nomenclature from the environmental impact assessment literature: primary impacts directly associated with actions or projects (e.g., presence of pathogens, displacement of communities, channelization) and secondary or indirect impacts (e.g., siltation, ecologic changes, parasite infestation, floods, drought, and community restructuring) that often are much harder to predict yet ultimately more significant. Impacts and causal factors may also be classified by distance as proximal or distal (Birley 1995; Birley and Lock 1999). Clearly, the focus on sustainability has increased the importance of the temporal dimension, for example, short- and long-term (including intergenerational) impacts.

Unintended consequences. Unintended consequences are a corollary following from these complex interactions and multiple outcomes. Drastic differences may result between short- and long-term outcomes and between local and regional effects. History is rife with examples: flood-control programs that led to flooding or greater prevalence of vector-borne diseases (Saenz et al. 1995; Sur et al. 2000); improperly treated water that irrigated crops and transmitted infectious disease (Liang et al. 2007); and large-scale irrigation projects that promoted mosquito breeding (Amerasinghe and Indrajith 1994; Tyagi and Chaudhary 1997). Additional examples are described in the case study below.

Data gaps, incompatible temporal and spatial scales of available data, and the cost of environmental monitoring. These items represent additional research challenges. Complete information on all relevant parameters is never available. Rather, information must be gleaned from multiple and sparse data sets, and knowledge and data gaps are common. As examples, linkages among environment, poverty, and health in urban areas are poorly known (Nunan and Satterthwaite 1999), as are complete transmission pathways for all but a few infectious diseases (Patz et al. 2004). Although remote sensing of water quality, water temperature, and soil moisture, as examples, may complement sporadically sampled data, such measurements often are only indirectly related to the main parameters of interest (Brando and Decker 2003; Lavery et al. 1993). Furthermore, the divergent temporal and spatial scales used in sampling may provide incompatible data (Waters Network 2008). Innovative data fusion techniques are needed to optimize the information that can be derived from existing measurements and to support the indicators needed or desired for research, planning, and evaluation.

Sustainability. Last, the lack of sustainability of water management projects is a daunting problem. Although many health outcomes have been improved in some countries, few interventions in developing countries have had lasting improvements, and most operate only with donor support. Research and policy must understand and appreciate the usefulness of context, which provides information about historical practices and trends in climate, economics, politics, social, and cultural conditions. Although sustainability implies continuity, changes can be rapid and unexpected, and a surprise-rich future should be anticipated. As expressed by Rammel et al. (2007), sustainability can be viewed through an evolutionary lens in which it is understood that while we may not know exactly what will change or how, we can anticipate that change will happen. This demands novel and flexible solutions and systems that can meet evolving circumstances (applying to both environmental and human systems).

Looking Forward: An Approach for Sustainability Research

A research framework appropriate for creating sustainable solutions to control water-related infectious disease must move beyond existing approaches. We suggest four necessary attributes:

- Interdisciplinary approaches and teaming that account for the complexity, scale, and dynamics of water-related infectious disease problems.
- Ongoing surveillance and monitoring that include not only the traditional public health indicators (such as mortality and morbidity), but also indicators from other relevant disciplines.
- Research agendas that use an extended time horizon on the order of decades—long enough to provide continuity and meaningful progress for data collection, policy development, implementation, and analysis, but short enough to allow system evolution and information updating. Five-year evaluations are suggested below.

- A systems approach that provides an overall framework to facilitate analysis, understand interactions/feedbacks, and promote collaboration among researchers with diverse backgrounds. As discussed below, this framework is well suited to the complex and interdisciplinary nature of the problem.

Overall, the envisioned approach will not only foster responsive cross-disciplinary research collaborations, but will be amenable to on-the-ground implementation, monitoring, and evaluation, as well as the training of a cadre of water and disease specialists and researchers. Note that we propose only a framework for research, not specific programs.

Systems approach. The systems approach increasingly is considered a useful problem-solving framework to deal with large and complex issues. A system is defined by its interrelated components that function together within a defined and explicit boundary, often to advance a common purpose. Many systems are hierarchical in nature, and some are amenable to computer simulation. Generally, systems methods encompasses iterative steps of defining the problem, gathering data, developing evaluative criteria, formulating and evaluating alternatives, and selecting, designing, and implementing the plan (Jewell 1986). Many disciplines contribute to these steps. By acknowledging the relationships among system components, specifically the feedback and reversibility of many interactions, the approach allows evaluation of alternative courses of action or scenarios. The systems approach strives for straightforward problem definition, assumptions, goals, objectives, and evaluative criteria, and it allows continuous assessment and updating as new information becomes available. Another strength is its ability to facilitate problem mitigation and active planning by identifying the processes and parameters that influence key outcomes (called sensitivity analysis) (Bender and Simonovic 2000; Simonovic 2000). Many water management problems have applied a systems approach using computer models to simulate physical processes (Jeppsson and Hellstrom 2002; Lund et al. 2006) and institutional factors, such as the capacity for interagency and organizational collaboration (Cassady et al. 2008; Temel 2005).

The proposed research framework acknowledges the dynamics of infectious disease transmission and integrates the disciplinary approaches. Figure 2 depicts linkages of key processes within the water-related infectious disease cycle. The four key interrelated components that constitute the water-related infectious disease transmission cycle are represented near the center of the figure:

- Pathogen prevalence and transmission correspond to vector ecology and proximal factors that affect vector breeding and pathogen transmission, for example, the presence of standing water.
- Relevant health indicators and disease burden represent results from surveillance and monitoring that show the status and trends of both ecologic and human health. Such indicators are selected and developed using knowledge of disease ecology within the context of existing surveillance systems for environmental and public health and can include standard measures, such as mortality, morbidity, and infection rates, and those tailored to local circumstances.
- Policy, infrastructure and interventions represent actions designed to influence human behavior in a positive manner, reduce risks of transmission, and otherwise lessen the disease burden, for example, improved hygiene and water safety.
- All decisions and interventions are made within the context and constraints of physical, political, economic, and social environments, for example, cultural views of water and hygiene, and the available economic resources.

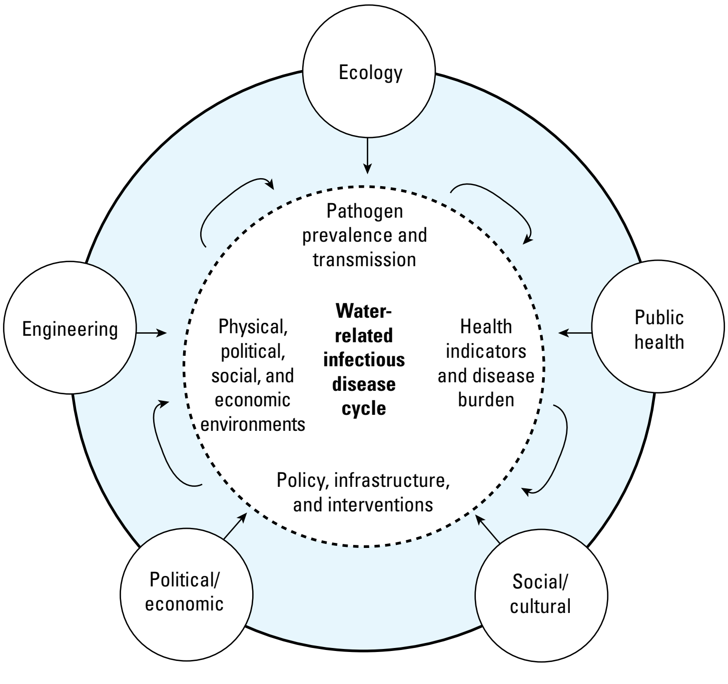

Figure 2. Conceptual framework of multidisciplinary health-based systems approach for understanding the water-related infectious disease cycle.

In Figure 2, we highlight the interdisciplinary teaming within a systems framework, specifically the five frames reviewed above (outer circles), designed to capture the complex dynamics and multiple temporal and spatial scales of water-related infectious disease problems. Rather than reducing the validity of traditional approaches, the proposed framework is intended to be integrative and problem oriented, incorporating these and other relevant and helpful disciplines or techniques. Although a systems approach is, by definition, multidisciplinary, we are calling for a deeper integration and collaboration between scientists in which constituent disciplines inform investigations of others and where hypotheses might even be jointly formed (Wear 1999).

The proposed approach is driven by the need to better address the burden of water-associated diseases, with improved human health being the principal objective. It could be argued that providing adequate access to water and proper sanitation and possibly fulfilling the needs and/or desires of communities are sufficient and more appropriate goals. As described above, however, most characteristics of the water-related infectious disease cycle (e.g., complexity, unintended consequences, data incompatibility, long time horizon, and interplay within the social/cultural/economic and other frames) suggest that health indicators are more relevant and more consistent than economic, political, or infrastructural indicators, which tend to be less stable, more susceptible to change, and sometimes irrelevant under changed circumstances. Furthermore, many health indicators are becoming increasingly standardized in terms of their definitions and data collection methods (Centers for Disease Control and Prevention 2006). For example, in the context of sanitary and water supply improvements, the focus would not be on the level of expenditures on new sewage systems, but on levels and trends of pathogens in the water supply, incidence trends of diarrhea, the numbers of outpatient visits to clinics for dysentery and intestinal worms, and the like. The proposed framework explicitly shifts the focus to health-based goals rather than economic targets and thus represents a radical reorientation for most development programs. Some movement in this direction is evidenced by a U.S. Environmental Protection Agency grant opportunity (Pongsiri and Roman 2007), a World Bank (2008) review that emphasized collaborative research (especially in exploring linkages between environmental sustainability and poverty), and recent discussions in the National Science Foundation/National Institutes of Health collaborative program on the ecology of infectious disease (National Institutes of Health 1999).

We also suggest that the research framework can be embedded in the policy process, following the approach taken in health impact assessment, discussed earlier—a structure that might help provide continuity of support. This may also be valuable for young and interdisciplinary research investigators, as officially sanctioned projects might help surmount some of the challenges of establishing trust and understanding among members of the research team, as well as help in funding and publishing interdisciplinary research (Turner and Carpenter 1999).

Ongoing evaluation is a critical component of the proposed approach. At the project level, evaluations must address environmental quality, impacts on livelihoods, health, household economies, and the overall cost and acceptability of the action. Distributional effects need to be carefully assessed to ensure equity of benefits. At a programmatic level, interventions and policy experiments should be evaluated for their intellectual contributions, repeatability, fostering of effective collaboration, and training opportunities, among others. Given the 20-year time horizon we argue for, formal evaluations might be conducted every 5 years by interdisciplinary researchers, a schedule allowing for evolution and the opportunity to modify components within the entire program as well as promoting the training of new investigators. Up-front structuring of data collection activities and indicators obviously would facilitate evaluation.

Complementary research tools. The proposed research framework needs to incorporate the latest research tools, including geographic information systems (GIS), process and simulation models, and statistical techniques. GIS has been used for many purposes, including designing early-warning systems (Fleming et al. 2007) and tracking disease outbreaks (Sarkar et al. 2007). Combined with satellite surveillance, it has been used to map vector breeding sites and other disease sources (Jacob et al. 2003; Njemanze et al. 1999; Polack et al. 2005). A wide range of models are used to study environmental changes and impacts on health and sometimes combined to study dynamics and interactions among environmental, ecologic, social, and pathogen factors that affect disease transmission (Eisenberg et al. 2007; Remais et al. 2008).

Given the complexity of water-associated infectious disease, statistical data mining and variable selection techniques using tree-based searches through the model space (Breiman 2001) may be useful. Latent variable models under a structural equation framework may provide an option for understanding causal pathways and interacting factors that lead to disease transmission. The study of water-related diseases inevitably involves various spatiotemporal covariates, with the spatial variables themselves often measured at different scales and with a nested interface. Such problems can be analyzed using wavelet-based methods, spatial process models, hierarchical or multilevel modeling frameworks, and Bayesian inferential methods (Banerjee et al. 2004), although the application of these methods to date has been limited. There are many opportunities to use these tools to great advantage in the evidence-based decision-making public health paradigm.

Case Study

A case study of water-associated disease in Ecuador illustrates the need for and application of the proposed approach. With the goal of providing transportation faster and cheaper than river boats, the Ecuadorian government built a 100-km road between the southern Colombian border and the Ecuadorian coast from 1996 to 2001. After completion of the main road, secondary roads continued to be built that linked multiple villages to the main road. This roadway network led to major changes in both the social structure and ecology of the region (Sierra 1999). Although there is evidence that road construction affects the incidence of vector-borne and sexually transmitted diseases (Birley 1995), impacts on diarrheal disease remain poorly understood. Further, although transmission of enteric pathogens has been linked to proximal factors of water quality, sanitation and hygiene practices, the relationship between distal social and ecologic factors (e.g., increased population density and regional scale water patterns) and diarrheal disease remains poorly understood (Curriero et al. 2001).

To help understand road construction–related diarrheal disease, Eisenberg et al. (2007) mapped a suite of distal environmental changes that can affect proximal environmental characteristics, which in turn can affect the transmission of enteric pathogens. Their framework incorporates processes at multiple spatial and temporal scales using regional, villagewide, individual, and molecular-level data. These data can be integrated using systems approach. To demonstrate the system's complexity, multiple outcomes, and the potential for unanticipated consequences, consider how road construction can affect diarrheal disease prevalence: Roads can lead to deforestation, which subsequently affects watershed hydrology, local climate, and pathogen transmission (Figure 3) (Curriero et al. 2001). Roads also increase flows of consumer products, material goods, and medicine and potentially improve access to health care facilities and health information. At the same time, short-term travel patterns are intensified, introducing pathogen strains into the communities. The population density in both existing and new communities created along the new roads can rapidly increase, but water supply and sanitation

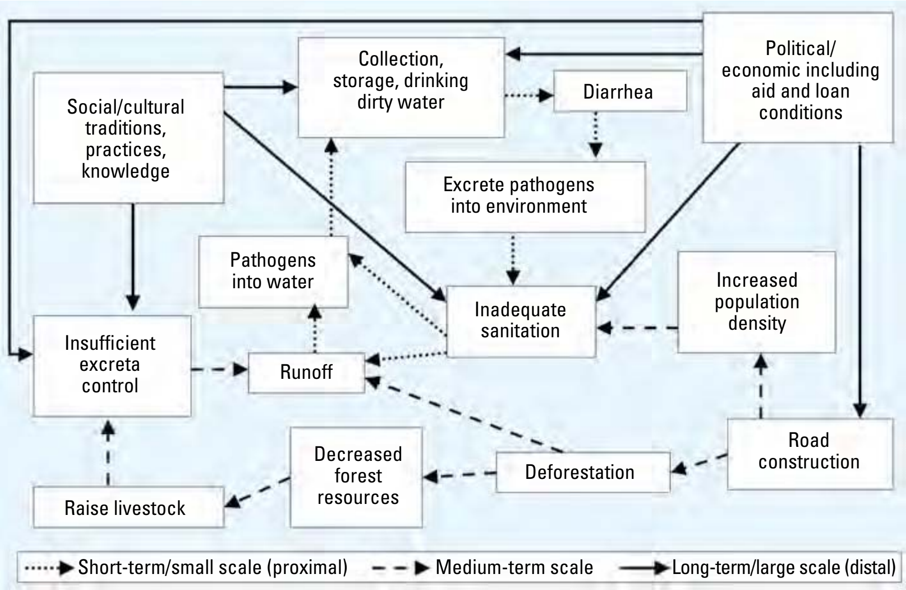

Figure 3. Example of distal, medium-term, and proximal components in the water-related infectious disease cycle in the Ecuadorian case study.

infrastructure frequently lags, thus increasing the likelihood of transmission of enteric pathogens. Similar changes can also be produced by dams, urbanization, agricultural practices, deforestation, and climate change.

Interventions at multiple points in the cycle and at different temporal and spatial scales can break the pathogen transmission cycle. For example, Figure 3 shows that although road construction and the resulting deforestation are linked to disease transmission, these medium-scale drivers are ultimately linked to distal drivers, such as country-level economic conditions and the agendas of development aid/loan programs. Deforestation can then lead to proximal drivers—such as soil runoff that increases pathogen transmission into water sources, and decreased forest resources—potentially leading to more intensive livestock husbandry to compensate for lost forest resources, which then may increase the risk of pathogen transmission via inadequate control of waste. An interdisciplinary systems approach can account for the varying temporal and spatial scales depicted in the figure and will foster collaboration in the collection and evaluation of data. Table 1 outlines several measurable indicators relevant to health and sustainability within the water-related infectious disease cycle appropriate for the Ecuadorian example and identifies key contributing disciplines. The table highlights the need for interdisciplinary collaboration starting with conceptualization of the approach and continuing throughout.

This case study demonstrates the significant and intersecting roles played by multiple disciplines in understanding the causal linkages between road construction and disease. As examples, the political/economic disciplines shed light on why the road was built and its impact on the local economy of the region, whereas anthropology/ethnoecology studies describe the relationships between these larger-scale political/economic factors and the community's social structures and how these affect behaviors, services, and infrastructures needed for disease prevention. In an analogous fashion, ecologic sciences and engineering describe impacts of the larger-scale processes on the environment in general and ultimately on water quality, and they also offer input into the assessment and design of actions to mitigate adverse environmental (and health) impacts. Public health has the role of both measuring the occurrence of disease through surveillance activities and evaluating the effectiveness of possible interventions. The challenge in such studies is to make these activities truly integrated and interdisciplinary. Barriers include differences in terminology and theoretical frameworks, which require working together to create protocols for collecting and analyzing data, and the need for sustained financial and institutional support, which can develop local capacity, understand the complex relationships, and ideally move beyond observational studies into intervention research. Ecuador could become a test case that both demonstrates the value of the proposed research approach and leads to improved health. Although many of the linkages between road construction and disease may be case-specific, such studies would show the utility of an interdisciplinary systems approach framework that incorporates the dynamics of infectious disease transmission within the social, ecologic, engineering, economic/political, and public health spheres discussed in this review.

Conclusions

We have argued that fundamental changes are needed in the structure and organization of research on water-related infectious disease and specifically for a systems- and health-based approach that can lead to sustainable strategies. After reviewing contributions of the key disciplines, we highlighted important themes and conceptual needs that include the complexity of and linkages (both proximal and distal) across ecologic, engineering, political, economic, anthropological, and public health spheres; the need to integrate data and methods used in the relevant disciplines, including surveillance activities tracking public health and other short-term and long-term indicators; and the multiple and often unanticipated outcomes as well as the long time frame needed to consider the sustainability of interventions addressing water-related diseases, all of which motivate an adaptable research framework. A research agenda using an interdisciplinary systems framework with an evidence-informed health outcomes focus and extended time horizon is responsive to these issues and builds on recent trends, although it may diverge from goals of the (economic) development paradigm. We used many short examples and a case study to illustrate the dynamics and complexity inherent in these problems. These show the ripe opportunities for interdisciplinary collaboration in data collection, analysis, and evaluation. The suggested systems-based research framework is amenable to methods and data culled from the ecologic, anthropological, and engineering fields, among others, and it facilitates knowledge sharing across the diverse disciplines involved. It can be embedded, we believe, in new initiatives in educational curriculum, research programs, policies, and intervention programs designed to control water-related infectious disease. This review is an initial step toward these goals.

Many challenges remain. More time and flexibility may be needed than is customary in disciplinary research. Interdisciplinary training at theoretical, methodologic, and analytical levels is needed. Program priorities and funding opportunities must be shifted. There has never been a more pressing yet more propitious time for such changes in approach, shifts in paradigms, and development of new interdisciplinary collaborations.

Table 1. Examples of indicators for water-related disease and control and the primary disciplines needed to contribute in the formulation and evaluation of each indicator.

Indicator	Social/ cultural	Political/ economic	Ecology	Health	Engineering
Changes in water quality and conditions (flow frequency, intensity, path; pollution and pathogen levels)			X	X	X
Ecologic and infrastructural capacity to withstand climatic changes (temperature fluctuations, rainfall variability)			X		X
Household- and community-level motivation for changes in water-seeking and water-using behaviors; intervention acceptability	X			X	
Human migration, settlement, and water-use patterns	X	X		X	
Economic conditions, access to potable water and health care providers		X		X	

Multiple disciplines contribute to most indicators.

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Spread of Antibiotic Resistance in the Environment Impacts On Human Health

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Abstract

Identifying the factors causing the emergence, transmission and maintenance of antibiotic resistance is imperative for the development of policies that effectively protect human health. This paper discusses how to apprehend the role of human-environment interaction in the spread of antibiotic resistance. It more specifically aims to:

1. Construct an ***integrative framework*** that covers the full range and different scales of the human-animal-environment-bacteria interactions, enabling computational models of the spread of antibiotic resistance through these systems. It proposes to model the flows of antibiotics, bacteria and resistant genes that interconnect seven compartments: human, animal, domestic wastewater treatment, animal waste treatment, air, water, and soil. A key objective is to ensure a close synergy between empirical and computational experimentation, using experimental data for model parameterization and performing computational exploratory experimentation to identify key discriminant parameters and to guide the design and realization of new experiments.

2. Identify the ***critical resistance mechanisms, acquisition mode and selective pressures***.

For a given antibiotic and type of bacteria, it is essential to start by identifying the most relevant resistance mechanisms and their mode of acquisition or propagation, enabling us to discuss conditions that will favor antibiotic spread in the environment, and subsequently in humans. We review the strengths, limitations and potential use of the disparate types of data available and discuss the need for cutting edge research to complement and fill critical data gaps.

3. Systematically explore how best to integrate at different levels of detail two ***modeling strategies:*** Equation Based Models (EBM) - that can best represent knowledge of fate-and-transport phenomena and demonstrate the movement and attenuation of antibiotics and resistant bacteria in different environmental media – and Individual Based Models (IBM) – that can account for the wide heterogeneity of the pertinent bacterial characteristics and are adaptive to changing environmental conditions. The aim is to determine the most parsimonious scale which includes all necessary processes.

4. Identify ***treatment strategies and key policy issues.*** The modeling of complex human-environment interactions and the creation of a wiki-based platform of open-source models will generate new knowledge that will: a) Challenge current antibiotic usage strategies in medicine, such as the simplifying principle "hit hard and long," which might promote long-term spread of antibiotic resistance. b) Provide transformative insights into the extent to which the use of antibiotics at sub-therapeutic levels for growth promotion in animals contributes to the spread of resistance. c) Identify and evaluate new strategies for water treatment that limit both emissions and intake of resistant pathogens.

1. Introduction Key Challenges and Project Scope

Identifying and understanding the factors causing the emergence, transmission and maintenance of antibiotic resistance is imperative for the development of policies that effectively protect human health. Antibiotic resistance is severely compromising quality of health care: ~19,000 persons die per year in the US after a hospital-acquired infection with antibiotic resistant bacteria. Community-based transmission and mortality are also significant (Klevens et al., 2007): a large increase in antibiotic resistance has been observed in the general population and in the environment. Community-based transmission likely occurs through marginally understood pathways involving environmental dispersion of resistance through human and animal waste, transfer through the environment, and subsequent exposure through food and water.

Antibiotics and antibiotic resistant bacteria are found in the soil-water phase, surface water, groundwater and even drinking water (Kolpin et al., 2002, Kummerer, 2004, Jones *et al.*, 2005; Pathak, Gopal, 2008; Pruden *et al.*, 2006; Schwartz *et al.*, 2003) yet their levels are currently unregulated. Most research has focused on hospital and community transmission; the amount and impact of antibiotics and antibiotic resistant bacteria found in the environment are largely unquantified.

Specifically, the following policy and scientific questions are of high interest:

- To what extent does the use of antibiotics at sub-therapeutic levels for growth promotion in animals contribute to the spread of resistance and are policy changes warranted?
- What are the critical mechanisms and major routes enhancing human exposure to resistant bacteria?
- Does exposure to low levels of environmental sources of antibiotics and antibiotic resistant bacteria play a significant role in the long-term emergence and elevation of antibiotic resistance in human?
- What are the most efficient waste water and drinking water treatment strategies to mitigate the spread of resistance?

There are available datasets on gene mutation, horizontal gene transfer, environmental bacterial survival, rates of human infection due to resistant bacteria, and multi-media transfer of bacterial pathogens which might be used to set the scene for a better understanding of the main mechanisms responsible for antibiotic resistance. However, integrating these complex, disparate data sources poses many challenges.

First, bacterial population sizes are *large and heterogeneous*. For example, a single gram of soil may contain 10^9 individual bacteria representing 10^4 different bacterial species (Fierer et al., 2007) providing huge potential for gene mutations and gene exchange among them. Similarly, the estimated number of bacteria associated with the human gut is enormous (10^{14} individual bacteria). While the estimated 500-1000 different bacterial species in the human microbiome mostly comprise commensal bacteria and bacteria promoting human health, bacterial pathogens are among them, and some commensals can act as pathogens (Sears, 2005, Sekirov, et al. 2006). In addition, the mechanisms of antibiotic resistance vary by antibiotic class and bacteria species.

Second, the relevant data operate at *widely different spatial* (from gene size to continental environmental transfer) *and temporal* (short term transmission to long term spread over decades) *scales.*

Third, these data are being collected across many disciplines, from hospital hygienists to wastewater treatment engineers, leading to *disparate data sets.*

Fourth, there exist large *data gaps*. Partial knowledge enables only a partial parameterization of the environmental complexity, often providing only upper and lower bounds for many parameter values. A comprehensive systems model - that encompasses all relevant processes and that can be used in an exploratory mode - will be imperative to identify data gaps and guide the direction of further research.

Fifth, there is a *high level of interdependency* between these already complex system components, making a pure empirical determination of long-term gene resistance transmission difficult or even impossible. Thus, complementary computational experiments are necessary to address hypotheses at a systems level such as "Broad exposure to low levels of environmental sources of resistance coupled with horizontal transfer of resistance gene elements play a significant role in the long-term emergence of resistance".

In response to these different challenges, the key methodological goals of this paper are to:

1. Construct an ***integrative framework*** that covers the full range of the human-animal-environment-bacteria interactions, enabling computational models of the spread of antibiotic resistance through these systems. The objective is to integrate databases and knowledge from widely different scales and disciplines to generate new insights into the overall system dynamics and to test hypotheses at a systems level.

2. Identify the ***critical resistance mechanisms and selective pressures***, reviewing the strengths and limitations of the disparate types of data available from each discipline. We will discuss the need for cutting edge research to complement and fill critical data gaps, and how these data might be interfaced to the overall system, taking advantage of the strong cross-disciplinary team of the authors.
.

3. Systematically explore how best to integrate two ***modeling strategies:*** Equation Based Models (EBM) - that can best represent knowledge of fate-and-transport phenomena and demonstrate the movement and attenuation of antibiotics and resistant bacteria in different environmental media – and Individual Based Models (IBM) – that can account for the wide heterogeneity of the pertinent bacterial characteristics and are adaptive to changing environmental conditions. To reflect the highly variable replication and gene transfer rates observed for the same populations in different environments, these populations should be characterized as a heterogeneous group.

4. To identify ***treatment strategies and key policy issues.*** Since municipal wastewater and animal waste product may be substantial reservoirs of antimicrobials and resistant bacteria it is essential to review and eventually optimize strategies to reduce emissions of antimicrobials and resistant bacteria from these sources.

The focus of this paper will be on bacterial resistance, whereas, we recognize that anti-microbial resistance in other microbes, including protozoa, fungi, and viruses is also of importance, but for which we have even less data.

2. Integrative Framework

Figure 1 presents the key elements of the proposed integrative framework. It consists of seven basic components corresponding to the following compartments: human, animal, domestic wastewater treatment, animal waste treatment, air, water, and soil. Several compartments include zones with higher potential for resistance gene transfer (e.g. microbial biofilms). The aim of the model framework is to computationally model how antibiotic resistance emerges and spreads in humans, animals, and throughout all environmental compartments by interconnecting these compartments to describe transfer flows of antibiotics, bacteria, resistant genes, and infected individuals. This framework will allow us to explore the system dynamics and analyze the level of coupling between components (Margni et al, 2004). For example, the use of antibiotics in animal production results in the presence of antibiotics and antibiotic resistant bacteria in animal waste. Animal waste treatment attenuates microbial populations and is dispersed into three environmental compartments (soil, water, air). Humans are exposed to these environmental compartments, leading to further human-to-human transmission.

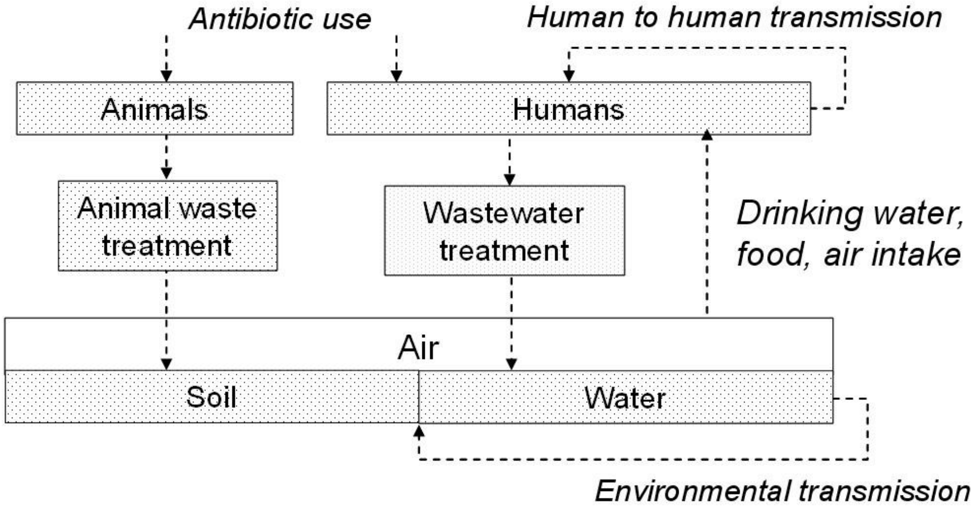


Figure 1. Schematic Description of the Proposed Integrative Framework to Model Environmental-Human Interactions. Arrows Represent Both Antibiotic and Resistance Flows to and From the Environment.

A long term goal of this framework is to ensure a close synergy between empirical and computational experimentation. Our shorter term objective is to extensively use the model system in an exploratory mode on a large set of potential parameters to identify potential attractors representing most probable states of the system and to identify the critical parameters affecting the system dynamics. These computational experiments will enable us to design and carry out critical empirical experiments to differentiate between various causes for resistance emergence.

The predictive power of the proposed framework highly depends on the quality of the model parameterization of each compartment and its customization to the local environmental conditions, the considered bacteria, class of antibiotics and resistance mechanisms.

3. Critical Mechanisms and Selective Pressure Ruling the Spread of Antibiotic Resistance in the Environment and Humans

This section provides a short overview of the various antibiotic classes, resistance mechanisms, mode of acquisition of resistance. It then identifies conditions favoring environmental spread and subsequent human exposure. It finally discusses the type of data that are increasingly becoming available.

3.1 Generalized Modes by Which Bacteria can be Resistant to Antibiotics

Bacteria typically come into contact with a wide variety of substances capable of causing them harm. These substances include naturally occurring (penicillin and streptomycin were originally isolated from fungi) or synthetic antibiotic agents that are used to treat bacterial infection. Compounds used as antibiotics can be narrow spectrum, affecting only a narrow range of bacterial species, or broad spectrum, active against a wide variety of bacteria. Different classes of antibiotics target different bacterial cell functions, such as cell wall synthesis (penicillin and other β-lactams), DNA replication (fluoroquinolones and other gyrase inhibitors), protein synthesis (streptomycin and other agents that affect ribosomes), and other important cellular enzymes (metabolite analogs such as sulfa drugs and trimethoprim). Bacteria may be inherently resistant to some antibiotics or may acquire resistance to agents to which they are initially susceptible. A variety of mechanisms may be involved in acquisition of resistance, and may be grouped into the following general categories: (1) alteration in the antibiotic target, (2) increases in the amount of antibiotic target, (3) production of substances that inactivate antibiotics, (4) altered uptake of the antibiotic into the bacterial cell, and (5) rapid transport of the antibiotic back out of the bacterial cell after it enters. These resistance mechanisms may be acquired via genetic mutation or by the acquisition of genes involved in conferring resistance. Gene acquisition can occur directly from the environment of via horizontal gene transfer from one bacteria to another. In the latter case, transfer may occur by (a) plasmid conjugation, (b) transformation, (the incorporation of free DNA into chromosomes), and (c) phage mediated transduction. Resistance spread may then occur by selective pressure and spread of resistant clones.

The following section illustrates how antibiotic resistance is acquired varies by antibiotic, bacteria, and resistance mechanism.

3.2 Resistance Mechanisms and Related Modes of Acquisition

(1) Alteration in the antibiotic target. Alteration of an antibiotic target can occur by the two mechanisms described above. That is, a bacterial cell can become resistant to an antibiotic by altering the antibiotic target through **mutational change,** an especially significant process when bacteria are exposed to relatively small concentrations of the antibiotic. Alternatively, bacteria can acquire completely different versions of the antibiotic target via **horizontal gene transfer** (ie, replacement of a bacterial gene with another that encodes a target that is relatively less susceptible to the activity of the antibiotic). For example, resistance to trimethoprim is due to the acquisition of **plasmid encoded** trimethoprim-resistant forms of dihydrofolate reductase, the enzyme targeted by this antibiotic.

(2) Increases in the amounts of the antibiotic target. Increasing the amount of the antibiotic target in the bacterial cell may counteract the effects of the antibiotic. For example, cycloserine which is structurally similar to D-alanine, acts as a competitive inhibitor of two sequential reactions in the synthesis of peptidoglycan in which D-alanine is incorporated. Cycloserine binds to the enzymes alanine racemase and D-alanyl-D-alanine synthetase. Elevated levels of both alanine racemase and D-alanyl-D-alanine synthetase due to **mutational changes** in genes regulating their synthesis results in relative resistance to cycloserine.

(3) Production of a substance that inactivates the antibiotic. Bacteria may be capable of producing substances capable of degrading or otherwise inhibiting an antibiotic. An example of this is the inactivation of β-lactam antibiotics by bacterial β-lactamase enzymes. The ability to produce β-lactamases is generally acquired when **plasmids** encoding these enzymes are taken up into the bacterial cell.

(4) Altered uptake of the antibiotic into the bacterial cell. In order to affect bacteria, most antibiotics must first bind to and then enter the bacterial cell. Inhibition of this process can render bacteria resistant to the antibiotic. For example, in bacteria such as *E. coli* and *Enterococcus faecalis*, cycloserine is only effective if a transport system for the uptake of D-alanine is present. Loss of some component of the alanine transport system can protect the organism against cycloserine action. This most often occurs due to **mutations**.

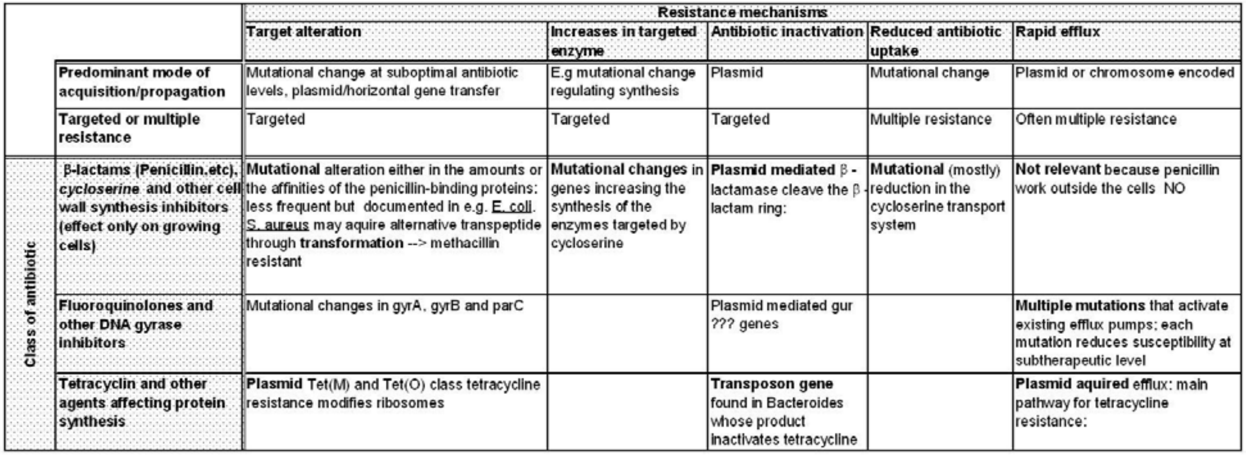
(5) Rapid transport of the antibiotic back out of the bacterial cell once it enters. Many bacteria can express efflux systems capable of transporting various substrates out of the bacterial cell. Resistance to some antibiotics can occur due to upregulation and over production of efflux systems capable of effectively pumping the antibiotic out of the cell before engagement with the antibiotic target. In other cases, bacteria may acquire new efflux systems. Resistance to **tetracycline antibiotics** is most often due to a **plasmid gene** which encodes a protein that causes efflux of tetracycline. Efflux-resistance mechanisms often result in resistance to multiple antibiotics.

For modeling antibiotic resistance for a given antibiotic and type of bacteria, it is useful to start by identifying the most relevant resistance mechanisms and their mode of acquisition or propagation. Table 1 illustrates this step for penicillin, cycloserine, fluoroquinolones, and tetracycline.

The acquisition mode of propagation will strongly affect the way antibiotic spread can be modeled (Table 2):

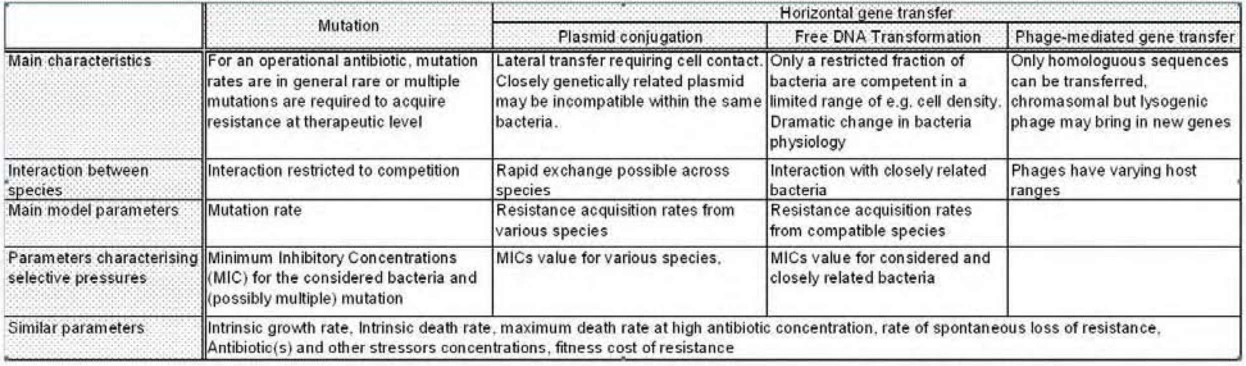
(a) Mutation is the acquisition mode with the least inter-species interaction, whereas (b) plasmid mediated resistance may generate high interaction across a large range of species. (c) Transformation implies that bacteria are competent. It generally occurs only for a limited number of bacterial strains - since it generally involves dramatic changes in bacterial development and for specific environmental conditions, e.g. only within a given range of cells densities.

Table 1. Most Frequent Resistance Mechanisms and Corresponding Acquisition Mode for Penicillin, Cycloserine, Fluoroquinolones, and Tetracycline



		Resistance mechanisms				
		Target alteration	**Increases in targeted enzyme**	**Antibiotic inactivation**	**Reduced antibiotic uptake**	**Rapid efflux**
	Predominant mode of acquisition/propagation	Mutational change at suboptimal antibiotic levels, plasmid/horizontal gene transfer	E.g mutational change regulating synthesis	Plasmid	Mutational change	Plasmid or chromosome encoded
	Targeted or multiple resistance	Targeted	Targeted	Targeted	Multiple resistance	Often multiple resistance
Class of antibiotic	**β-lactams (Penicillin,etc), *cycloserine* and other cell wall synthesis inhibitors (effect only on growing cells)**	**Mutational** alteration either in the amounts or the affinities of the penicillin-binding proteins: less frequent but documented in e.g. E. coli. S. aureus may aquire alternative transpeptide through **transformation** --> methacillin resistant	**Mutational changes** in genes increasing the synthesis of the enzymes targeted by cycloserine	**Plasmid mediated** β -lactamase cleave the β -lactam ring:	**Mutational** (mostly) reduction in the cycloserine transport system	**Not relevant** because penicillin work outside the cells NO
	Fluoroquinolones and other DNA gyrase inhibitors	Mutational changes in gyrA, gyrB and parC		Plasmid mediated gur ??? genes		**Multiple mutations** that activate existing efflux pumps; each mutation reduces susceptibility at subtherapeutic level
	Tetracyclin and other agents affecting protein synthesis	**Plasmid** Tet(M) and Tet(O) class tetracycline resistance modifies ribosomes		**Transposon gene** found in Bacteroides whose product inactivates tetracycline		**Plasmid aquired** efflux: main pathway for tetracycline resistance:

Table 2. Characteristics of the Different Propagation Modes and Typical Model Parameters



	Mutation	Horizontal gene transfer		
		Plasmid conjugation	Free DNA Transformation	Phage-mediated gene transfer
Main characteristics	For an operational antibiotic, mutation rates are in general rare or multiple mutations are required to acquire resistance at therapeutic level	Lateral transfer requiring cell contact. Closely genetically related plasmid may be incompatible within the same bacteria.	Only a restricted fraction of bacteria are competent in a limited range of e.g. cell density. Dramatic change in bacteria physiology	Only homologuous sequences can be transferred, chromasomal but lysogenic phage may bring in new genes
Interaction between species	Interaction restricted to competition	Rapid exchange possible across species	Interaction with closely related bacteria	Phages have varying host ranges
Main model parameters	Mutation rate	Resistance acquisition rates from various species	Resistance acquisition rates from compatible species	
Parameters characterising selective pressures	Minimum Inhibitory Concentrations (MIC) for the considered bacteria and (possibly multiple) mutation	MICs value for various species,	MICs value for considered and closely related bacteria	
Similar parameters	Intrinsic growth rate, Intrinsic death rate, maximum death rate at high antibiotic concentration, rate of spontaneous loss of resistance, Antibiotic(s) and other stressors concentrations, fitness cost of resistance			

3.3 Selection and Spread of Resistant Clones: Conditions Favoring Environmental Spread and Subsequent Human Exposure

Understanding key mechanisms and model parameterization enables us to discuss conditions that will favor antibiotic spread in the environment, and subsequently in humans.

Selective pressure for antibiotic resistant strains comes from the widespread use of antibiotics in medicine and agriculture, industrial metal pollution, and from competition within natural microbial communities. Evidence is also emerging for another environmental selective pressure, organic chemical contamination. Chlorinated phenols - originating from chlorination disinfection and phenols in organic matter - can contribute to the survival of multidrug resistant opportunistic pathogens by promoting the expression of multiple multidrug efflux pumps. Therefore, the importance of chemically-induced multidrug resistant phenotypes for opportunistic pathogens in natural and built environments needs to be determined.

Biofilms are ubiquitous in the aquatic environment and several factors related to biofilms may contribute to the spread of antibiotic resistance. One of the factors is high frequency of horizontal gene transfer in biofilms. Another factor is the protection that biofilms offer against disinfectants, which may reduce bacterial death rates. To better understand the spread of antibiotic resistant bacteria and antibiotic resistant genes in biofilms in the water cycle, field survey data are required to complement laboratory model systems.

Environmental spread could enhance human resistance when there is progressive resistance acquisition through multiple mutations, as illustrated in table 1 for fluoroquinolones. Resistance at therapeutic levels is achieved through multiple mutations that activate several existing efflux pumps. However, each mutation reduces the susceptibility at subtherapeutic levels and a single mutation may be selected for in hyper-sensitive bacteria at the very low antibiotic concentrations that are typically observed in the environment. This pre-selection may enhance the likelihood of multiple mutations in humans.

Hot-spots may occur in certain environmental media, e.g. in the case of disposal of intensive animal farm wastes or in the case of large hospital wastewater releases into wastewater treatment reactors that may lead to high antibiotic levels combined with high nutrient availability. This may create local reservoirs of resistant bacteria that can then be further transferred and spread.

Fifth, direct transfer in the food chain may enhance resistance transfer and requires further attention.

3.4 Strength and Limitations of Available Data for Modeling Purposes

What is the present data to understand the environmental spread of antibiotic resistance and related human exposure? This part will be completed based on the symposium presentations in:
- Discussing strength and limitations of existing data in different environmental compartments and for animal/in-host modeling.
- Discussing the different types of data and their use for system modeling (parametrization of gene acquisition rates, characterization of selective pressure by e.g. Minimum Inhibition Concentrations, overall evaluation of resistance build-up in various compartments.
- Discussing cutting-edge research to fill these gaps.

To make the development of such modeling platforms practical, we suggest to initially focus on resistance emergence for a few groups of antibiotics (e.g., quinolones, tetracycline and macrolides). Selection of antibiotics can be based on the importance of their use as human and animal therapeutics and in subtherapeutic applications, availability of information on and complexity of the mechanisms of resistance, availability of molecular methods to quantitatively detect resistant bacteria and resistance genes, availability of methods to quantify antibiotics in complex environmental matrices, and the availability of preliminary data (Zilles et al., 2005; Jindal et al., 2006; Amin et al., 2006; Angenent et al., 2008; Zhou et al., 2008; Shimada et al., 2008, Zhang, et al., 2008). To limit the initial complexity, we suggest to first study the spread of resistance in a limited number of bacterial populations. Preliminary data suggest that four relevant bacterial phylogenetic groups - for which the abundance can be quantified experimentally -could account for 70-80% of the total bacteria and up to 80% of the total resistance in a soil amended with swine manure (Zhou et al., 2008). The complexity and heterogeneity of the different compartments can then be progressively increased to a more representative level and appropriate resolution.

4. Modeling Strategies for the Long-term Environmental Spread of Antibiotic Resistance

A typical sequence for modeling may include the following steps: 1. Identification of main resistance mechanisms and corresponding acquisition mode for the considered antibiotic. 2. Identification of possible selection pressures/stressors (multiple antibiotics, other pollutants) and their concentrations; 3. Identification of compatible species. 4. Model parameterization for the most relevant acquisition mode, resistance mechanism and considered species. 5. Determination of typical antibiotic concentrations and of hotspots. 6. Determination of bacterial dynamics at considered modeling level. 7. Identification of critical data gaps and of lever point for limiting resistance spread.

Complementary levels of detail: Each of the framework compartments (section 2) may be modeled at three complementary levels of detail: a) A parsimonious model, consisting of environmental attenuation and growth rates, can combine a pathogen transmission multimedia model with a population prevalence model (Eisenberg et al, 2004, 2007; Smith et al 2002). b) At a more detailed level, we can model the mass balance of resistance genes and bacterial population growth in environmental compartments, accounting for mutation, horizontal gene transfer and for the response of the immune system in human and animals hosts (building on principles of Gammak et al., 2005). At this level we can model, in parallel, the antibiotic concentration within the environment and within the host. We can combine our environmental multi-media model with physiologically based pharmaco-kinetic models for within-host modeling in animals and humans (the IMPACT model: Pennington et al., 2005 and 2006; Jolliet et al., 2007). c) The third level will apply individual based modeling (IBM) techniques to model the interactions between individual humans and individual bacteria, developing new computational strategies to address this high complexity (Lardon et al., 2008; Xavier et al., 2007). Here we can also account for horizontal gene transfer and gene mutations and explore the importance of chemically-induced multidrug resistant phenotypes of opportunistic pathogens.

This strategy can result in a toolbox of alternative sub-models of varying complexity for each of the seven main components. From this, a set of sub-models can be selected to construct a particular full model of the whole system. Thus, a given full model could consist of simple EBM sub-models for some compartments and a complex IBM for other compartments. Such a modular approach will allow us to computationally explore the space of combinations of sub-models to discover which combinations are best suited for addressing specific questions and hypotheses.

Innovative use of computational thinking: Developing a conceptual model not only encourages us to explicitly describe what we believe are the key components, causal mechanisms, and interactions of the system, but it also focuses our attention on the most uncertain aspects of the system and enables us to identify the most sensitive data needed to address our research problems and to guide the design of new empirical studies. The effects of varying parameters can be analyzed in a systematic fashion, providing a deeper understanding of the system's behavior, including how the overall system responds to particular changes. Systematic exploratory analyses (Bankes, 1993; Bankes, 2002; Lempert etal, 2002) of potential intervention strategies can be carried out in various scenarios. By identifying main attractors in the parameter space, we can determine what data are the most important to improve our models and design critical empirical experiments to differentiate between various causes for resistance emergence. We can also discover "lever points" in the system, i.e., parameter values which can be used to guide the design of effective intervention strategies.

5. Treatment Strategies and Key Policy Issues to Prevent Resistance Spread.

A large fraction of the antimicrobials used in agriculture and human medicine are transferred to the environment because some antimicrobials are poorly adsorbed by humans and animals, with up to 75% of the administered antimicrobials being excreted. Therefore, municipal wastewater and animal manure are substantial reservoirs of antimicrobials and resistant bacteria. Horizontal gene transfer from bacteria originating from these sources to indigenous soil bacteria has been demonstrated (Jensen et al. 2002) raising the concern that drinking water sources and food supplies could be contaminated through such routes.

Strategies to reduce emissions of antimicrobials and resistant bacteria from these sources include:
- Waste treatment strategies to limit discharges of antibiotics, metal and organic pollutants that induce antibiotic resistant phenotypes, and resistant bacteria. Membrane bioreactors will play an important role because of their ability to increase the removal of contaminants and retention of biomass.
- Assessing the relative contributions of point source discharges and non-point source discharges. The latter includes urban storm water runoff and agricultural emissions.
- Recommendation on the use of antibiotics for humans and animals.
- Treatment measures to limit intake of pathogens and antibiotics though drinking water and the food chain.

By addressing the full range of human-animal-environment interactions, the proposed integrated model platform constitutes an essential step toward developing a scientific-based risk assessment of resistant bacteria. Synergies that result from a close cooperation between real-world experimentation and computational experimentation may lead to several breakthroughs. It may:
- Challenge current antibiotic usage strategies in medicine, such as the simplifying principle "hit hard and long," which might promote long-term spread of antibiotic resistance.
- Provide transformative insights into the extent of which the use of antibiotics at sub-therapeutic levels for growth promotion in animals contributes to the spread of resistance and whether policy changes are warranted.
- Identify and evaluate new strategies for water treatment that limit both emissions and intake of resistant pathogens.
- Demonstrate in a broader sense how "computational thinking" can be used in the scientific process to impact our daily life!

6. Outlook and Key Factors of Success

A key part in understanding complex systems like antibiotic resistance is the extensive use of experimental data to guide the construction and evaluate computational models and, in turn, the use of computational results to guide experimental designs. This powerful (and necessary) strategy can only be made possible by complementary expertise in investigator teams, involving modelers and experimentalists in various field such as multi-media modeling, transmission modeling, individual based modeling for complex microbial systems, water and wastewater treatment, animal waste treatment and antibiotic resistance in these systems, microbial processes, including gene transfer, in the aquatic environments, molecular epidemiology, and transmission of resistance, including mechanisms of spread of resistance determinants from environment to humans. We also advocate that additional funding should be made available to address the spread of antibiotic resistance at system level, in addition to present funding that is mainly dedicated to research in individual disciplines

Concurrently to research efforts, we suggest developing a wiki-based, virtual educative network on the modeling of antibiotic resistance. The network will be started by a multidisciplinary core group of faculties from various disciplines and research students, and will enable them to interact with interested students worldwide. The integrated modeling platform and its sub-models described above would constitute a sound basis to consistently integrate the specific contributions from students of different fields, organizing an open source wiki site to enable researchers worldwide to experiment and test hypothesis using the developed models or existing experiments. Such a platform would also enable researchers to publish their own models for individual or multiple compartments and compare or integrate them with those developed by our team.

The focus on bacterial resistance is a useful beginning, but we recognize that anti-microbial resistance in protozoa, viruses is also of importance, but for which we have even less data.

In short, it is only by exploring the overall system dynamics using complementary experimental and computational approaches that we can understand complex systems like antibiotic resistance. What makes the evolution and spread of antibiotic resistance complex are the heterogeneous components that exist at multiple scales, and are interconnected by complex topologies resulting in various direct and indirect positive and negative feedbacks.

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Development of a Sustainable Water Resource Policy For Bolivia, South America

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Abstract

Future climate change and population growth are expected to stress existing water resources in many regions around the world. In Bolivia and other parts of South America, water availability and quality are major problems and the additional stress on this resource is likely to exacerbate existing water-related issues and create new water-related crises and confrontations. To mitigate and adapt to future water-related issues that will arise from climate change, policymakers must develop and implement sustainable water resource strategies that address future global change on this resource. There are many challenges to developing a sustainable water resource policy, including: (i) accurately predicting regional scale climate changes, (ii) estimating how these climate changes will affect watershed hydrology, and (iii) using these predictions to create effective water policy given local social, economic, political and cultural conditions.

In this paper, we describe efforts at the University of Michigan to overcome these scientific challenges through multidisciplinary research that draws upon the expertise of physical and social scientists, with knowledge in climate change, climate modeling, hydrology, and water resources policy making and management. Through this collaboration, we are developing a long-term water resource management strategy that can be implemented by local policymakers in Bolivia. Our initial goal is to develop a methodology for translating regional climate predictions into water resource predictions that can be effectively utilized in policy making. To this end, we have designed a three-component research plan that integrates regional climate modeling over South America, catchment-scale hydrological modeling, and assessment of policymaking and management processes in Bolivia. Our research will produce: (1) regional-scale predictions of climate and hydrological variables (rainfall, evaporation, surface flow) for future climate change scenarios over tropical South America using a state-of-the-science climate-land surface model, (2) catchment-scale predictions of the impact of climate change on river discharge (water availability) and drainage basin hydrology, and (3) better understanding of the policy and management dimensions of the changes in water resources due to future climate change and policy guidelines, tailored to Bolivia, for mitigating and/or adapting to these changes.

Our research efforts as described here are currently focused on Bolivia and South America. However, the challenges to predicting future water availability and developing sustainable water resources are not limited to South America or to poorer nations. The current drought in the southeastern United States and water shortages in Atlanta are appropriate examples. Finally, it should be recognized that changing water resources could have widespread consequences that extend well beyond the region influenced by climate change. As an example, growing populations and limited water resources in the southwest Unites States have renewed calls for a national water policy that could substantially change the ways in which Great Lakes water resources are currently managed.

1. Introduction

Future climate change and increasing human demand through population growth and increased affluence will create severe pressures on water resources in many regions of the world (Kundzewicz et al., 2007). Future climate change is expected to alter the global hydrologic cycle intensifying both regional flooding and drought (Meehl et al., 2007), precipitation variability (Trenberth et al., 2003), and surface runoff and water availability with regional-scale consequences for economies and ecosystems (Fig.1; Milly et al., 2005). Adaptation to future water availability through effective integrated water management is a critical issue confronting many regions across the globe (Kundzewicz et al., 2007).

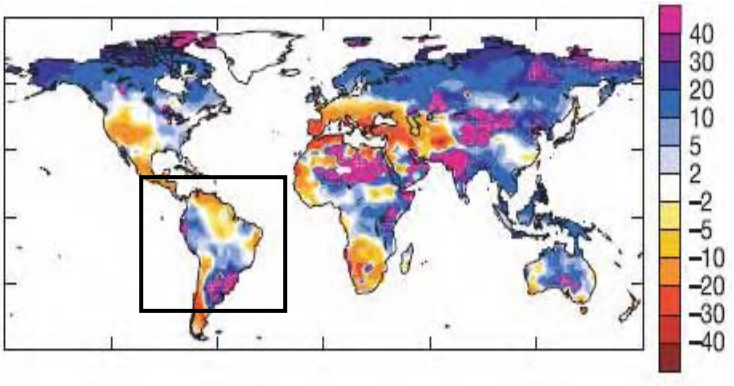

Figure 1. Relative change (%) in surface runoff for 2041-2060 using an ensemble of GCMs (Milly et al., 2005). Note that significant increases and decreases are predicted for South America. We simulate the influence of climate change on water resources at a high resolution and couple this response to a hydrologic model. Our regional climate model domain is outlined in black.

Tropical regions are particularly vulnerable to hydrologic variability and its impacts on water resources. This issue is serious in South America where many people live in or near the brink of poverty. For example, in Bolivia, the second poorest nation in South America, water availability and quality are an acute problem. As of 2001, approximately 26.5% of the population did not have access to potable water, and only four major cities had wastewater treatment facilities (Pan American Health Organization, 2001). Water resources and their management have impacts that affect human health, biodiversity and environmental resources. The number of Latin American people experiencing water stress is expected to grow due to climate change, increasing between 7 and 77 million people by the 2020s (Magrin et al., 2007).

The causes of Bolivia's and other South American countries water problems are multiple and complex. Although Bolivia lies mainly within the tropics, the distribution of rainfall is highly seasonal and variable, leading to large geographic disparities in water resources. In addition, natural climate variability has a substantial and adverse effect on South American water resources. For example, climate variability associated with the El Niño phenomenon causes seasonal flooding in the lowlands of northwest Bolivia and drought on the western highlands. In 1998/99 and 2007, El Niño flooding left thousands of people homeless, led to outbreaks of malaria and cholera, and destroyed croplands and livestock. In 1998/99, costs associated with El Niño were equivalent to 7% of Bolivia's gross domestic product (EIRD, 2000). In the future, precipitation variability and extremes are predicted to intensify. In addition, climate-vegetation models have predicted large decreases in the extent of the Amazon rainforest with continued anthropogenic CO_2 emissions (Cook and Vizy, in press). Since much of the precipitation that falls over the central Andes originates in the Amazon basin, large-scale Amazon deforestation may have profound consequences for water resource availability in Bolivia and the central Andean region.

Not all of South America's water problems are due to climate. The lack of a comprehensive water policy; inadequate infrastructure; inefficient use of water in agriculture; pollution of rivers and lakes due to mining, industrial, and biological contamination; and deforestation and increased erosion are all factors that contribute to water stress in Bolivia and throughout South America and must be considered in any integrated water management strategy (US Army Corps of Engineers, 2004). However, many of these factors will be affected and exacerbated by future climate change.

Most South American countries are not prepared for future climate change and lack strategies and capacities for adapting to or mitigating the impacts of climate change on water resources. This is partly explained by the many challenges Latin American countries face beyond climate change. However interest in climate change is increasing in the region especially in response to the emergence of international climate programs such as the UNFCC and Kyoto. In the water sector the negative impacts of climate change are particularly acute given the region's well-documented socioenvironmental vulnerability to climate variability (El Niño and La Niña) (Lemos and Oliveira 2004, Broad et al. 2002, Valvidia et al. 2000). The development of a long-term water management strategy for South America requires an understanding of future climate change on regional scales and its impacts on the scale of individual drainage basins. Most predictions of future climate change over South America have been made using global circulation models (GCMs) (e.g. Smith and Lazo, 2001; Ruosteenoja et al., 2003; Milley et al., 2005). GCMs have provided tremendous insights into climate change on a global scale. However, because of their coarse spatial resolution, GCMs do not adequately simulate hydrological processes and vegetation change on catchment scales, and therefore cannot provide predictions that are useful for long-term planning. One limitation to long-term planning, highlighted in the 2007 IPCC report (Kundzewicz et al., 2007), is the need for quantitative estimations of climate change on water resources. Another, is the need to assess how current policy and management systems are/will be able to prepare and respond to these changes.

Accurate predictions of water resources are not enough. Case studies in Northeast Brazil, Bolivia and Peru have shown that socio-economic, political, and cultural conditions can limit the utility of seasonal climate forecasts (Lemos et al. 2002, Broad et al. 2002, Valdivia et al. 2000). For example, in Brazil, policymakers initially exaggerated the potential usefulness of seasonal forecasting, creating disenchantment when expectations were not met (Lemos et al., 2002). In addition, institutional and organizational factors play a pivotal role in the ability of policy makers and water managers to incorporate climate information in their decision making process (Lemos in press, Rayner et al. 2005). An effective water strategy must be built with these constraints and opportunities in mind, and incorporate end users' needs and decision-making behavior.

2. An Approach to Developing Water Policy for the Future

In the following sections, we outline a research strategy for developing water management strategy for central South America that accounts for future climate change and can be implemented by local policy makers. The specific tasks of our research efforts are described in detail below. In short, they include: (1) prediction of regional climate through downscaling techniques using global and regional GCMs; (2) estimation of the impacts of future climate change on regional hydrology through implementation of a catchment-scale hydrologic model; (3) assessment of policy making processes and institutional opportunities and constraints to the use of climate/hydrological predictions for water management and planning in Bolivia through interviews with policymakers and end users. These tasks will culminate in three deliverables: (1) regional climate predictions for future climate scenarios over tropical South America, (2) hydrological predictions of variability in river discharge (i.e. water availability) and drainage-basin hydrology in the La Paz drainage basin, Bolivia, and (3) policy guidelines, tailored to Bolivia, for mitigating and/or adapting to changes in water resources due to future climate change.

We are currently developing and evaluating this approach. In the long-term, our research goal is to realize a strategy that can be applied to other regions, including the United States. However, the scientific obstacles are not insignificant. In the following sections, we describe these challenges and our strategies for dealing with them.

3. Component 1: Regional Climate Prediction

3.1 Regional Climate Modeling

Accurate climate predictions are essential to predicting climate impacts on water resources and developing policy. Climate models are complex, powerful tools that can be and have been effectively used to provide predictions of future climate change (e.g. Milly et al., 2005). However, there are uncertainties associated with these models stemming from (i) their relatively coarse spatial resolution, (ii) uncertainty in future emissions scenarios, and (iii) inaccuracies due to the incomplete and/or incorrect representation of physical climate processes. We reduce the uncertainties associated with (i) and (ii) by downscaling global model predictions using a state-of-the-science regional climate model with a grid resolution of 25 km and by simulating a range of emissions scenarios. As a proof-of-concept, we are using boundary conditions from a single GCM in our regional climate model predictions; however, we are aware of differences between GCMs and plan to use model ensembles in future work.

3.2 RegCM3

Due to the increased spatial resolution and ability to capture land surface heterogeneity, regional climate models are better equipped than global models to evaluate water resources in regions of complex terrain. For this reason, we are utilizing the RegCM3 regional climate model (Pal et al., 2007) for present day and future simulations to evaluate the impact of future climate on water resources in South America. The RegCM3 is a grid-point limited area model, which simulates climate over a region of the globe and requires climate data at the domain boundaries. Reanalysis data is utilized as boundary conditions for present-day scenarios, and global climate model simulations provide these conditions for future scenarios. The RegCM3 has a hydrostatic dynamical core (similar to the NCAR/PSU MM5; Grell et al., 1994) and a full radiation package (CCM3; Kiehl et al., 1996), allowing for the change in climate with the presence of greenhouse gases and atmospheric aerosols. RegCM3 has been tested and shown to successfully simulate regional climate in a variety of domains throughout the world (c.f., Giorgi et al., 2006). Further details about RegCM3 can be found in Pal et al. (2007) and references therein.

Recently, RegCM3 has been updated to include a state-of-the-science land surface model, the Common Land Model version 3 (CLM3) (Steiner et al., 2005; Steiner et al., in preparation). This allows a more detailed and accurate treatment of the land surface energy balance, surface hydrology, and vegetation. The inclusion of CLM in RegCM improves the ability of the regional model to simulate climate. Past work has shown that an early version of CLM (CLM0) coupled to RegCM improved the simulation of surface climate in East Asia (Steiner et al., 2005). Recent work indicates that CLM3 greatly improves the precipitation and land-atmosphere interactions in

RegCM3 over regions of strong land-atmosphere coupling, such as the African monsoon region (Steiner et al., in preparation). We expect that the inclusion of CLM3 will also lead to substantial improvements in the prediction of South American climate and will be essential for accurate predictions of precipitation and evapotranspiration at the watershed scale.

The CLM3 is a community-based land surface model developed at the National Center for Atmospheric Research for integration with climate models (Oleson et al., 2004). The model simulates the exchange of energy, momentum, water and carbon between the land surface and the atmosphere by a series of biogeophysical parameterizations. Within each atmospheric model grid cell, CLM3 treats land surface heterogeneity by the "mosaic" method (Koster and Suarez, 1992), which divides each cell into a subgrid hierarchy composed of land units (representing glacier, wetland, lake, urban, and vegetated land cover), and a second and third hierarchy for vegetated land units, including different snow/soil columns (for different vegetation fractions) and plant functional types (PFTs) (Oleson et al., 2004). Biogeophysical processes are simulated for each landunit, column and PFT separately, and then averaged for return to the atmospheric model. Simulated biogeophysical properties include 1) vegetation composition, structure and phenology, 2) absorption, reflection and transmittance of solar radiation, 4) absorption and emission of longwave radiation, 5) momentum, sensible heat, latent heat, canopy evaporation, and transpiration fluxes, 6) heat transfer in soil in snow including phase changes, 7) canopy hydrology, 8) snow hydrology, 9) soil hydrology, and 10) stomatal physiology and photosynthesis, 11) lake temperatures and fluxes, 12) routing of runoff from rivers to oceans, and 13) emission of biogenic VOC.

3.3 Climate Change Scenarios

In order to evaluate the impact of future climate on water resources in South America, we are developing decade-length simulations at a 25km resolution focused on the northern portion of South America (Figure 1). These simulations include:

1. Present day simulations (1990-1999) driven by NCEP or ERA reanalysis data boundary conditions and prescribed sea surface temperatures, and by GCM boundary conditions using either the ECHAM5 model (Roeckner et al., 2003) or the NCAR CCSM (Collins et al., 2006).
2. Future climate simulations for two climate scenarios in order to provide a range of possible climate outcomes:
   - a short-term future simulation (2010-2019), and
   - a long-term future simulation (2050-2059).

   Boundary conditions for the two future climate simulations are derived from a GCM, such as ECHAM5 model (Roeckner et al., 2003) or the NCAR CCSM (Collins et al., 2006). For the future climate, we utilize global climate model output for boundary conditions from the two IPCC scenarios (IPCC, 2007):
   - A1B scenario, representing a scenario of rapid economic growth balanced across various energy sources (mid-range emissions)
   - B1 scenario, representing continued and integrated growth with technological improvements (lower emissions).

For the present-day and future climate scenario simulations, the change in surface climate, including temperature, precipitation, cloud content, solar radiation are analyzed, as well as the and the seasonal and interannual variability of these climate parameters. Additionally, climate and CLM3 model output (e.g., evapotranspiration, soil moisture) from these three scenarios are used as input into the catchment hydrologic model discussed next.

4. Component 2: Assessment of Climate Change on Water Availability

4.1 Background

Drainage basins, or catchments, define a portion of a landscape where precipitation and snow melt drain downhill into a river, lake or ocean. Drainage basins are separated from each other by topographic high points, or drainage divides. Basins of different size can be defined and form a fundamental unit for understanding water stores and fluxes because the majority of water that exits a basin as river discharge originates as precipitation on the catchment.

In this study, we quantify the impact of climate change on the La Paz river drainage basin in northern Bolivia **(**Figure 2**)**. This river and associated tributaries have a drainage basin area of ~800 km^2. This basin was chosen because it contains the largest urban area in Bolivia (cities of La Paz, El Alto, and Viacha) with an estimated population of 1.6 million. Furthermore, this region covers a large range of elevations (up to ~3000-4000 m) with variable vegetation types, and semi-arid to humid conditions. As such, future climate change has potential to severely impact water resources and vegetation in this catchment. Finally, La Paz is the capital of Bolivia and responsible for legislation that could impact water resource management in all of Bolivia. Quantification of changes in water resources in this catchment set the backdrop for our analysis of water resource management and policymaking in section 5.

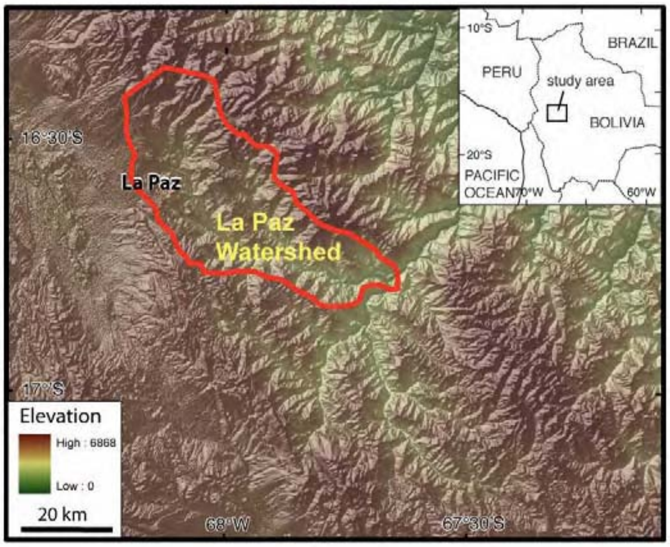

Figure 2. Digital elevation model of the La Paz watershed and surrounding region. Predicted future changes in precipitation from our regional climate modeling are used as input into the TOPMODEL hydrologic model to quantify hydrological changes in the La Paz watershed.

4.2 Catchment Scale Hydrologic Modeling

Present and future changes in precipitation from our climate model predictions are used to calculate variations in runoff and surface water availability in the La Paz drainage basin. Daily variations in precipitation will be input to the TOPMODEL hydrologic model to track changes in river discharge. TOPMODEL is a well-established and freely available rainfall-runoff model that bases predictions on an analysis of watershed topography (e.g., Beven and Kirkby, 1979, Beven, 1997, 2001). The program simulates hydrologic fluxes of water such as the infiltration-excess overland flow, saturation, overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing through a catchment.

Because hydrologic parameters can be highly variable and difficult to constrain, the TOPMODEL approach is to minimize the number of free parameters. The required model inputs include daily catchment-averaged precipitation and evapotranspiration, a digital elevation model, the mean soil transmissivity, a transmissivity profile decay coefficient, a root zone storage capacity, unsaturated zone time delay, and channel routing velocities. Model outputs include contributing area maps for runoff and river discharge hydrographs. We use river discharge predictions as a measure of future changes in water availability for inhabitants of the La Paz watershed, and for policymaking practices discussed in section 5.

Our estimation of input parameters and application of TOPMODEL follow the approaches of Molicova et al., (1997), Ostendorf and Manderscheid, (1997), Lamb et al., (1997), and Beven and Wood (1983). Catchment specific inputs are partially available from the Instituto Geographico Militar (2000). A 30-m horizontal resolution digital elevation model is generated using existing Aster satellite data. The range of possible input parameters and their uncertainties are determined by using a Bayesian based Monte Carlo simulations for TOPMODEL parameter estimation (GLUE approach, e.g. Romanowicz et al., 1994). Using this approach, model inputs are calibrated via a comparison between modern predicted and observed (Guyot et al., 1988) discharge.

4.3 Hydrologic Modeling Scenarios

We are conducting two different model scenarios to evaluate changes in water availability. In each scenario, the catchment hydrology and discharge are quantified using output from the climate models.

Scenario 1: Model calibration to modern climate. First, model inputs are calibrated by comparing predicted discharge with observed discharge (Guyot et al. 1988) using stream gauge and meteorological measurements in the La Paz drainage basin. This step is essential for characterizing the range of model inputs (mainly the average soil transmissivity) possible for the watershed and for calibrating TOPMODEL. Second, the calibrated TOPMODEL is used to simulate discharge resulting from regional simulations of modern climate (section 3). These simulations form our baseline simulations for comparison to future simulations, and are compared with modern stream gauge observations to evaluate model performance and our methodology. Depending on the outcome of this step, we may or may not need to refine our methodology through, for example, further downscaling of our regional climate model predictions.

Scenario 2: Future predictions of water availability. The calibrated TOPMODEL is used to predict changes in seasonal river discharge for short-term (2010-2019) and long-term (2050-2059) future simulations. These future predictions are differenced from our baseline simulation to evaluate changes in magnitude, interannual variability, and seasonality of water availability in the La Paz catchment and neighboring urban areas. These results form the basis for developing water management guidelines in Bolivia.

5. Component 3: Water Resource Management and Policymaking

The potential for climate forecasting to support decisionmaking and improve proactive planning to mitigate negative effects of climate variability and change has been long theorized (Glantz 1996). However empirical research on the subject has painted a much more complex picture in which practical application of climate forecasting (especially El Niño forecasting) has been constrained by a number of factors including access to information, communication and comprehension of probabilistic information (Nicholls, 1999); lack of availability of alternative technologies and low forecast skill (geographically and temporarily) (Lemos et al. 2002, Broad et al. 2002); and the formal and informal institutional and organizational environments that shape decision making (Callahan et al. 1999, Rayner et al. 2005, Lemos in press). Yet, through all the criticisms, the expectation of utility of climate information for decision making and planning has persisted and more recent research has shed light on growing evidence of the positive impact climate predictions can have on water management (Pagano et al. 2002). In principle, climate knowledge can contribute to more effective water management by informing stakeholders about expected stresses resulting from negative impact of climate change. Policy makers can then plan ahead to reduce water systems' sensitivity to these impacts and to increase overall adaptive capacity to respond, cope and recover from these negative impacts. In this context, the ability to transfer knowledge and adopt innovation is an essential factor in building adaptive capacity to climate change (Smit, Burton et al. 2000).

Most empirical studies of the use of information in policy find the institutional context in which information is produced and used has a fundamental impact on the ability of policymakers to incorporate new information tools in their decision-making process. For example, recent research on the use of climate information in water management in the United States suggest that: a) water managers are heavily constrained by institutional arrangements such as water laws, related regulations, institutional linkages, local politics, inter-agency competition, etc. which make water management systems inflexible and resistant to the introduction of new decision-making technology; b) water decision-making systems are greatly fragmented and complex, spanning multiple scales and conflicting jurisdictions, c) change is hard to implement because of inertia built into the system by large and expensive infrastructure, private interests, and regulatory agencies; d) current state-of-the-art climate forecast information is perceived as too uncertain, lacking in geographical and temporal specificity, lacking in interpretation and demonstrated utility, and too unreliable (low skill) for water managers' decision making needs; and e) there is still a significant disconnect between information producers and users (Pulwarty and Redmond 1997, Callahan et al. 1999, Carbone and Dow 2005, Rayner et al. 2005).

The use and usability of climate information for water management is modulated by several factors including availability of resources, perception of 'fit' between available information and decisionmaking needs and institutional opportunities and constraints to adopt innovation (Lemos, in press). Figure 3 depicts a simplified model of the opportunities and constraints to the use of climate information by water managers (Lemos, in press).

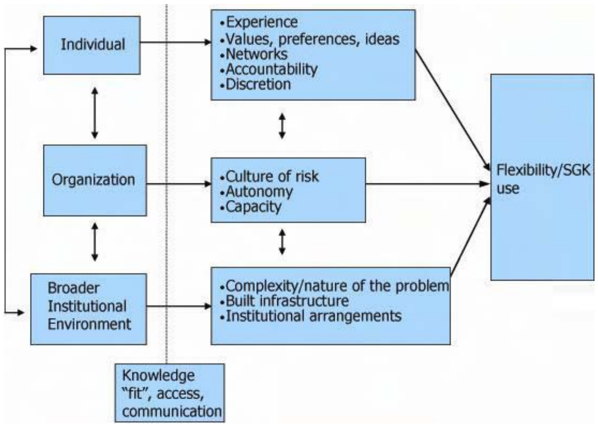

Figure 3. Simplified institutional model.

In this study we assess these factors by carrying out an in-depth qualitative assessment of current management practices, past adaptive actions and knowledge needs in Bolivian water management organizations. At the policy/management level, the field team conducts in-depth interviews with policy and decision-makers at the watershed, state, and federal levels. Key informants are identified through purposeful, opportunistic sampling where individuals "snowball" (refer to other individuals, and the original list of persons consulted grows according to recommendations of the interviewees themselves). In this case, snowball selection is appropriate because, rather than formal hypothesis testing, the main goal of such interviews is to gauge policymakers' perceptions of their constraints and opportunities to use climate information in decision-making.

6. Conclusions/Anticipated Outcomes

The availability of water resources in a changing climate will be one of the most important issues confronting many regions, including the nations of central South America. Effective water policy can mitigate the effects of changing water resources, but requires prediction of future water availability at an appropriate scale. We have designed and begun to implement a strategy for moving from regional climate prediction to policy development. Our strategy is novel and important in the following ways:

- In South America, the impacts of future climate change have received little attention, are much less certain, and will likely impact a large portion of the population. The assessment of climate impacts on regional and local scales is an emerging field with considerable room for growth, and represents the first component of our proposed research project. Our implementation of a state-of-the-science land-surface model represents a major advance that will likely lead to improved simulation of land-surface hydrology.
- The second component of strategy, investigating the impact of climate change on water resources, has been highlighted in the 2007 IPCC report as a research area that requires development and innovation. In general, the downscaling and translation of climate change to scales of human interest is a significant challenge. Our integration of climate prediction to catchment-scale hydrologic modeling directly addresses these issues, and will be an important investigation of how to couple these processes across different spatial scales.
- The third component of our strategy is integral to producing predictions that have practical utility. By empirically assessing the opportunities and challenges for the use of climate predictions in water management, this study has the potential to inform policymakers about state-of-the-art decision support tools for building the capacity of water systems to adapt to climate change and to provide scientists with information on data needs from users. This interaction between the physical and social science communities is essential to a fully integrated and policy-relevant effort in climate prediction and global change research. In this sense, this study may have a direct effect on social and economic planning for the mitigation of negative global climate phenomena, with real benefit to vulnerable groups in Bolivia and other parts of the world. Additionally, by examining political and cultural aspects of climate predictions applications in the water sector, this study aims at contributing to analytical frameworks within the policy sciences, such as social constructivism, policy analysis, and the sociology of science.
- Finally, this research project is truly multidisciplinary and brings together expertise in disparate fields, including Earth surface processes and hydrology, regional climate modeling, climate change and modeling, and human dimensions of climate change and environmental

policymaking. This effort bridges physical and social science disciplines that have traditionally been separated by cultural divides.

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Graham Environmental Sustainability Institute
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Establishing the Research Agenda
March 26-27, 2008

Emerging Contaminants in Rural Water Systems: Establishing the Research Needs

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1. Introduction

The nexus between water quality and public health in the rural environment is complex. Non-point sources of both chemical and biological contaminants are predominant and there is little monitoring and understanding of the system as well as the types of pollutants and emerging contaminant risks. Emerging contaminants are those for which documented incidences in water supplies have increased in recent years. Many of these contaminants are currently not regulated. In addition, numerous chemicals and microorganisms that have not historically been considered to be pollutants have emerged as prominent agents that may transmit waterborne disease to humans.

A wide array of water contaminants are associated with water in rural areas (fertilizers, pesticides, animal and human pathogens, pharmaceuticals etc.). Particularly important categories of emerging contaminants of concern that may originate in rural areas and end up in rural water systems are zoonotic pathogens (pathogens that may infect both animals and humans), antibiotics (and possible resultant antibiotic resistance genes), and cyanotoxins (produced by toxic algal blooms). The potential presence of emerging contaminants in combination with current agricultural waste, wastewater, and drinking water management practices indicate an increased risk of exposure to harmful agents via water in rural areas.

2. Sources and Effects of Water Contaminants in Rural Systems

Rural areas are increasingly characterized by high density agriculture, large quantities of animals in relatively small spaces, and lack of advanced treatment systems for animal and human waste and wastewater. Figure 1 presents potential sources of contamination of surface water and groundwater in rural areas. Excess fertilizers and nutrients, pesticides, animal enteric pathogens, and human enteric pathogens are some of the contaminants that are observed in rural areas. The adverse effects of these contaminants on human health and the environment are numerous and some of them are listed in Table 1.

Water pollution in rural systems impacts the environment and therefore indirectly impacts human health in ways that are not well understood. For example, harmful algal blooms are increasingly observed in the US and worldwide and their presence is correlated with excess nutrients originating in high density agricultural areas. Worldwide, animal and human deaths and disease have been correlated with exposure to cyanotoxins produced by harmful algal blooms. Also, development of antibiotic resistance genes is an emerging issue of great concern with potential serious consequences such as the possibility un-controllable infections.

There are also direct impacts of water pollution on human health in rural communities. These direct impacts are demonstrated by the number of waterborne outbreaks that are observed in these systems. It is well known that poor water quality poses a direct threat to human health. It has been reported that 1.5-12 million people die per year from waterborne diseases (Gleick, 2002). Most of the waterborne disease outbreaks worldwide and in the US are associated with rural drinking water systems. According to Craun *et al.* (2006), in the US, during the 12 year period of 1991-2002, 207 waterborne disease outbreaks and

433,947 illnesses were reported; 42% of these outbreaks occurred in non-community water systems, 22% occurred in individual systems such as private wells, and only 36% occurred in community systems. In most cases drinking water supply in rural areas is provided by groundwater wells that in some cases are shallow. Between 1981 and 1998, 50% (210 of 417) of the reported waterborne disease outbreaks were linked to contaminated groundwater (Craun, 1992; Craun *et al.*, 2003). Also, Lee *et al.* (2002) reported 696 outbreaks in the United States between 1971 and 2000, of which 59% were linked to groundwater.

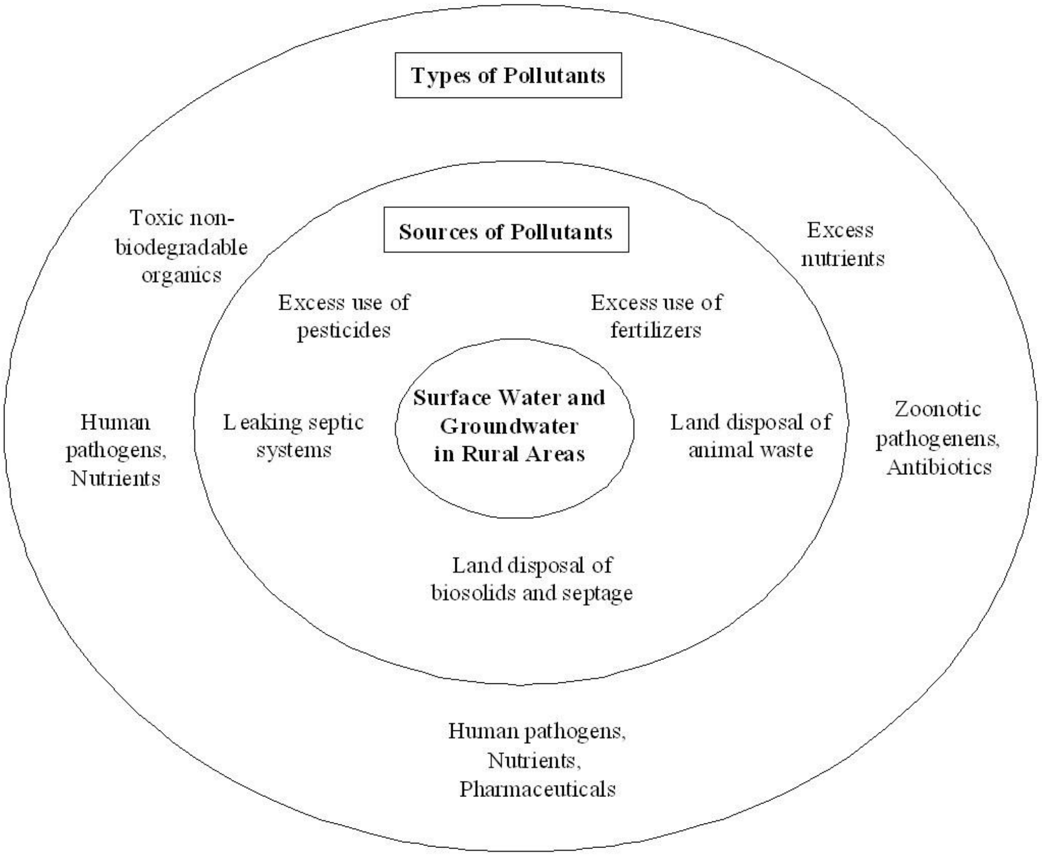

Figure 1. Sources of Water Contaminants in Rural Systems

Table 1. Potential Adverse Effects of Water Contaminants

Types of Pollutants	Adverse Effects on the Environment	Adverse Effects on Human Health
Excess nutrients	Blue-green algae blooms	Exposure to cyanotoxins
Zoonotic pathogens	Animal infections	Human infections
Antibiotics	Antibiotic resistance genes	Antibiotic resistant infections
Human pathogens		Human infections
Toxic organics	Toxicity to aquatic life	Carcinogenesis

3. Current Water Management Status in Rural Systems in the US

Currently water management and testing in rural water systems is minimal or non-existent. Table 2 summarizes the current situation in rural areas: drinking water is minimally treated; animal waste from livestock production facilities is often land disposed without prior treatment; domestic wastewater is often treated on-site without regular monitoring; and biosolids from municipal wastewater utilities are often applied to land in rural areas. Water quality monitoring and water quality protection in rural areas is important because of the potential of increasing risk of human exposure to emerging waterborne contaminants.

Table 2. Water and Wastewater Management in Rural Areas

Drinking Water
• Drinking water is often provided by private or community groundwater wells in close proximity to septic systems and livestock manure storage and land application areas. • Drinking water often receives no or minimal treatment (chlorine addition). • Drinking water is rarely monitored.
Animal Waste
• Increasing concentration of livestock in larger production facilities in developed countries • High density subsistence agriculture in developing countries. • Untreated animal manure applied to land. • Potential transport of microbial contaminants, pharmaceuticals, pestisides and other contaminants to surface water and groundwater.
Domestic Wastewater
• Domestic wastewater managed in private septic or seepage systems. • Poorly functioning septic systems may leak contaminants to groundwater.
Biosolids Disposal
• Biosolids (treated municipal wastewater sludge) from municipalities applied to land in rural areas. • Untreated septage from individual wastewater systems applied to land in rural areas. • Potential for transport of contaminants to surface water and groundwater.

4. Pathogens

The possibility occurrence of zoonotic pathogens and human pathogens in rural waters is significant since animal waste and human wastewater is minimally treated in rural systems. Several zoonotic pathogens and human pathogens, especially virures are considered emerging contaminants. Current information on their occurrence, detection methods, transport pathways and overall risk for infection is limited.

Most of the reported waterborne diseases outbreaks in the US were related to microbial agents (parasites, bacteria and viruses), some to chemical agents, and some were of unknown etiology. The failure to identify etiologic agents is often due to lack of sensitive analytical techniques. For example, a recent survey by the Centers for Disease Control and Prevention (CDC) reported that one sixth (5 out of 30 cases) of drinking water-associated waterborne disease outbreaks during 2003-2004 were of unknown etiology because of a lack of available analytical methods (Liang *et al*., 2006). The Environmental Protection Agency suspects that many of the outbreaks due to unidentified sources were caused by enteric viruses (USEPA, 2006).

According to USEPA (2006) fecal contamination from livestock manure handling and storage facilities is one of the most important sources of groundwater microbiological pollution. Manure and other animal wastes contain high concentrations of infectious zoonotic pathogens such as viruses, protozoa and bacteria (Table 3: derived from Meslin, 1997; Slifko *et al*., 2000; Sobsey *et al*., 2001; Hubalek, 2003;

Gannon *et al*., 2004; Cliver and Moe, 2004; Palmer *et al*. 2005). Water contaminated with zoonotic pathogens is a suitable vehicle for human exposure.

Table 3. Infectious Zoonotic Waterborne Pathogens

Viruses Hepatitis E virus, Norwalk-like Calicivirus (some strains), Rotavirus A (some strains), Adenovirus (some strains)
Bacteria *Salmonella, Campylobacter, Escherichia coli, Aeromonas hydrophila, Yersinia enterocolitica, Vibrio cholerae, Leptospira*
Parasites *Cryptosporidium parvum, Giardia lamblia*

A recent outbreak in a small farming community in Canada indicates that the potential of human infections caused by zoonotic pathogens is real and may have serious consequences. More than 2,300 people in the town of Walkerton, Ontario suffered gastrointestinal illness and seven died when its shallow water supply was contaminated by manure pathogens from a nearby farm after more than five inches of rain fell over a five day period in May, 2000 (Hrudey and Hrudey, 2004).

Zoonotic viruses and human viruses are of particular interest for the following reasons: viruses are the smallest of all pathogens and their small size can facilitate transport through the soil; viruses are found in groundwater; most groundwater outbreaks of unknown etiology are thought to be of viral origin; viruses have low die-off rates; viral infections may lead to chronic health effects.

Figure 2 describes potential sources of viral pollutants in a typical rural community in the US. The figure shows that groundwater and surface water in rural areas may get contaminated from land application of manure, biosolids and septage; and by potentially leaking septic systems. Human exposure may occur through drinking water (usually untreated groundwater), irrigation and recreational uses of surface water.

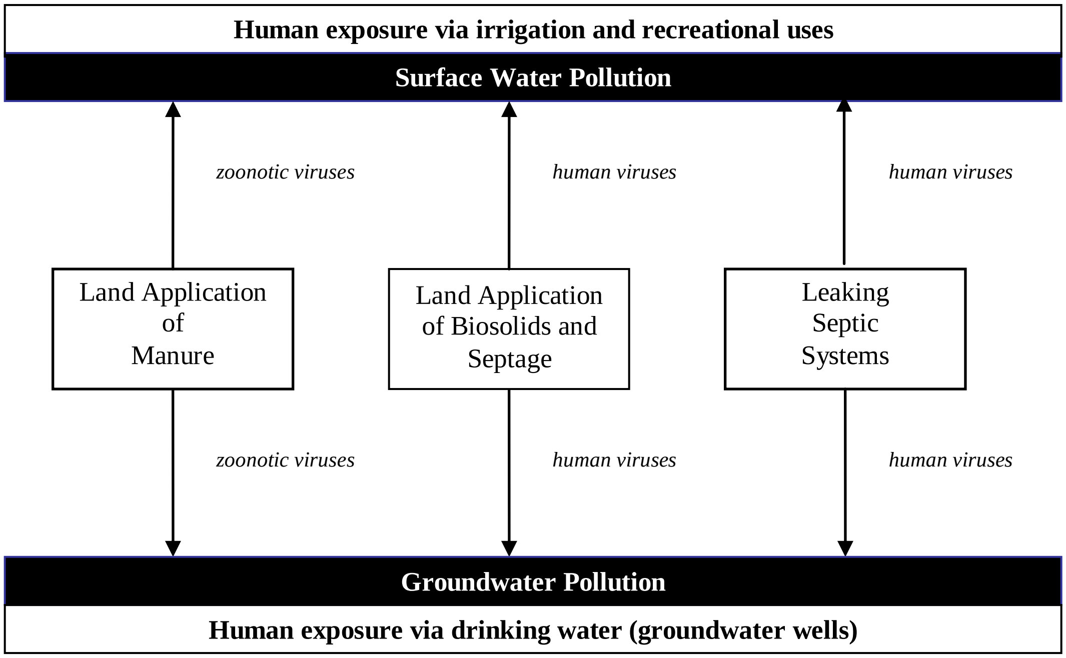

Figure 2. Potential Sources of Water Pollution in a Typical Rural Community in the US

5. Antibiotics

In the past, the environmental fate and effect of pharmaceuticals was largely ignored since the benefit was assumed to greatly outweigh any environmental concern. This perspective however changed in 2002 when USGS scientists published a survey of organic contaminants, including pharmaceuticals in 139 streams in 30 states in the US (Kolpin *et al.* 2002). Since then, numerous other studies confirmed the widespread distributions of pharmaceuticals in surface and groundwater.

Large quantities of antibiotics are consumed in animal agricultural production and a significant fraction of these antibiotics are excreted in animal manure. Table 3 summarizes the occurrence of antibiotics in manure (Aga *et al*., 2003; Campagnolo *et al*., 2002; Kumar *et al*., 2004; Macauley et al., 2006; Mackie et al., 2006), surface waters (Boyd & Furlong, 2002; Campagnolo *et al*., 2002; Kolpin *et al*., 2002; Lindsey *et al*., 2001; Stackelberg *et al*., 2004; Yang & Carlson, 2004; and groundwater (Batt *et al*., 2006; Campagnolo *et al*., 2002; Karithikeyan & Meyer, 2006; Mackie *et al*., 2006). The land application of animal manure results in contamination of surface and groundwater. An emerging issue of concern is the development of microorganisms with antibiotic resistance genes in rural areas.

Table 3. Selected Antibiotics Found in Manure, Surface Waters, and Groundwater in the US

Antibiotic	**Class**	**Manure Concentration (µg/L)**	**Surface Waters Concentration (µg/L)**	**Groundwater Concentration (µg/L)**
Chlorotetracycline	Tetracycline	0.1 – 7,900	0.10 - 0.69	
Tetracycline	Tetracycline	0.26 - 410	0.06 - 0.14	0.5 - 0.09
Lincomycin	Lincosamide	3 – 1,470	0.05 - 0.73	1.4
Tylosin	Macrolide	3,300 – 4,000	0.05 - 0.28	
Sulfamethazine	Sulfonamide	3 – 1,240	0.05 - 0.22	0.076 - 7.6

6. Cyanotoxins

Cyanotoxins are emerging contaminants that are associated with rural water pollution, lakes, ponds, ditches, and even small rivers or stagnant areas in rivers. Some species of fresh water cyanobacteria that make up algal blooms produce high levels of toxins, resulting in what are commonly called “harmful algal blooms.” The toxins are generally referred to as cyanotoxins. One of the basic reasons of increased occurrence of harmful algal blooms and the associated production of cyanotoxins, has been the increased nutrient loading of freshwater originating from farming areas. Blooms of toxic cyanobacteria have occurred worldwide for many years and have led to illness in humans and to the death of animals (Carmichael *et al*., 1988, 2001; Mahmood *et al*., 1988; Yu, 1989; Edmonson, 1991; Teixera *et al*., 1993; Kotak *et al*., 1995; Harada *et al*., 1996; Ueno *et al*., 1996). Cyanotoxins of high acute toxicity are of most concern, and include hepatotoxins (toxins that affect the liver) such as microcystin, and neurotoxins (toxins that affect the nervous system) such as anatoxin.

7. Research Needs

A systems approach is needed to address the issue of emerging and even conventional contaminants in rural water systems. The initial steps in developing practical solutions will be to indentify and document the characteristics of the rural environment (occurrence of contaminants, assessment of current water and waste management practices etc.), analyze the existing scientific information to further the understanding of the system, and identify key gaps in knowledge. Table 4 outlines some areas in need of further research. There is a need to investigate advanced analytical detection methods that allow quantification of emerging contaminants and source tracking to effectively address the issue of rural water quality. Use of broad based methods which could screen large numbers of contaminants would be of great interest. In addition, transport mechanisms of emerging contaminants in soil and water systems, exposure pathways, and risk assessment of human exposure to contaminants in rural systems need to be evaluated. Lastly, optimization of water and waste processes that are applicable to rural areas is needed. Investigation of the impact of climate change in the rural environment is of interest. It is known that climate impacts agriculture and water systems, but the intersect between climate change water and health at the scale of the rural environment is not understood.

Table 4. Emerging Contaminants in Rural Systems: Research Needs

Detection and Occurrence
Advanced Analytical Methods • *Microbiological Contaminants*: Rapid quantitative PCR methods in combination with infectivity methods • *Chemical Contaminants*: environmental sample preparation, LC/MS/MS, low detection limit methods Source Tracking • Correlations between conventional and alternative microbiological indicators and emerging pathogens • Correlations between conventional chemical indicators and emerging chemical contaminants
Transport
Transport mechanisms of emerging contaminants from manure and biosolids to groundwater and surface water. • Physiochemical processes such as sorption, speciation, biotic and abiotic transformations of contaminants in soil and water. • Advanced source tracking laboratory techniques coupled with nested field sampling and process modeling.
Exposure Pathways and Risk Assessment
Risk assessment of human exposure to contaminants. • Identification of direct exposure pathways (drinking contaminated groundwater, exposure to contaminated surface water via irrigation and recreational uses) • Identification of indirect exposure pathways (algal toxin blooms, development of antibiotic resistance genes etc.) • Emerging contaminant data compilation. • Adverse effects of long-term exposure to trace-level contaminants in water. • New approaches to evaluate toxicity of emerging contaminants. • Risk assessment model development.
Waste and Water Treatment
Optimization of agricultural waste treatment processes to remove and inactivate emerging contaminants. • Optimization of existing techniques (land application and crop systems). • Investigation of the feasibility of alternative techniques for treatment of animal waste (advanced systems such as membrane bioreactors etc). • Investigation of the feasibility of co-treatment of human and agricultural waste. Optimization of sludge processing and biosolids disposal • Evaluation of removal and fate of emerging contaminants Optimization of drinking water treatment in rural systems • Investigation of alternative techniques for treatment of groundwater used for drinking (chlorination, UV, combination)

To effectively address the problem of water pollution in rural systems, a comprehensive management plan is needed that integrates the values and needs as well as the efforts of all stakeholders within a risk analysis framework. Cooperation of farmers, township officials and individual homeowners is critical to achieve an effective plan. Awareness and education of responsible parties is a first step to an integrated plan and requires education of farmers, township officials, individual homeowners and future water quality professionals. Interdisciplinary collaborations of scientists, engineers, and other professionals are essential. Experts in emerging contaminant detection and quantification, environmental and agricultural engineers, chemists, microbiologists, soil scientists and toxicologists need to work together with modelers, statisticians, risk assessment professionals, public health professionals, public outreach professionals and environmental law professionals.

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March 26–27, 2008

Cyberinfrastructure for Risk Forecasting and Communication: Application to the Great Lakes Observatory System

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Abstract

Environmental sensing encompasses a broad range of systems (surface waters, groundwater, atmospheric, etc…) and spatially distributed attributes (microbial, chemical, physical) that describe the system and its perturbations in response to human interference (industrial discharge, agricultural runoff, etc…). Microbiological pollution represents one of the most widespread impairments of potable and recreational waters, yet the sampling design for public health protection exhibits significant uncertainties due to sample selection constraints, and the delay in obtaining analytical results for effective decision-making. With the advances in wireless sensor technology, networks have the promise to provide useful spatio-temporal representation of environmental signals that cover large geographical areas. As State and Federal agencies have started to invest in these systems, there is a need to design network optimization strategies that explicitly incorporate sensor characteristics, microbiological criteria and economic constraints in the decisions. To enable adoption of these technologies, we need to ensure that the value proposition of environmental sensing cyberinfrastructure is defined not only from a technical perspective (i.e. What technical problems are we trying to solve?), but also from a market-based perspective (i.e. What are the business fundamentals that will allow these technologies to come to the market?).

These concepts capitalize on on-going early stage data collection efforts by the Great Lakes Environmental Research Laboratory (GLERL) in Lake Erie (wireless sensor hubs to analyze causes and forecasting of hypoxia), the Macomb County Health Department in Lake St. Clair (wireless chemical, and off-line microbial analysis at water intakes), the Great Lakes Commission (GLC) managed Great Lakes Observatory System (GLOS), the NSF-supported WATer and Environmental Research Systems Network (WATERS Network; http://www.watersnet.org/), and the Macomb County Public Health Department which manages the Lake St. Clair Regional Monitoring Project (http://www.lakestclairdata.net/). Leveraging each of these, currently separate, efforts towards deploying a data-driven sensing network for risk forecasting and communication in the Lake Huron-Lake Erie Corridor will allow the University of Michigan and its private and government partners to position itself to establish a cyberinfrastructure testbed in the Great Lakes region under the NSF Major Research Equipment and Facilities Construction (MREFC) program. Funded by congressional appropriation in 2011, this program releases funding to provide unique capabilities at the frontiers of science and engineering. Several authors of this white paper (Finholt, DePinto), and the Association of Environmental Engineering and Science Professors (AEESP; Adriaens, Vice President; Love, Board Member) have been involved over for the last few years in defining the science, education, and cyberinfrastructure needs of the WATERS Network. This paper illustrates technical advances and market-based strategies in cyberinfrastructure (hardware, software, data integration and visualization) as applied to address microbial sensing needs.

The overarching goal of the white paper is to develop a framework to establish a microbial and chemical risk forecasting cyberinfrastructure network along the Lake Huron-Lake Erie corridor.

1. The WATERS Network

The WATERS Network is a distributed network for research on complex environmental systems. It emphasizes research on the nation's water resources related to human-dominated natural and built environments. The network will be comprised of: interacting field sites with an integrated CI; a centralized technical resource staff and management infrastructure to support interdisciplinary research through data collection from advanced sensor systems, data mining and aggregation from multiple sources and databases; cyber-tools for analysis, visualization, and predictive multi-scale modeling that is dynamically driven. As such, the network will transform workforce development in the water-related intersection of environmental science and engineering, as well as enable educational engagement opportunities for all age levels. The scientific goal and strategic intent of the Network is to transform our understanding of the earth's water cycle and associated biogeochemical cycles across spatial and temporal scales-enabling quantitative forecasts of critical water-related processes, especially those that affect and are affected by human activities. This strategy will develop scientific and engineering tools that will enable more effective adaptive approaches for resource management.

The need for the network is based on three critical deficiencies in current abilities to understand large-scale environmental systems and thereby develop more effective management strategies. First we lack basic data and the infrastructure to collect them at the needed resolution. Second, we lack the means to integrate data across scales from different media (paper records, electronic worksheets, web-based) and sources (observations, experiments, simulations). Third, we lack sufficiently accurate modeling and decision-support tools to predict the underlying processes or subsequently forecast the effects of different management strategies. The network will foster cutting-edge science and engineering research that addresses major national needs (public and governmental) related to water and include, for example: (i) water resource problems, such as impaired surface waters, contaminated ground water, water availability for human use and ecosystem needs, floods and floodplain management, urban storm water, agricultural runoff, and coastal hypoxia; (ii) understanding environmental impacts on public health; (iii) achieving a balance of economic and environmental sustainability; (iv) reversing environmental degradation; and (v) protecting against chemical and biological threats. WATERS has been supported by $ 1M of NSF funding for 3 years has a Program Office, and has supported pilot projects across the US. The Program Office and committee have been established to prepare an application for MREFC funding in 2011.

Figure 1. Lake Huron –Erie Corridor

Why the Great Lakes? There is a strong rationale for choosing the Great Lakes in general, and the lake Huron-Lake Erie corridor as a test bed. First, they are representative of the challenges facing the management of large water bodies in the United States and elsewhere in the world. Second, the lakes are a critical freshwater resource for the United States and Canada, impacting national economic sectors such as agriculture, power generation, steel production, shipping, drinking water and bottling industries, tourism, and natural resources management. Also, given the potential impacts of climate change on water resources in more arid areas of the western (and now Southeastern) U.S., there will be a growing pressure to divert Great Lakes water to those areas, thus creating a significant management issue. In addition, it will be possible to take advantage of existing programs and partnerships in collecting data and planning research activities.

The CI will take into account the properties of collected data, and the representation and utility of the collected data. To maximize the utility of the network information to public stakeholders and for research purposes, the proposed project will focus on translating the modeled data using (near) real time communication modes, including interactive axis grid displays, and teleconference uplinks. Advancing the theoretical understanding of spatio-temporal risks through an application-driven sensor network design, and implementation of an effective risk communication strategy through environmental CI, offers unique advantages to integrate sensor network implementation in policy designs for multi-stakeholder source water protection.

2. Microbial Sensing: Problem Definition and Motivation

Microbiological contamination represents one of the most widespread impairments of potable source water and recreational waters. To protect public health and ensure the microbiological and chemical safety of source water, the USEPA has required the development of source water assessment and protection programs (SWAP) to delineate the source water protection area, to inventory contaminant sources and to determine the susceptibility of the source area to contamination. Implementation of these plans requires extensive monitoring programs for biological and physical water quality indicators, in support of the quantitative guidelines developed for human health protection. Specifically for microbiological pollution, the guidelines usually recommend collecting a minimum number of water samples, estimating the density of a target (indicator) organism in the samples, computing a number of summary statistics and comparing them with predefined limits [EPA-86, NRC-04]. Information on the presence and levels of pathogenic organisms is required routinely and quickly in order to monitor the risk of waterborne disease to human health, often using a combination of microbial analysis and predictive (pathogen loading) modeling tools [EPA-99]. In most cases, there continues to be a lack of scientific data to support monitoring schemes that would provide the most meaningful information about whether the guidelines are met. For example, the EMPACT (Environmental Monitoring for Public Access and Community Tracking) Beaches project [EPA-05] recently reported on how the compounded uncertainty of the collected summary statistics and the delay in obtaining analytical results led to misdiagnoses of problems and therefore to incorrect recreational water management recommendations.

To reduce the uncertainty associated with delayed decision-making, a wide range of model types, and complexities, are used [summarized in EPA-99]. Considering the quick turnaround time needed for decisions of a recreational and consumptive nature, simple models are most often used. Computer models that predict pathogen concentrations by simulating the dominant mixing and transport processes in the receiving water include modules to characterize point and non-point sources of pathogens to establish the loading rates, estimate the dominant fate and transport processes to predict pathogen distribution, and interpret the model output to find the pathogen concentration at a point of interest to determine the need for an advisory. The predictive capability of available methods and models exhibits considerable uncertainty in space and time, and requires either measured pathogen concentrations (diagnostic) or surrogate triggers to validate the likely occurrence of a microbial event.

Advances in wireless technology and the design of intelligent sensors have the promise to improve environmental monitoring of water bodies, by providing useful spatio-temporal representations of environmental signals over large geographical areas [EGPS-01, SOPHME-04]. A wireless sensor network needs to be co-optimized to sample physical heterogeneity while maximizing network longevity and robustness under harsh environmental conditions, characterized by internal (e.g. calibration) and external (e.g. weather) failure [SBWMAMRTRG-03]. Network designs such as multi-hop wireless mesh, biologically-inspired decentralized management, and tiered embedded networks have been proposed to address the robustness and longevity concerns, but have to date not been significantly constrained by specific environmental applications [e.g. PK-05].

The current deployment of wireless networks is largely limited to fixed-buoy systems focused on water quantity and physical characteristics of oceans and watersheds. Yet, public health officials are increasingly taking an active interest in wireless sensing technology to improve modeling and forecasting of public health and ecological risks, as well as for real-time monitoring of existing exposure [ASEGE-03]. For example, NOAA's Great Lakes Environmental Research Laboratory (GLERL) has deployed the Real Time Environmental Coastal Observation Network (RECON) pilot in the Lake Huron-Erie corridor. RECON (Figure 1) consists of six wireless observation systems that make detailed real-time scientific data - including various combinations of wind and wave information, air temperature, current and temperature profiles, dissolved oxygen, pH, turbidity, and water temperature - available through the Internet. Collected information is housed on servers located at GLERL (Ann Arbor) for both real-time and archival access. GLERL has agreed to make this data freely accessible to share experiences in design and implementation -- such as difficulties in establishing reliable data transfer protocols -- of the RECON infrastructure in order to inform the development of tools for the optimization of sensor networks.

These properties would be applicable to microbial systems, whose behavior is adaptive and responds to variations of various parameters in their environment, such as temperature, redox potential, pH and organic carbon, as well as extreme weather events such as precipitation and wind- or current-induced mixing [RDG-88, CPRL-01, JGRPCW-05]. The challenge presented to a wireless network design with application to microbial contamination is to align microbial action criteria with sensor characteristics (surrogate measurements vs. diagnostic analysis) as constrained by the economics of network deployment

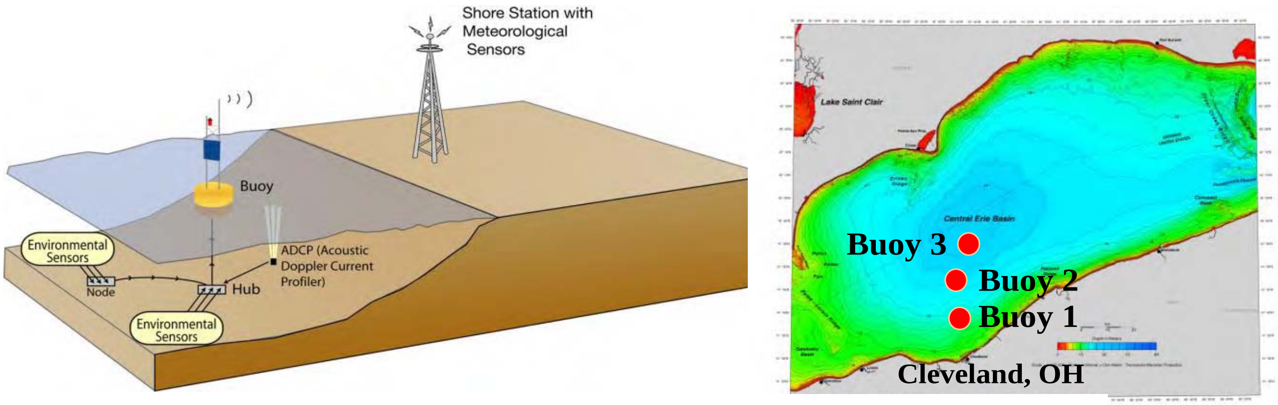

Figure 2. Configuration and Deployment of RECON in Lake Erie (NOAA-GLERL)

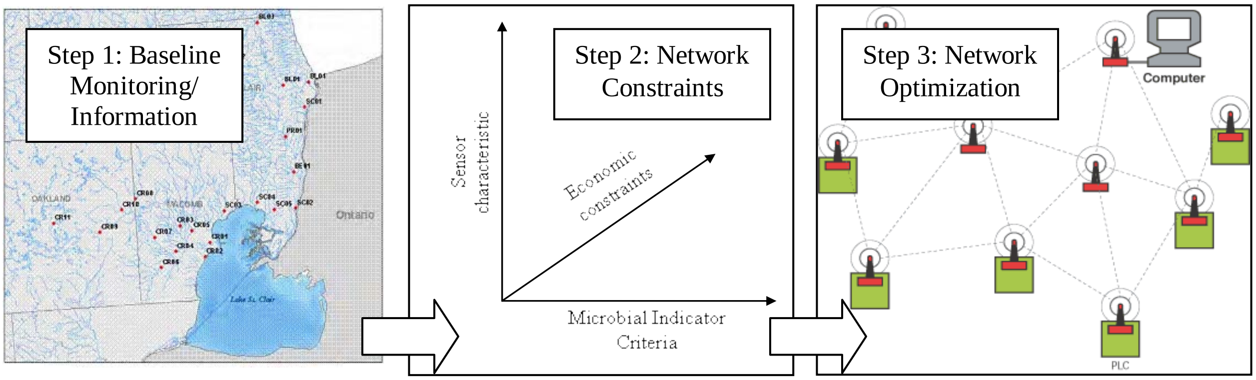

Figure 3. Conceptualization of the Proposed Wireless network Optimization Strategy for Microbial Attributes Constrained by Environmental Monitoring and Economic Considerations

within the physical boundaries and a priori knowledge of the natural system (Figure 3). The opportunity to advance the theoretical understanding through an application-driven network optimization strategy will aid in the integration of wireless sensor networks for source water protection.

3. Dynamic and Measurement of Microbial Indicators and Ancillary Data Source WATERS

The main causes of microbial contamination in surface waters include municipal discharges such as non-disinfected or poorly disinfected sewage treatment plant (STP) effluents [HEHHSLAC-93], combined sewage overflows (CSO) [MDMT-96], and urban stormwater [e.g. DM-93]. While the fecal pollution impacts of STPs have been recognized for a long time (and considered in locating STP outfalls either offshore in deep water or downstream from urban areas) CSOs and stormwater are discharged throughout urban areas and impact the receiving water and its uses [e.g. NRC-98]. Extreme precipitation and high water tables decrease the efficiency of onsite sewage disposal and may increase the likelihood of microorganisms in water systems. Increased urbanization has and will continue to alter watersheds and freshwater flows, resulting in contamination from both point sources and nonpoint sources.

Waterborne bacterial pathogens include *Salmonella*, *Shigella*, *Vibrio*, *Campylobacter*, *Yersinia*, and pathogenic *E. coli* strains. Indicator bacterial analysis includes total coliforms, fecal coliforms, E. coli, fecal streptococci, enterococci, and *Clostridium perfringens* [FMH-00, NRC-98], though problems remain in their use. This is in part due to the discrepancy in microbiological screening between finished waters, and source or recreational waters [AGGLSY-99], considering the range of point and nonpoint sources of fecal contamination. To fulfill various regulations, early warning of potential microbial contamination requires a rapid, simple, broadly applicable technique. For applications of health risk confirmation and to identify the source of a microbial contamination problem, the time frame and investment in indicators, indicator approaches, and methods must be greater [NRC-04]. ***The necessity for both descriptive and predictive analysis of these highly complex microbial ecosystems requires accurate detection and quantification of microbial parameters as a function of matrix variables describing the relevant physico-chemical environments on both a spatial and temporal basis.*** Databases such as EPAs Storage and Retrieval (STORET) system indicate that the distribution of water quality indicators, and the relationship between microbial and surrogate parameters for microbial events is highly site specific. Surrogate indicators for microbial pathogens, such as particles [BHBRLMA – 05], bacteriophages [LMMCCGCGSSJ-03], pH, temperature, redox potential, turbidity, and organic carbon [BROV-02; A-

05], and wet/dry weather events [e.g. JGRPCW-05], have been observed at statistically significant levels, and are used in predictive models.

The prediction of pathogen concentrations in source waters is largely based on simulating the dominant mixing and transport processes, and by incorporating multiple input parameters [EPA-99]. Considering the non-conservative nature of microbial contamination, its irregular distribution in space and time [e.g. EPA-05, JGRPCW-05], and variable concentration due to growth and interaction between microbial communities, the statistical output afforded by these models often results in misdiagnosis of water quality problems and incorrect management decisions. New modeling approaches such as artificial neural networks (ANN) have shown promising applications for microbial quality prediction in surface waters [e.g. NLB-02, BL-03], due to the capacity of these models to be trained, and interpret complex, inter-related, and often non-linear, relationships between multiple parameters. However, ***these models do not explicitly address the spatial and temporal microbial distribution and its associated uncertainty, and therefore do not inform monitoring network placement.***

3.1. Water Quality Metrics

Quantitative tests for indicator bacteria are used in monitoring surface drinking water intakes because these waters often show evidence of fecal contamination and are usually treated with filtration and disinfection. Interpretation of indicator data in recreational water applications is different again because the exposure can be more irregular and involves a more limited population at risk. Hence, wireless network design can only be optimized once data quality criteria are defined and quantified. ***Data quality is defined as the ability of the sensor network to represent the parameter distribution within the entire system, where this ability is defined based on specific criteria.*** Depending on the application or water quality management goal, these criteria may include: (i) Minimization of average uncertainty in spatial distribution; (ii) Minimization of single maximum point uncertainty in the system; (iii) Maximized ability to determine whether the parameter is above/below a given threshold at a receptor node. The choice of criteria and its associated requirements for network design will be aligned with NRC [NRC-04] recommendations (Figure 4) for phased monitoring. In all cases, however, the data quality assessment goes well beyond issues of measurement precision and sensor calibration. The implications for this task are that speed, cost, specificity, and sensitivity will drive the achievable data quality metrics and thus the associated network design objectives.

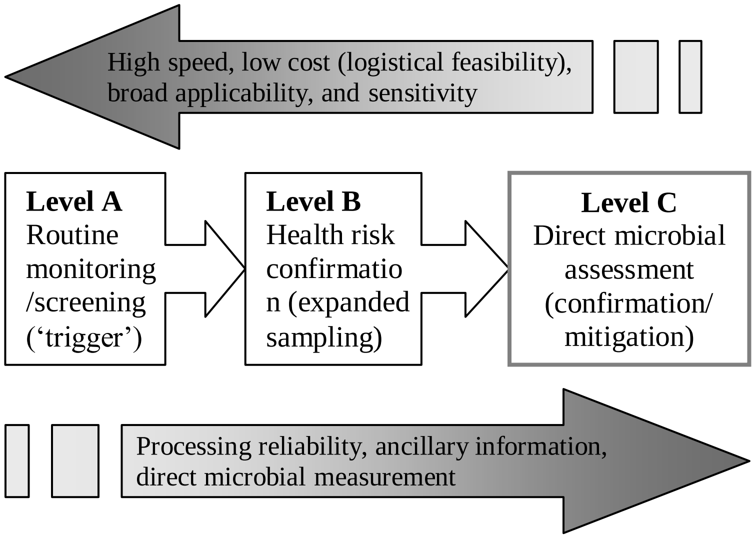

Figure 4. Phased Monitoring Framework for Selection of Data Quality Criteria for Waterborne Pathogens, Indicating Needs and Criteria of Network Attributes

Level A. Data quality for screening and routine monitoring is characterized by an emphasis on good spatial and/or temporal coverage and frequency of monitoring. Hence, the cost per node is a major driver for comprehensive sampling for screening purposes with broad applicability to a number of geographic locations, various types of watersheds, and different water matrices are preferred. Considering this driver, the sensor nodes will focus on collecting ancillary data, and on using spatial/temporal correlations between physical/chemical measurements and microbial events to inform the spatial characterization of possible microbial events, rather than using direct microbial analysis. Work in this task could include setting up univariate and multivariate statistical correlations using ANOVA- and ANN-based analysis of Lake St. Clair Data (http://www.lakestclairdata.net/), as well as review of published literature to inform the goal of minimizing the average spatial uncertainty of a potential emergent trigger of an emergent microbial problem in Step 2. Once screening has identified a potential problem ('trigger' event), the second phase involves more detailed information to confirm public health risks.

Level B. Data quality for health risk assessment is characterized by more extensive sampling to "maximize the ability to determine whether a microbial threshold criterion is exceeded at selected receptor nodes." The aim of Level 2 actions is to assess the need for further management actions (e.g., beach closures, boil-water orders). Hence, the data quality is driven by risk classification with quantified uncertainty (e.g. 95% chance that a target threshold is exceeded). A typical approach involves expanded sampling with supplemental information (ancillary and microbial) to determine whether the response is repeatable over space and time and to determine whether the signal persists. From a sensor network perspective, ancillary data predictions will be informed by increasing microbial indicator attributes (i.e. increase in sensor heterogeneity), and more reliable processing methods are used to confirm that the result is not an artifact. Exceedance criteria of source water for drinking and recreational uses, as well as sampling frequency criteria (e.g. days to weeks for recreational waters) may be used as recommended by EPA [e.g. EPA-86. EPA-98, EPA-03], using either a maximum concentration or summary statistics (geometric mean of at least five samples collected over 30 days). Monte-Carlo type simulations could be applied to the correlations developed or used for Level A, to evaluate the impact of measurement and correlation uncertainty on the predictive outcome of the threshold or the relevant summary statistics used for guidance criteria.

Level C. Data quality for source identification and mitigation is a diagnostic assessment of confirmed microbial contamination and identification (source attribution), and represents the highest level of sensing in terms of specificity and sensitivity (impacting cost, response time, and power requirements). The assumption is that source identification will be based as a first approximation on error-prone, but easy-to-use, metrics such as the fecal coliform:fecal streptococci (FC:FS) ratios (>4: predominantly human, <0.7 non-human) to imply human and non-human sources of contamination [e.g. F-74, ECDVMM-97]. Rather than using mean values, a frequency distribution within indicative values will be used to inform the network design. Molecular deterministic methods used for identifying microorganisms are expensive and time-consuming and will be incorporated as a cost-function for network design considerations, rather than as a water quality measure.

3.2. 'Trigger' vs. Diagnostic Sensing Technology

The highly heterogeneous nature of microbial occurrence and activity or viability in natural systems indicates a need for distributed microbial sensing capabilities. The current approaches for microbial (indicator) detection and quantification in source water emphasize off-line membrane-culturing (24 hour), molecular tools (hours), or flow-cytometry (FCM)-based (minutes) analyses, techniques which to date are sub-optimal because of time delay, cost, or ease-of-use reasons. Hence, the integration of distributed sensing with economic constraints of the cost of the network will require a technology implementation commensurate with the phased criteria described in Figure 4. 'Trigger' technology provides early warning of impending hazard, whereas diagnostic technology quantitatively and specifically describes the type of hazard (Figure 5).

State-of-the-art microbial sensors compatible with wireless network systems emphasize optical detection methods for chlorophyll content, and flow cytometers, which are capable of quantifying total numbers, and some target organisms. Both the RECON system and the Networked Aquatic Microbial System (NAMOS), which consists of ten stationary buoys and one mobile robotic boat for real-time, in-situ measurements and analysis of chemical and physical factors governing the abundances and dynamics of microorganisms at biologically-relevant spatiotemporal scales, focus on chlorophyll measurements. Woods Hole and UT-Galveston have deployed field FCM systems for microbial monitoring of plankton; bacterial sensors are either off-line or near real-time but have not been deployed in open water systems. The array of different technology platforms currently available for microbial sensing is provided in Table 1.

Near-term technological capabilities for achieving automated, low-cost ($500 per sensor node), and robust detection of microbial parameters of interest in field settings have focused on micro-electromechanical systems (MEMS) and improvements in the environmental application of molecular tools [IAAW-99, SSR-02, GSA-04, NRC-04]. To achieve acceptable specificity and applicability in the environment, the performance characteristics (e.g., detection limit, setup time, adaptability, matrix interferences) of these approaches vary [reviewed in GSA-04] Once relevant spatio-temporal correlations between surrogate (non-microbial) and diagnostic variables for microbial events are incorporated in a spatial modeling and uncertainty analysis framework, sensor network designs can be informed based on the types and characteristics of sensors that would be required to capture the parameter field [ASEGE-03]. The development of a sensor that can function in a real environment is a far greater challenge than one that can operate in a lab; to achieve the sensitivity, selectivity and reliability that is necessary, we use a multi-modal approach where one "sensor" can sense many different analytes, or can sense one analyte with many different sensitivities.

Table 1. Comparison of Selected Technology Platform Attributes for Microbial Sensing

Methodology	**Detection Limit[a] (cfu/mL or cfu/g)**	**Setup Time**	**Adaptability**	**Matrix Interference**
Plating Techniques	1	1-3 days	Excellent	Low
Bioluminescence	10^3-10^4	½ h	Low	Medium
Piezoelectric	10^6	5h	Good	High
Impedance	1-10^5	6-24 h	Moderate/good	Medium
Flow Cytometry	10^2-10^3	½ h	Good	Medium
Acoustic	$5x10^4$-10^6	3h	Moderate	High
Electrochemical	10^3	½-2 h	Low	Low

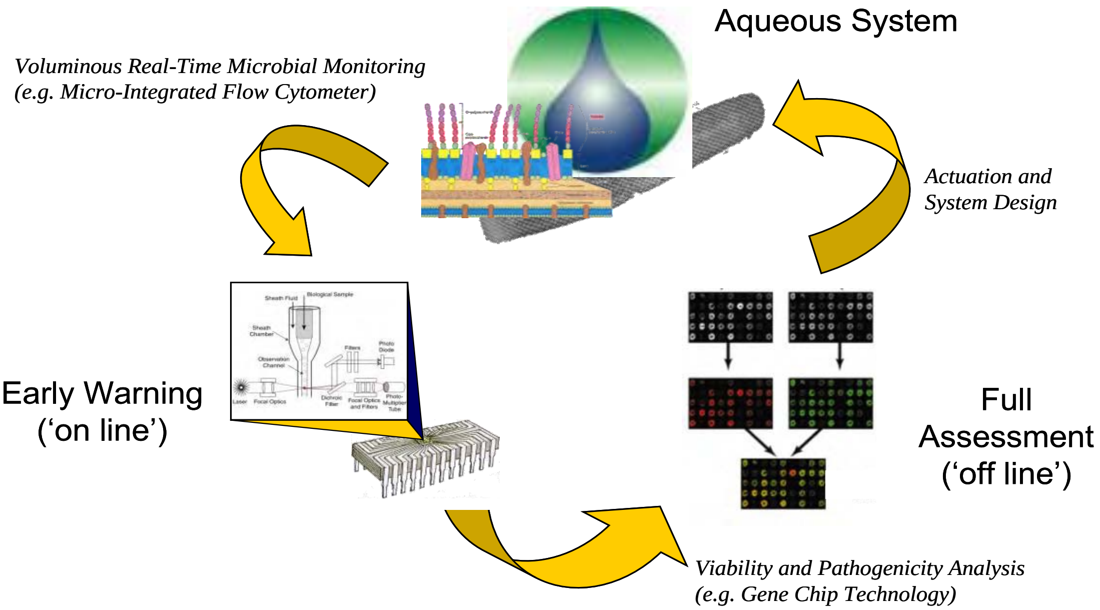

Figure 5. Microbial Sensing for System Management: Trigger vs. Diagnostics

4. Spatial Modeling and Uncertainty Analysis

Microbial parameters exhibit significant variability both spatially and temporally. A recently released report put together by the US EPA [WBMSSD-05], for example, notes that microbial parameters at beaches exhibit "some form of systematic spatial variation" that was not adequately accounted for by the depth at which samples were taken. Although this has been recognized for some time, few methods are available to identify and take into account this heterogeneity. In order to effectively propagate the information provided by measurements in time and space, statistical methods need to be able to quantify the degree of spatial variability and use this information to estimate microbial parameters at unsampled locations in a probabilistic framework. The methods should be able to quantify and ultimately reduce the uncertainty associated with the spatial distribution of microbial parameters.

Geostatistical and multiscale statistical modeling tools provide a framework for achieving the goal outlined above, and have begun to be incorporated in a limited number of studies. The field of geostatistics, or the theory of regionalized variables, was introduced by Matheron [M-63, M-71] and is an adaptation of least squares methods to quantities that are correlated in space. Geostatistical interpolation methods were first developed in mining engineering. Much of the early applications were in subsurface environments, describing the spatial distributions of geological structural parameters [JH-78], hydrogeological parameters [K-97] and soil properties [G-97]. More recently, the generality and adaptability of the geostatistical approach has led to a wide range of applications in the earth and environmental sciences, including a limited number of applications to the estimation of surface water quality parameters and contaminant loads [LEP-97, JCC-97, BML-00, AGSEE-03, GS-04, MK-05].

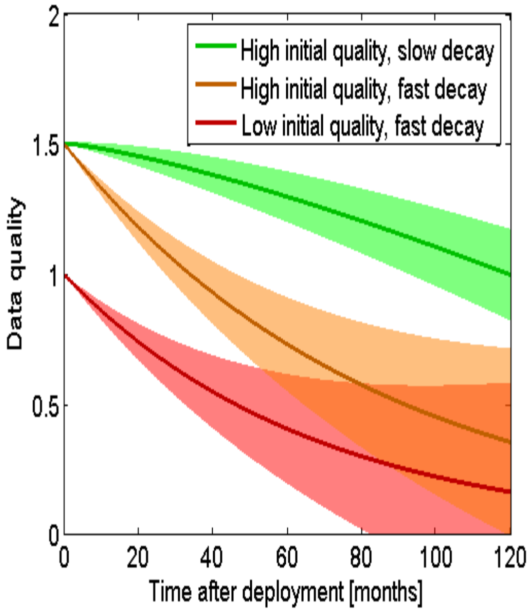

Figure 6. The Objective of Sensor Networks is to Develop a Methodology that is Able to Deliver High Initial Data Quality and a Slow Decrease in Data Quality as Sensors Begin to Fail. An Additional Desirable Feature is a Relatively Low Level of Uncertainty About a Network's Ability to Continue Delivering High Data Quality over Time. The Green Represents the Optimal Scenario of a High Initial Data Quality, a Slow Anticipated Decrease in Data Quality over Time, and a Relatively Low Level of Uncertainty Regarding Future Performance. The Orange and Red Lines Represent Sub-optimal Design, with either a Lower Initial Data Quality Level, a Faster Decrease in Quality over Time, and/or a Higher Level of Uncertainty with Regard to Future Performance.

Geostatistical approaches model the spatial and/or temporal distribution of a parameter as a random field, described by a covariance function that captures the degree to which information is lost as one moves away from sampled locations. Kriging-based methods not only provide a Best Linear Unbiased Estimate (BLUE) of the distribution of a parameter of interest, but also characterize the uncertainty associated with that estimate. This makes them ideally suited to analyzing limited environmental data and to designing monitoring network that can effectively capture the spatial and temporal heterogeneity of physical, chemical and biological parameters.

In surface water quality monitoring, basic geostatistical methods have been applied in a few instances. As part of its EMPACT Beaches Project [WBMSSD-05], the EPA constructed variograms (although did not call them by that name) designating the expected variance between pairs of measurements of indicator densities taken at a given separation distance. This work clearly indicated that spatial correlation was present. Posa and Rossi [PR-91] applied a geostatistical approach to estimate dissolved oxygen concentrations in the Mar Piccolo of Tarato, Italy. Little et al. [LEP-97] used ordinary kriging (a geostatistical interpolation approach where the underlying process is assumed to have a constant but unknown mean) to interpolate measurements in Murrells Inlet, South Carolina, including coliform and other data. No cross-correlations between variables were considered. Bellehumeur et al. [BML-00] used geostatistical simulation methods to estimate the spatial distribution of lake acidity (pH) on the Canadian Shield. Gardner et al. [GSL-03] and Gardner and Sullivan [GS-04] used geostatistical methods to analyze stream temperature data. They considered different spatial and temporal scales of variability by implementing a complex nested variogram model to explain the observed distributions. These recent works demonstrate the potential of geostatistical approaches for interpreting spatial patterns of water quality data. However, these studies all focused on analyzing either a single type of data, or considered different data types independently. Novel approaches are needed to jointly assimilate the variety of data that can be collected using a wireless sensor network and that can take into account the time-dependent decay of the data quality as a function of power depletion, accidental loss of a sensor, and other decays. Three data decay functions are illustrated in Figure 6; the goal for an optimized sensing network is to have high data quality and slow decay rates of sensor quality.

A variety of works have also explored the design of monitoring networks based on a criterion of minimizing the uncertainty of the interpolated product [e.g. C-91]. For surface water systems, the possibility of using geostatistics as a monitoring network design tool was described by Jassby et al. [JCC-97] for San Francisco Bay. The design of a wireless sensing network for microbial attributes involves several factors and constraints not considered by existing methods, typically developed for groundwater applications. First, the hydrodynamics of surface water systems make it unlikely that the covariance structure of the parameter fields will be stationary in space. As such, the field cannot be described by a single variogram or covariance structure. Recent and ongoing work at the University of Michigan and Michigan Technological University has focused on developing tools for identifying and quantifying spatially-variable covariance structures that can represent the variability in the degree of physical heterogeneity of a natural system [AM-06]. This work is also developing novel methods for sampling network design based on such heterogeneity. Second, a variety of auxiliary (or trigger) variables can be measured in surface water systems that may provide additional information about microbial parameter distributions. Geostatistical methods can incorporate information on such auxiliary information in a statistically rigorous manner. Third, existing methods optimize monitoring arrays based primarily on the criterion of reducing uncertainty in areas of interest, but without considering constraints and criteria imposed by other elements of the network**.** ***In the case of a wireless sensor network deployed in a surface water environment, technological issues of network longevity, robustness and communication must be considered in conjunction with scientific monitoring criteria.***

5. Wireless Sensor Networks and Testbeds

Over the past decades, antennas, radio transceivers and processors have been greatly improved in terms of form, size, and power efficiency. Such progress in wireless communication technologies together with marked advances in micro-electromechanical systems (MEMS) has enabled the integration of sensing, actuation, processing, and wireless communication capabilities into tiny sensor devices, which are envisioned to be made increasingly inexpensive, energy-efficient, and reliable. At the same time, the advances in mobile ad hoc networks have enabled the development of *wireless sensor network*, a subject of extensive study within the networking research community in recent years, whereby sensors may be deployed to self-organize into networks that serve a variety of applications.

These applications range from scientific data gathering, environmental monitoring and pollution detection [AC-00, IG-99, BGS-00, BEGH-01], to building smart homes and laboratories [AS-00, E-00, HK-00, PGPMG-00]. Specific examples include the ZebraNet project [LSZM-04], which used GPS-enabled sensors to monitor the zebra migrations in Kenya, the monitoring of nesting habitats of birds and environmental conditions such as temperature and humidity in Maine [MPSCA-02, SPMC-04], which used the Berkeley Motes [MICA2], habitat monitoring [CEHZ-01], health [KKP-99], and the monitoring and detection of car theft [PK-00]. Wireless sensor networks are well suited for these applications due to their rapid and inexpensive deployment (e.g., compared to wired solutions). They can be deployed (e.g., airborne) to areas otherwise inaccessible by land. The low cost and low energy nature of these sensors also makes them easily disposable (if made bio-degradable).

Along with this wide range of emerging applications, there have been extensive studies on building protocols, software, as well as simulation and emulation tools that help bring these applications to reality, for example, different sensor platforms [WINS, MICA2, MBCISSWC-02, SS-02] as well as operating systems [TinyOS, LC-02, LSZM-04]. Applications most relevant to the project outlined here are waterborne sensor networks for the monitoring of marine ecosystems, water quality, and contaminants. Few examples exist, and those that do focus on multivariate ocean monitoring (e.g. ARGO system) for plankton, algal blooms and other ecosystem degradation parameters [EGPS-01, PK-05].

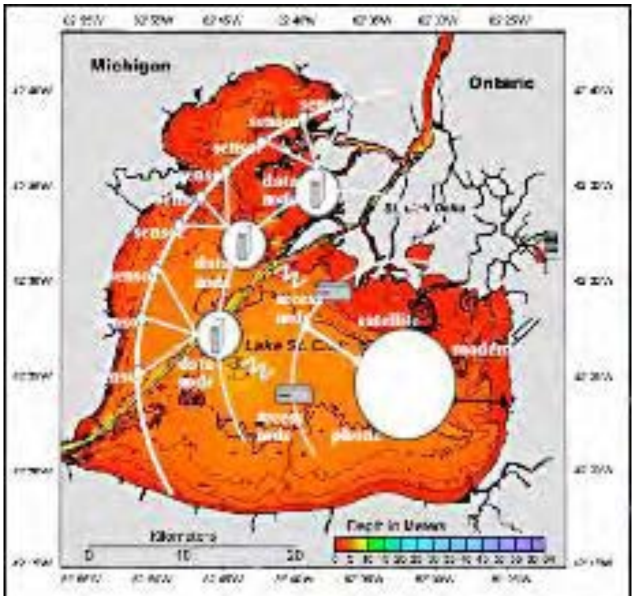

Figure 7. Conceptual Testbed in Lake St. Clair

The network optimization approach could be based on a tiered communication structure such as shown in Figure 7. Wireless waterborne sensors are then deployed similar to RECON. The ones closest to shore can form the first tier of the network and potentially serve as relays for other sensors that located further away. Each tier is located further away from shore. The number of tiers formed will explicitly incorporate the area of the sensing region and the transceiver capability of the sensors. Failure functions will be incorporated in the network design to evaluate the impact of sensor degradation and data loss on the spatio-temporal interpretation of microbial data. Generalization of the network design methodology for monitoring programs in other lakes, with emphasis on the Great Lakes basin, will use a scenario-testing approach in the iteration model. Since the data quality metrics impact the design criteria for the network, both in terms of environmental (spatio-temporal) constraints and network robustness (in terms of communication and data heterogeneity), this Step will provide a data-driven design space for wireless network implementation in environmental systems.

Various co-authors have been working to apply these techniques with various plug-in (or off line) sensors to the specifics of an environmental system (scale, available data, and data quality objectives). Real-world constraints will prove invaluable to answer the question: “How does a priori information influence the design of networks co-optimized for environmental and network failure constraints?” The application testbed for this project may capitalize on the Lake St. Clair system, which is part of the Lake Erie basin and is located on the border between southeastern Michigan and southern Ontario. The lake is connected to Lake Huron to the North by the St. Clair River and to Lake Erie to the south by the Detroit River, and exhibits the largest delta system (and thus contributing contaminant sources) of all the Great Lakes. This testbed may be proposed because: (i) a database with parameters collected over eight years is available online (http://www.lakestclairdata.net/); (ii) a wireless data collection system is being implemented at the water treatment plants that can serve as a benchmark for the models, (iii) the availability of a high resolution numerical hydrodynamic model, developed by Prof. Guy Meadows at the University of Michigan, designed to model the transport and dispersion of microbial and other constituents in this basin; and (iv) results generated from network optimization based on a well-characterized system will help with generalizing the methodological approach to the Lake Huron-Erie corridor, currently instrumented by GLERL. Given the monitoring that has taken place in the Lake St. Clair basin, and the impending data from the wireless systems at the water intakes, this would enable us to apply our methods at a 200m resolution within the lake area.

6. Data Compilation and Communication

Ecosystem management at the scale of the Great Lakes will require significant advances in data management and computational capabilities. Existing programs designed to support environmental observatories have emphasized the compilation and federation of existing data from multiple sources. To complement and leverage these efforts, the ERC will implement a new grid-based computational infrastructure with a research focus on the deployment of high performance simulation models. The new *Great Lakes Grid* (GLGrid) will be based on the New York State Grid (NYS Grid), developed by project co-leader Miller with support from NSF. The NYS Grid, which currently includes computational and data systems throughout New York State (including UB and Cornell), will be extended to include UM and other systems involved with Great Lakes Research, and will provide access to government researchers and regulatories (USEPA and NOAA Great Lakes and Ecosystems Research labs), as well as private-sector partners. The administration of GLGrid will be coordinated by UB's Center for Computational Research under Miller's direction.

In addition to deploying a dedicated grid infrastructure, current efforts will develop and evaluate the necessary interfaces and "middleware" needed to deploy and optimize high-performance ERC simulation models. Research needs will emphasize (1) development of secure and high-performance grid technologies that allow for the integration of high-end computers, data, networking, and visualization, as well as sensors, imaging devices, and databases; (2) implementation of grid technologies, dynamic resource classification for fast processing on homogeneous parallel platforms, and the distributed computation for individual computational tasks on heterogeneous platforms; (3) development of technology for building a common core database platform on the grid, the development of distributed search technology utilizing heterogeneous databases, large-scale distributed text searching, and intelligent storage controller development; and (4) portal development to promote access to a wide range of users at all levels, pre-college, college and the general public.

Dr. Finholt and colleagues at UM's Collaboratory for Research on Electronic Work (CREW) have conducted extensive research on how new technologies enable new ways of organizing work, both for providers and users of the technology, as well as in both academic and business environments. Similar to a recent NSF-sponsored evaluation of the Teragrid, the GLGrid evaluation will: (a) provide specific information to GLGrid managers that will increase the likelihood of GLGrid success; and (b) give ERC and NSF leaders and policy makers general data that will assist them in making strategic decisions about future directions for cyberinfrastructure. In particular, GLGrid will be evaluated in terms of progress in meeting user requirements, impact on research practice and outcomes, quality and content of GLGrid education, outreach, and training efforts, and satisfaction among GLGrid partners.

7. Conclusions and Research Questions

Technology development for environmental sensing infrastructure is governed by addressing technological and societal/market needs. Substantial investment in materials, devices and modeling software for implementation of sensor networks has advanced our technological understanding of the critical elements required to accomplish this objective. Yet, the deployment of sensor nodes (multiple sensors in a spatial network) remains costly and fragile, and the data feedback from these nodes is often too slow to impact decision-making or to forecast hazardous events, either using trigger or diagnostic data. Leveraging the strengths at our Michigan institutions has the potential to position us to capture a cyberinfrastructure node as part of the WATERS program.

To better understand the needs and integration of the various aspects of building an appropriate cyberinfrastructure for the Great lakes system, the breakout session will seek to resolve outstanding questions and approaches in the following areas, not limited to microbial sensing needs :

1. *Data Specification and Collection: What do you want to Forecast About the Ecosystem?*

Wireless network design can only be optimized once data quality criteria are specified. We define data quality as the ability of the sensor network to represent the parameter distribution within the entire system, where this ability is defined based on specific criteria. Depending on the application or water quality management goal, these criteria may include: (i) Minimization of average uncertainty in spatial distribution; (ii) Minimization of single maximum point uncertainty in the system; (iii) Maximized ability to determine whether the parameter is above/below a given threshold at a receptor node. The choice of criteria and its associated requirements for network design include speed, cost, specificity, and sensitivity that will drive achievable data quality metrics and thus the associated network design objectives. For example, the Lake St. Clair pilot collects general water quality data (e.g. oxygen, pH, conductivity) every 15 minutes, chemical data (e.g. halogenated compounds, petroleum hydrocarbons) every few hours, and microbial data on a weekly basis). The RECON system provides general water quality data in similar timeframes.

2. *Modeling and Interpretation: What is the Quality of Information Provided by the Measured Attributes?*

The design of a wireless monitoring network that maximizes a specific measure of data quality must be based on the spatial and temporal covariance structure of microbial and related environmental parameters, available baseline measurements, and information about the hydrodynamics of the system. Spatial statistical methods (geostatistical and multiscale modeling tools) provide an integrated framework for defining the optimal design criteria for minimizing the uncertainty associated with the characterization of microbial parameters in recreational and potable waters. This topic will utilize this framework to (i) discuss modeling tools to quantify the uncertainty in the spatial and temporal distribution of water quality parameters related to microbial attributes, (ii) translate the spatial distributions and their uncertainty into an overall measure of data quality, and (iii) optimize the network to maximize the overall data quality at the time of deployment and in the presence/absence of sensor failure.

3. *Visualization and Communication: Conceptualize the Utility of the System and its Interactions*

This section will address how models inform our physical understanding of the ecosystem. In addition, we will discuss (1) ontology and model integration across the biotic, abiotic, and socio-economic domains, and (2) integration of computationally-, data-, instrument-, and sensor-based grids along with the design, development, and deployment of fundamental cyberinfrastructure middleware and tools to make the use of such systems transparent to the end user. These projects will complement and extend similar ongoing national efforts within the environmental science and engineering communities, which emphasize cyberinfrastructure projects for disciplinary-focused programs (e.g., hydroinformatics and ecoinformatics). The outcome of this topical area is to provide tools for a variety of stakeholders that will enable them to assess and manage the impacts of natural and anthropogenic stressors on regional ecosystem resources.

4. *Sensor Network Deployment: Data- and Model-Driven Infrastructure for Forecasting*

This topic will address the development of sensor network configurations that satisfy (i) low power requirements for network placement, and (ii) data utility. The configurations will include nodes that can be as simple as a temperature sensor, or as complex as a complete environmental sensor system that measures and correlates temperature, pH, dissolved oxygen levels, and specific microbia biomarkers. While some of these sensors can be "off the shelf" components, the geographical extent and diversity of the data collection region dictates that specialized sensor systems be developed. These sensor systems will be designed to simplify addition to an existing sensor network; the interface to the network will be standardized, while the sensing components will have whatever functionality is desired for a particular location. Experiences from currently deployed systems and utility-driven networks (e.g. tiered communication systems) will be discussed.

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Complex Interactions among Land, Water, and Harmful Algal Blooms

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1. Introduction

Harmful algal blooms (HABs) are a significant threat to human and ecological health in marine and freshwater systems around the world. Humans are exposed to toxins produced by dinoflagellates and diatoms in marine ecosystems by eating contaminated shellfish or inhalation of aerosolized toxins. In freshwater, HABs are commonly formed by cyanobacteria that contaminate drinking water and foul recreational sites. HABs also affect the biodiversity and functioning of aquatic food webs. HABs are integrally coupled to human activities throughout the watershed and to natural factors that vary with time and space. The proliferation of these algal species into sufficiently high densities to form blooms is largely the result of anthropogenic eutrophication, but also can be regulated by a variety of environmental factors such as grazing, water column turbulence, nutrient forms and ratios, temperature, and climate. The goal of this paper is to highlight the complex interactions governing the proliferation, impacts, and management of HABs as well as to provide the elements of a framework that can be used to guide a multi-institutional research program having the ultimate objective of managing human activities to reduce risks of freshwater HABs.

Bloom-forming, toxic cyanobacteria are a significant threat to water quality and resource utilization in the Great Lakes. In the Great Lakes, the dominant toxic cyanobacterial species is typically *Microcystis aeruginosa*, a colony-former that can form dense surface scums in calm conditions due to the high buoyancy of the cells. Cyanobacterial blooms were a very visible sign of nutrient enrichment in shallow, stratified parts of the Great Lakes in the 1960s and 1970s. While phosphorus reduction strategies reduced cyanobacterial biomass during the late 1980s and early 1990s, *Microcystis* blooms have resurged since 1995 and been present consistently each summer since then (Brittain et al. 2000, Vanderploeg et al. 2001).

Freshwater ecosystems are impacted by multiple anthropogenic stressors that act over a variety of spatial and temporal scales that make them susceptible to cyanobacterial blooms. Historically, early attention on the impairment of freshwaters in North America focused on the effects of increases in nutrient loading (eutrophication), first from point sources of nutrients and, more recently, from diffuse watershed activities (non-point pollution) as a result of urban sprawl, changes in agricultural practices, etc. Cyanobacterial HABs are favored by increases in nutrient loading (Trimbee and Prepas 1987, Downing et al. 2001) as well as decreases in N:P ratios (Smith 1983, Smith and Bennett 1999) that characterize anthropogenic increases in loading (Downing and McCauley 1992). A second major driver of impairment, one that is now on center stage in the Great Lakes region, is invasion by nuisance aquatic species (Ricciardi 2001). In recent decades, there has been an acceleration in the rate of establishment of invasive species in the Great Lakes as a result of increasing global trade (Mills et al. 1993, Lodge et al. 2006). In particular, there has been a demonstrated positive effect of dreissenid mussels (*Dreissena* *polymorpha* and *D. profunda*) on the abundance of toxic cyanobacteria (Sarnelle et al. 2005). *Microcystis aeruginosa* seems to be particularly sensitive to the influence of dreissenid mussels. This phytoplankton species grows into large ungrazable colonies, forms surface scums in calm weather, and produces a class of potent toxins (microcystins) that attack the liver (Reynolds 1984, Chorus and Bartram 1999) and so threaten water quality, public health, and lake recreational value. Large increases in *M. aeruginosa* biomass and microcystin concentrations subsequent to mussel invasion have been documented in a variety of North American lakes with low to moderate nutrient levels, including many inland lakes in Michigan (Vanderploeg et al. 2001, Nicholls et al. 2002, Raikow et al. 2004).

Global change will likely increase risk of HABs via processes caused by climate change, population growth, and agricultural intensification for food and biofuels. As a group, toxic bloom-forming cyanobacteria are favored by higher temperatures (Tilman et al. 1986, Weyhenmeyer 2001, Park et al. 2004) and reduced mixing (Reynolds et al. 1987, Paerl 1988). Increased temperatures and longer periods of thermal stratification in lakes are predicted for climate change in the Great Lakes and many regions throughout the world. A continuing rise in concentrations of CO_2 and other greenhouse gases is predicted to increase mean air temperatures on much of the globe, including North America, by at least 3°C on average by the year 2050 (IPCC 2007). A recent mesoscale climate model with realistic precipitation frequencies suggests that summer temperatures across eastern US, including the Great Lakes region, may be even warmer than predicted previously by the larger scale models: summer mean air temperatures could rise by up to 5.5°C by 2085 (Lynn et al. 2007). High summer temperatures will also lead to longer and more stable stratification periods that will reduce mixing and nutrient supply from hypolimnion (deep part of the water column) to the epilimnion (upper water column) of temperate lakes (Brooks and Zastrow 2002; Lehman 2002). Recent studies indicate that longer and more stable stratification periods associated with climate change may promote the growth of cyanobacterial HAB species (Jöhnk et al. 2008). Second, increased air temperatures will reduce the amount and duration of snow cover (Hayhoe et al. 2007), which may be responsible for decreased lake water levels observed in the Laurentian Great Lakes (Assel et al. 2004). Higher air temperatures are already increasing the ice-free period, both due to later lake freezing and earlier ice breaking (Magnuson et al. 2000). Collectively, these climate-driven changes in lake physics and chemistry may decrease primary productivity, which will alter the flow of energy and nutrients to higher trophic levels (Brooks and Zastrow 2002; O'Reilly et al. 2003). In addition, changes in atmospheric temperatures are expected to increase the temporal variability of precipitation events (e.g., storms and droughts) over much of the globe (IPCC 2007, Kharin et al. 2007), which will alter the timing and frequency of nutrient inputs to aquatic ecosystems. These climatic changes may have non-linear responses that will make it difficult for scientists and managers to predict the occurrence of HABs and other important ecosystem services provided by freshwater environments.

Nowhere are human health issues so tightly coupled to the environmental health of coastal regions than in the Great Lakes because of 1) the high concentration of humans, major cities and industries in the watershed and 2) the direct provision of drinking water from the Great Lakes to over 40 million people. Human health can be explicitly tied to water quality and despite major advances in the last several decades, the water quality of the Great Lakes remains at risk due to population growth and stresses along the shore line, increased land use, climate impacts and emerging contaminants. Cyanobacterial harmful algal bloom species can threaten water quality in the Great Lakes due to their capacity for producing a wide range of toxins, including hepatotoxic microcystins, neurotoxic anatoxins and dermatotoxins (Carmichael 1997) which have been responsible for human and animal illness and mortality in many parts of the world (Carmichael 1997). Potentially significant routes of human exposure to cyanotoxins in the Great Lakes are through drinking water supplies, recreational contact in nearshore regions where scums accumulate, and fish consumption (Brittain et al. 2000, Dyble et al. 2008). Preliminary studies (Dyble et al. 2008) have documented the presence of the toxin microcystins in the Great Lakes, at times exceeding the recommended World Health Organization drinking water standard of 1 µg L^{-1} in the water column and the 20 µg L^{-1} recommended recreational exposure standard in surface scums.

Toxicity is only one of the many problems associated with HABs and nuisance algae. They can reduce many valued ecological attributes, such as aesthetic values that affect tourism and property values plus the biodiversity that regulates sustainability of our biosphere. For example, massive accumulations of the filamentous green algae *Cladophora* on beaches of the Great Lakes were historically hazardous to businesses and individuals that planned vacations at the beach. Recurrences of *Cladophora* problems are evident in the Great Lakes despite successful reductions in the nutrient loads. The recurrence is complexly related to nutrient loading because of zebra mussels. Increasing light penetration in regions of Saginaw Bay and Lake Erie has allowed the growth of previously light-limited benthic algae, such as *Cladophora* (e.g., Pillsbury et al. 2002, Higgins et al. 2005a and b*)*. In addition, zebra mussels focus nutrients to benthic habitats by filtering plankton and excreting pseudofeces which leach nutrients. Nutrient focusing by zebra mussels is the second key factor hypothesized to have enabled the expansion of *Cladophora* to regions where phosphorus concentration would normally be too low to support its growth (Hecky et al. 2004; Bootsma et al. 2005). In addition to the aesthetic problems associated with *Cladophora*, recent work shows that this filamentous green alga may also provide habitat for microbial pathogens that could pose a human health risk (Ishii et al. 2006, Olapade et al. 2006, Ksoll et al. 2007). Thus nutrient regulations may become much more important in coming years due to many algal-related problems emerging from unpredictable consequences of invasive species.

Predicting the presence of HABs in aquatic environments and quantifying the risk to human health is a major scientific challenge which requires an understanding of the biological and chemical interactions that control growth and toxicity, as well as the pathways over which they are transported from sources to regions of potential human exposure. Human interaction with the Great Lakes occurs primarily in the near-shore region where dilution is minimal (due to strong along-shore versus offshore transport) and the likelihood of human contact is greatest. Process-based modeling is a useful tool that when coupled with laboratory and field observations provides a framework to test hypotheses about blooms, identify major sources of nutrient and particulate flux and evaluate future scenarios under uncertainty. This approach provides an integrated framework to examine complex interactions between watershed-scale processes, lake-wide circulation and near-shore processes in shallow vegetated areas subjected to wind and wave action. Coupled physical-biological models, which aim to accurately represent population dynamics and hydrodynamic transport, are effective tools for studying these interactions, predicting outbreaks of toxic and nuisance organisms, and assisting in the management of aquatic resources. To adequately predict the occurrence and severity of HABs, we also need to develop mechanistic models of planktonic food webs, with a realistic description of competitive and predator-prey interactions of HAB species with the rest of phytoplankton and zooplankton, respectively. These models have to include the dependence of net growth of HAB species and other plankton on key physical and chemical drivers, such as lake circulation, turbulence, temperature, irradiance and concentrations of major potentially limiting nutrients. Upwelling, resuspension, groundwater discharge, runoff, and loadings from tributaries are important processes that need to be included in the modeling. Recent studies have shown that for given light and nutrient regimes there are critical levels of turbulence that afford a competitive advantage to and trigger blooms of *M. aeruginosa* (Visser et al. 1996; Huisman et al. 2004). In large lakes and the open ocean, turbulence is driven by the breaking of surface waves, convective instability due to temperature and density differences as well as the breaking of internal waves at density interfaces. Adequate characterization of turbulence and the light climate are important and the assumption that the entire water column is uniformly turbulent may be inadequate for the purpose of predicting the onset of blooms. Interactions between submerged macrophytes, currents, waves and suspended sediment in shallow areas can result in positive or negative feedbacks since the bottom shear stress is a function of all these variables.

Therefore, the development of the mechanistic models combining biotic interactions and realistic physical and chemical forcing, together with the real-time monitoring of the physico-chemical conditions, can improve the our capabilities to forecast HABs. All of these challenges require integration of modeling with both field and laboratory observations over a broad range of disciplines including aquatic biology, chemistry, ecology, watershed hydrology and hydrodynamics. Observations are required to constrain parameters used in models and to test the skill of model predictions. Conversely, models can inform the acquisition and analysis of observations by providing a broader context from which to interpret necessarily limited data collection. An important goal is to use integrated experiments, modeling and observations to test potential management strategies for HABs and pathogens and assess their risk to human health.

2. Cyberinfrastructure Needs for HABs

Cyanobacterial HABs are a good example of the need to develop cyberinfrastructure to monitor susceptible waters for degrading of water quality and develop risk assessment strategies for protecting human health. There has been significant progress in the development of various components for this cyberinfrastructure, which will be discussed here in addition to future needs as related to HABs.

3. Data Input Needs

There is always a high demand for environmental and experimental data to develop and calibrate modeling approaches. While more input data always improves the predictive capacity of models, there are not always long-term data sets available. Needed are parameters that are easily measured and are good indicators of bloom development. We need spatially and temporally resolved estimates of physical and chemical parameters such as turbulence, circulation patterns, light availability and attenuation coefficients, and spatial distribution of major macro- and micronutrients that will be used to force mechanistic models of HAB blooms.

Developing an ecological forecasting model for HABs is necessary to predict the timing, extent and location of blooms, in order to protect waters used for drinking and recreation. Additionally, such models can be used to better understand the ecological impacts of HABs and how additional stressors, such as a new invasive species, might impact the system. The NOAA Great Lakes Environmental Research Laboratory (GLERL) has just been funded to conduct a 5 yr study on the impacts of multiple stressors (including nutrients, invasive species, climate change) on water quality in Saginaw Bay (Lake Huron), with important endpoints including toxic cyanobacterial HAB concentrations and benthic algal biomass (predominately *Cladophora*, which can end up as "muck" on the shorelines). By coupling modeling, observational and experimental studies with stakeholder workshops and socio-economic analyses, the project will result in models that are adaptable across ecological systems and multiple stressors as well as one that provides managers with a means to understand and manage stressor interactions unique to their system. Data input is essential to these efforts and historical data and regular monitoring data collected over the course of the project will be used to inform a number of different modeling approaches.

4. Hardware Research Needs

The high data demand for modeling inputs calls for high frequency sampling, which can be expensive, time-consuming and, even with the best efforts, not able to sample with enough frequency or spatial coverage to detect all the locations in which nearshore blooms may have a detrimental impact. Traditionally, HAB blooms have been detected and quantified using ship-based sampling followed by cell counts or other microscopy-based analysis. However, blooms can be patchy and move with currents, making them at times easy to miss unless an extensive sampling schedule is employed. Additionally, the delays due to the time needed for sample processing can also result in missing a bloom. *In situ* sensors are essential for both sampling with high enough frequency to develop an early warning system at critical locations as well as collecting data that can be used to inform a predictive model for bloom formation and transport. An ideal platform for such monitoring is buoys, which can support and power sensors and transmit the data collected back to shore.

Sensors for detecting cyanobacterial HABs are still in the development process. *In situ* fluorometers for measuring chlorophyll *a* are used to detect when phytoplankton biomass increases, but these will not discriminate between the many algal types. More specific are phycocyanin sensors, which detect the pigment specific to cyanobacteria. Again, this is still a broad sensor since it will detect non-toxic cyanobacteria and a few other algal groups such as cryptophytes in addition to the targeted cyanobacterial HABs. Buoy-mounted phycocyanin sensors are being tested as an indicator of the potential for a HAB bloom, to trigger ship-based sampling to confirm the identity of the bloom. Among other useful sensors are *in situ* flow cytometers capable of a real-time detailed characterization of phytoplankton communities, including HAB species, based on chlorophyll fluorescence and light scattering signatures, available as buoys or submerged installations (http://www.cytobuoy.com/). Since not all cyanobacterial blooms are toxic, from a human health perspective it is important to distinguish between toxic and non-toxic HAB species present to best protect human health. Sensors capable of detecting toxins and molecular-based sensors for detecting toxic cells based on the genes controlling toxicity are currently in development.

5. Software Research Needs

There has been a substantial amount of work in the past few years to better understand the distribution and dynamics of cyanobacterial harmful algal blooms (HABs) in western Lake Erie and Saginaw Bay. Maps of the distribution of *Microcystis* cells and the toxin microcystin, experimental work on the impacts of light and nutrients on *Microcystis* growth and toxicity, molecular-based methods for detection of toxic cells and statistical correlations between environmental factors and HAB densities and toxicity have all provided a strong framework for the development of models for forecasting HABs. A combination of satellite imagery and hydrodynamic modeling shows great promise in leading to an operational HAB forecast system.

Cyanobacterial blooms are surface-forming and thus can be detected remotely using specific characteristic reflectance wavelengths. Using MERIS satellite imagery, Wynne et al. (2008) has documented that surface reflectance at 681nm may be a useful indicator of *Microcystis* concentrations in the Great Lakes. This MERIS imagery has been combined with the Great Lakes Forecast System by R. Stumpf (NOAA-NOS) and D. Schwab (NOAA-GLERL) to model the existence and movement of *Microcystis* blooms in Lake Erie. This employs the use of a 2-dimensional Lagrangian element tracking model that take inputs of currents, winds, and initial cell concentrations provided by satellite imagery. Preliminary results are encouraging, further development of this forecast system will require both field sampling and optimization of the algorithms to correlate surface reflectance to *Microcystis* cell densities. These modeling efforts will serve as an operational and proactive, predictive facility on which to base (and initiate) event-response resource management, potential public health risks, and mitigation efforts concerning growth and potential toxicity of cyanobacteria blooms in the Great Lakes.

Due to the complexity of the ecological systems involved and the potential for chaotic behavior, as well as due to the dependence of HAB formation on weather conditions that can be reliably forecast only short periods into the future, specific HAB forecasts will remain short-term and need continual updating (much like weather forecasts), even given optimal models and input data. However, predictions of average HAB conditions (like climate predictions) have the potential to be made further in advance. The necessarily short-term nature of specific HAB forecast should not be seen as a drawback to these models, but rather presents a communications challenge; to get up-to-date HAB forecasts and monitoring results to the operators of drinking water intakes, recreational area managers, lake shore residents, and other stakeholders in a timely manner.

6. Communication Research Needs

Communication with stakeholders such as resource managers, wastewater utility operators, and policy makers, as well public outreach and information, are important parts of HAB research. Manager input and involvement in developing key variables for monitoring is essential to develop a program that is accessible. Stakeholder workshops are also essential to determining which issues are of public concern and how they affect public use of the water. The involvement of citizen volunteers in sampling lakes for microcystin concentrations has also provided a mechanism for the public to become invested and involved in improving local water quality. Citizen sampling also provides the only feasible means of obtaining data on levels of HAB toxins at the shoreline across a very large number of sampling sites. A pilot program funded by the Michigan Department of Environmental Quality demonstrated that citizen sampling can provide large quantities of high quality data at low cost (www.michigan.gov/documents/deq/wb-swas-inlandlakes-algaereport08_222846_7.pdf). Additionally, a series of HAB workshops were held in Michigan, Ohio and Wisconsin in order to inform the public about HABs, find out from stakeholders (including water utility operators, beach managers, lakefront homeowners) what issues were important to them and increase their knowledge about HABs. However, as most of the general public has limited to no knowledge of the existence or impact of HABs in drinking and recreational water, developing means of communication continues to be important.

In addition to the importance of including stakeholders in all stages of research and increasing the public knowledge about HABs, an important area for cyberinfrastructure development will be the ongoing communication of HAB forecasts to relevant water managers and the public. As better HAB models and real-time forecasts are developed a parallel effort is needed to develop ways to disseminate this information through the internet, local professional or homeowner networks, or partnerships with traditional media.

7. Conclusion

Cyanobacterial HABs are a considerable water quality issue in the Great Lakes and other US inland lakes. While significant progress has been made in detection and prediction of HABs in the Great Lakes, there is still a great need for the development of cyberinfrastructure to protect ecosystem and human health.

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Graham Environmental Sustainability Institute
WATER
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March 26–27, 2008

Impact of Watershed Changes on Estuarine Morphology and Aquatic Life

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Abstract

We present a framework for a quantitative assessment of the impact of watershed changes on estuarine and wetland morphology. By linking some key factors of river bed morphology to biota, a quantitative measure of the sustainability of aquatic life is also developed. We present a novel approach for nesting a high resolution estuarine morphology model in a large scale watershed model. The integrated watershed-estuarine model is used to perform a formal sensitivity analysis of estuarine bed morphology to various hydrologic changes at the watershed level. The width of beaches, the depth and context of sediments, the cohesion of grain particles and the overall strength of the soil matrix are linked to an aquatic habitat model, resulting in a robust tool for assessing the impact of climatic change and land use practices on specific species. The simulation scenarios over long-term periods are therefore able to establish quantitative measures for creating sustainable aquatic systems.

1. Introduction

Increased attention has been recently focused on the long-term effects of land use practices at the watershed level, which are occurring concurrently with an accelerated rate of change in water re-allocation and consumption. In particular, human interference with the erosion and sedimentation processes is considered responsible for many undesirable implications to the aquatic habitat of wetlands and estuaries. Although, destruction of one habitat inevitably creates another, the changes invariably result in loss of quality in water balances, throughput, and biota. Because the ecological services in these areas are especially rich for wetlands and estuaries, the consequences of such local changes are not well understood at the watershed scale.

On the other hand, the process-scale dynamics of hill-slope-channel erosion and streamflow sediment yield are well understood, being strongly affected by the spatial heterogeneity in soil and bedrock, vegetation cover, and topography. The rainfall-runoff mechanism is the primary driver of these dynamics, exhibiting high heterogeneity over a number of spatial and temporal scales and a strong dependence on antecedent conditions. Consequently, changes in watershed headwater land use, as well as changes in key forcing elements of the hydrologic cycle may alter the characteristics of local runoff production and erosion processes. This, in turn, may lead to the adverse effects of excessive sedimentation and unstable hydrology of estuarine and wetland habitats.

Compensation or mitigation of these changes is currently limited due to our inability to accurately assess the impact of any specific land use practices that are related to the propagation of hydrometeorological constraints through a non-linear hydrological system. The processes involved are characterized by such vastly different spatial and temporal scales that until now studies of habitat sensitivity to land use changes have been mostly empirical exercises. For example, morphological changes in an estuary typically take several decades to manifest themselves, as sedimentation rates increase slowly following urbanization or deforestation of some parts of the watershed. The depth of water flow in the estuary is gradually reduced, the width of beaches increases, the wave patterns are altered and the balance of sand, mud, and water is modified.

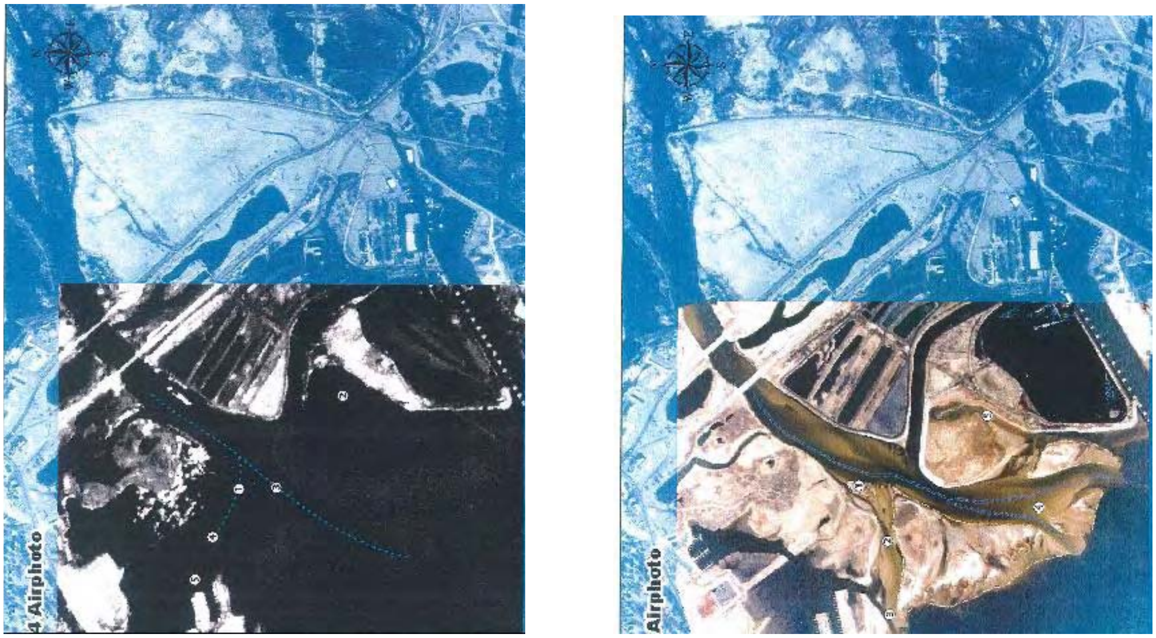
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Figure 1. Aerial Photos of Muskegon River Estuary

Figure 1 shows a typical example of such changes using aerial photographs of the Muskegon River estuary over a period of thirty years (Baird, 2001). The photographs show a dramatic change of the estuarine morphology, but offer little help in quantifying the causes of this change. It is also difficult to predict further limits of this evolution and whether or not remedial measures can have any effect at all. Even if alternative scenarios for watershed management were available, it would be impossible to quantitatively assess how long it would take to restore the estuary to its original state and provide relevant uncertainty bounds. Finally, the transfer of qualitative interpretations from one watershed to another is not meaningful, as most of the information derived is site specific and the underlying physical and ecological components are difficult to scale. It is therefore clear that physical processes occurring in the headwater drainage basin are critical and need to be considered for meaningful and robust evaluations.

This paper presents a predictive sensitivity analysis model that can quantify each of the processes involved, can explain how past practices have led to the present state, and suggests alternative land use approaches for the future. The model is also capable of interpreting anticipated perturbations in the hydrological cycle as a result of deviations from mean climate. The present approach aims at integrating large-scale watershed eco-hydrologic processes with long-term morphological changes in channel and estuary bathymetry. Furthermore, the model interprets constituent hydro-geomorphic state information and directly translates it to habitat quality metrics, such as favorability indices of fish habitat. Due to the imposed mechanistic design, the present model permits experimentation with alternative land use and hydro-meteorological scenarios, thus allowing the determination of sensitivity patterns and the implementation of sustainable strategies for compensating human interference with the natural processes in the watershed. Thus the approach described in the following can have a significant impact on our efforts to reverse unwanted morphological changes in wetlands and to restore damaged aquatic habitats.

As an integrated outcome, the present model provides a tool that can determine sedimentation rates from hydro-meteorological conditions, and the associated river bed evolution and habitat changes. The framework can also predict bed material composition, i.e., sand and mud fractions, thus defining channel vegetation growth. Specific habitat conditions are quantified by physical and biological parameters that are directly related to hydrodynamic conditions of the wetland or estuary. The model also provides an accurate assessment tool capable of identifying critical source areas of erosion as well as annual sediment yields for a given watershed. Overall, the integration of a spatially-distributed, physically-based hydrologic model with a model of erosion and channel sediment transport provides an ideal instrument for evaluation and prognosis for basin management and stewardship purposes.

2. Basic Principles and Model Construction

The following analysis is based on previous studies of the various components of the system with custom-made models of watershed hydrology (Ivanov et al., 2004; 2008a) and bed evolution processes (Bradford and Katopodes, 1999), leveraged by the long-term studies of channel characteristics on aquatic habitat (Jacobus and Webb, 2005).

In the present framework, a large-scale watershed model represents the front-end to the proposed impact assessment model. The hydrological model ingests a variety of data that characterize watershed topography, vegetation, soil type, and land use properties. Additionally, the hydrological model accounts for general meteorological forcing, e.g. precipitation, radiation and atmospheric turbulence. In areas susceptible to erosion, the locally produced event-scale runoff is then translated into sediment yields. Using the generated runoff and eroded particles as input, a transport model simulates the redistribution of sediment both as bedload and as suspended load across the basin drainage network. The long-term simulations allow the representation of characteristic hydro-geomorphic seasonal dynamics. Thus, at the framework back-end, this provides the necessary information for the evaluation of rates of change of stream and estuary morphology, as well as changes in aquatic habitat quality.

A distributed, high resolution, hydrologic and energy balance model is be used in this research. The model of choice is tRIBS-VEGGIE (Ivanov et al., 2004; 2008a) and arguably represents one of the most powerful tools of its kind. It combines explicit and dynamic simulation of vegetation and hydrological states over complex terrain. In addition, the model has the ability to propagate uncertainty in simulations. Figure 2a shows a schematic of the tRIBS-VEGGIE model that has been successfully applied to several large scale watersheds (Ivanov et al., 2004). tRIBS-VEGGIE is a fully distributed, physically based hydrologic model that offers a sophisticated parameterization of hydrological processes coupled with a model of vegetation dynamics (Ivanov et al., 2004a,b and 2008a,b).

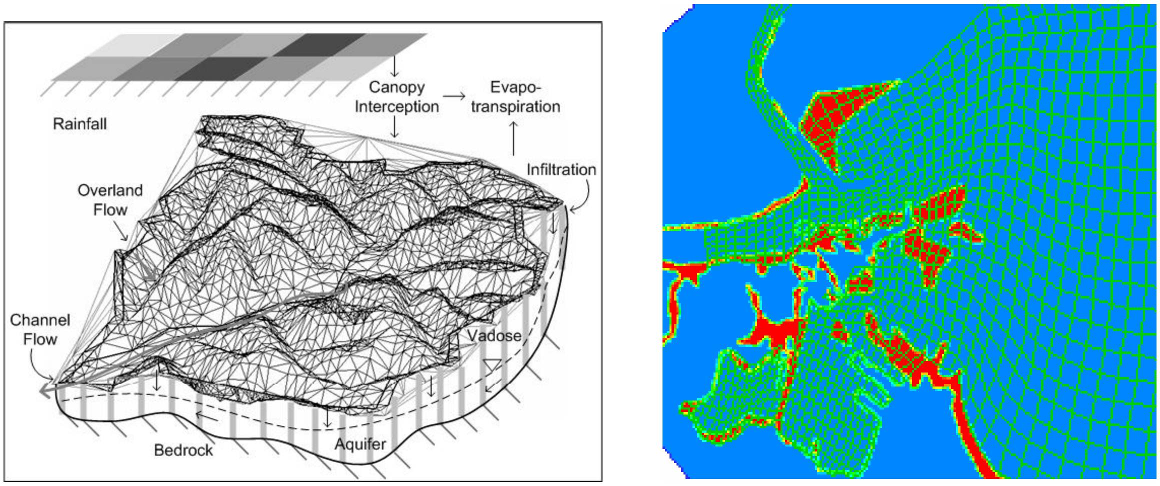

Figure 2. Watershed (a) and Estuarine Morphology (b) Models.

The model stresses the role of topography in soil moisture redistribution and accounts for the effects of sloped, heterogeneous, and anisotropic soil. The model includes physical representations of rainfall, interception, evapotranspiration, infiltration with continuous soil moisture accounting, and runoff routing. The tRIBS-VEGGIE model resolves a variety of hydrologic processes at very fine temporal (minutes to hour) and spatial (10 to 100 m) scales. Catchment topography, land use, vegetation, and soils are explicitly considered.

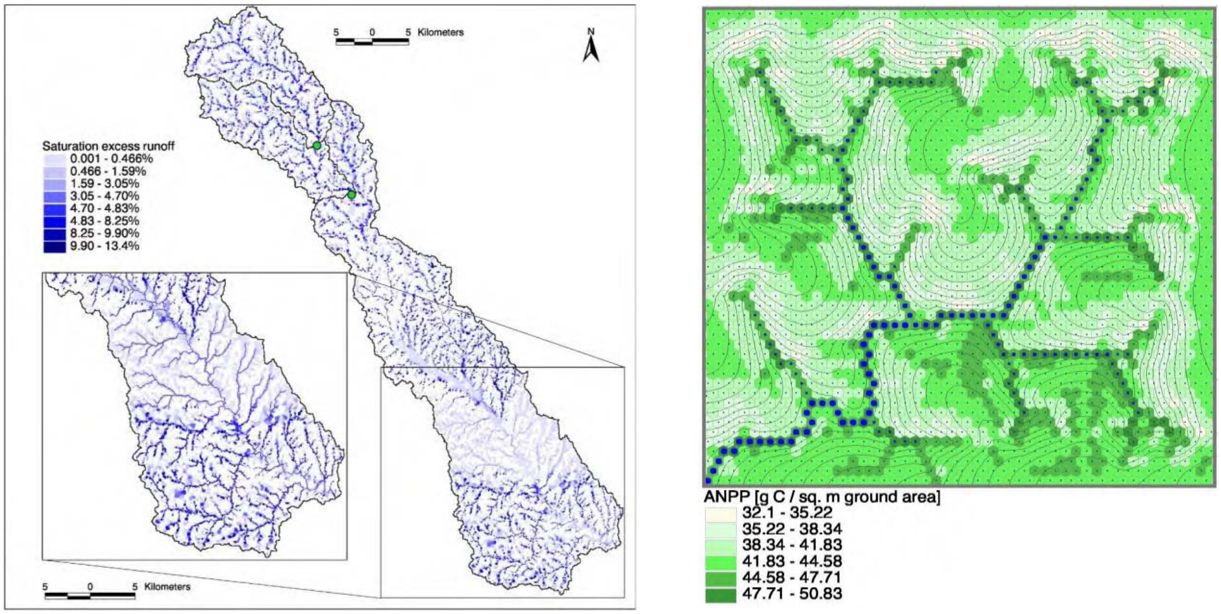

Figure 3. a.) Frequency of Occurrence of Saturation Excess Runoff as a Percentage of the Total Simulation Period (06/1993–07/2000) for the Blue River Basin (OK) b.) Mean Annual Above-ground Net Primary Productivity Simulated for C_4 Grass on Loamy Soil in a Synthetic Domain. The Climate of New Mexico was Used to Force the Modeled Dynamics. Blue Circles Show the Relative Magnitude of Surface Contributing Area. Spatial Resolution is ~30 m.

Model discretization is such that areas of higher moisture probability are sampled at a finer resolution (Vivoni et al., 2004). tRIBS (TIN-Based Real Time Integrated Basin Simulator, with static vegetation) was part of the DMIP-1 model intercomparison (Ivanov et al., 2004b) demonstrating its capabilities representing the hydrology of several large-scale watershed in Oklahoma (e.g., Figure 3.a).

The dynamic vegetation module (VEGGIE) was recently added to tRIBS (Ivanov et al., 2008a) in order to mimic the dynamic interactions of plants with hydrological processes. VEGGIE captures the fully coupled system of bilateral feedbacks and reproduces biophysical processes of canopy radiative transfer, emission and energy partition. The model evolves structural characteristics of vegetation and its composition via simulation of photosynthesis, respiration, turnover, allocation, recruitment, and phenology. The framework explicitly accounts for morphological and biophysical differences among multiple vegetation types that can be present in a given element. Overall, the framework links the hydrological and eco-physiological features of vegetated surfaces in a unique manner. As a part of recent study, the tRIBS-VEGGIE framework was used successfully for modeling the C_4 grass productivity of a semi-arid area in New Mexico (Figure 3.b, Ivanov et al., 2008b).

Figure 2b shows the turbidity and bed evolution model (T-BEM) of Bradford and Katopodes (1999) applied to the Muskegon estuary. The computational grid corresponds to the area shown in Fig. 1, thus demonstrating the ability of T-BEM to predict correctly the morphological changes in the estuary. For example, Fig. 2b shows several sediment deposition areas in the Muskegon estuary, as predicted by the bed morphology model. T-BEM has been successfully used for predicting submarine fan behavior (Imran et al, 1998), depositions from mine tailings in the Great Lakes (Bradford and Katopodes, 1999b), and the identification of offshore oil deposits (Bradford et al, 1997). In these applications, T-BEM has proved to be accurate and robust over time scales varying from minutes to hundreds of years. T-BEM accounts for the simultaneous movement of water and sediments, and dynamically couples the suspended load to bed materials. It also keeps track of deposits and thus can assess the mud and sand content of the bed, as well as the strength of the overall soil matrix. As shown in Fig. 4, T-BEM has the ability to predict the formation and disappearance of submarine canyons, and is the only know model capable of capturing the phenomenon of sediment ignition (Bradford and Katopodes, 1999a).

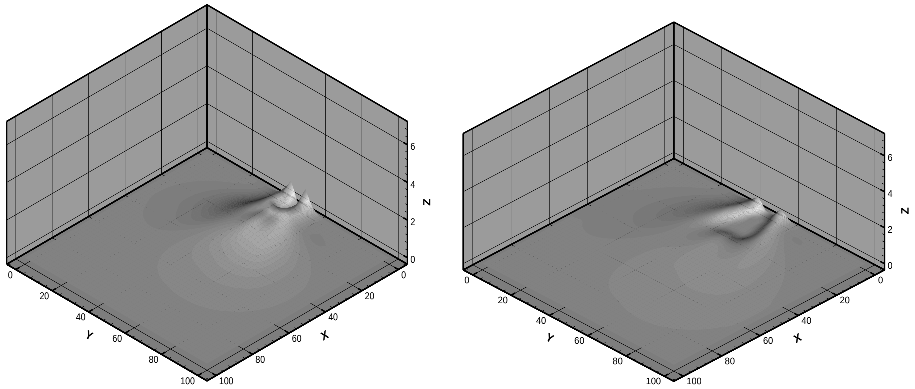

Figure 4. Deposition and Erosion of Multi-grain Sediments in a Shallow Estuary. Initially, Sediment is Deposited near the River Mouth. At Later Times, High Flow Events Erode the Bed Away.

The hydrodynamic component of the model has the ability to predict temperature and salinity, so T-BEM is equally applicable to fresh and salt-water estuaries and wetlands. The model also computes dynamically the location of the free surface, so the depth of flow, velocity field, turbulent characteristics and shear stresses near the bottom are available at all times. Finally, T-BEM can compute the fate and transport of chemicals in the system. Of course, the source and the rate of sediment production or chemical loading must be provided as input, which makes the integration with tRIBS-VEGGIE crucial. Once this coupling is accomplished, the land use practices that precede the increase in soil erosion or the source of chemical loading becomes transparent to the estuarine and wetland processes.

3. Integration of Mechanisitc Models with Ecological Information

The focus of this research is to integrate tRIBS-VEGGIE, T-BEM and a novel aquatic habitat model. Combined together, the above models can provide scenarios translating climate and land use changes into impacts on estuarine morphology and aquatic life. By also performing a systematic sensitivity analysis, we can also arrive at quantitative results and uncertainty bounds for assessing the impact of such changes and to provide alternative scenarios that ensure the sustainability of aquatic systems.

tRIBS-VEGGIE provides the input for T_BEM. The computational grid of the latter is be nested in the grid of the former, so the two models operate in parallel regardless of their individual scales. Data are filtered both spatially and temporally, so the integration of the two models becomes seamless. This is a delicate process that has been only recently refined in the context of coupled surface and subsurface water flow (Avendt and Katopodes, 2005). In a system that attempts to integrate two variables one of which varies at a rate that is several orders of magnitude higher than the other, the mathematical formulation often leads to stiff equations that are difficult to solve. However, a process has been developed in which the slow variable can be integrated asymptotically without knowledge of the fast variable. Furthermore, by viewing the slow variable time scale as a quasi-steady state of the fast variable, relaxation methods are used to guide the fast variable towards this quasi-steady state without worrying about the details of the smallest time scales. These multi-time scale integrators have been used successfully in wetland modeling and their adaptation to proposed model is straightforward.

The integrated tRIBS-VEGGIE-T_BEM model is next combined with an ecological information model that is capable of receiving hydrodynamic data and converting them to habitat parameters. Specifically, spatially-distributed depth and flow data are used in identifying parametric relationships for habitat characteristics (Bouma et al., 2005). Velocity and shear data are mapped to relationships for fish stability and maneuverability (Webb, 2006a). Temperature data is linked to fish habitat identification (Webb, 2006b) and finally, waves and eddies are associated with fish behavior and habitat distribution (Webb et al., 2008). Most of the parametric relations of the habitat model are empirical; however, the integrated model is validated using real field data. It has been shown that as the depth of flow in an estuary is gradually reduced, as the width of beaches increases, as the wave patterns and eddies are altered, and the balance of sand, mud, and water is modified, strong correlations between these hydrodynamic variables and fish habitat are developed. Thus, following validation, the ecological information parametric formulation becomes a robust and reliable module of the overall watershed-estuary model.

Specific habitat conditions are quantified through physical and biological states that are directly connected to the hydrodynamic conditions of the flow. The mathematical model tracks each specific sediment size and its cohesion characteristics. During deposition, the model also stores the location and consolidation characteristics of the bed, and its sand, silt and clay content. Next, the anchoring effects of early vegetation are modeled as a function of root type, root age, sediment grain size and bed shear. The static resistance to uprooting at the different ages of vegetation is related to soil moisture dynamics, shear acting on the biomass, and the erosion of the soil matrix supporting the root. As water flows around each plant, the drag and lift forces are computed as functions of local velocity. At the same time, erosion near the base of the plant is assessed, thus permitting the model to predict the stability of aquatic vegetation. In turn, the latter provides information on the strength of the soil matrix and thus the erodibility of the bed. This provides a two-way transfer of information between the hydrodynamics and the habitat that has not been previously quantified.

4. Sensitivity Analysis

The integrated watershed-estuary-habitat model is used as the engine for a formal sensitivity analysis (Sanders and Katopodes, 2000). Using the adjoint sensitivity method, we perform a systematic study of the factors affecting aquatic life in wetlands and estuaries. The precise impact of climatic change or alternative land practices at the watershed level can be quantitatively assessed if one system parameter is varied while all others remain constant. The effect of such variation on a specific target, e.g. habitat component, represents the sensitivity of the habitat to each parameter change.

The model calculates alternative scenarios for the impact of alternative land usage by first calculating the sensitivity of a selected habitat index to changes in a watershed parameter. The tedious task of sensitivity calculation has been reduced by the use of equations which are adjoint to the governing equations (Sanders and Katopodes, 2000). The discrete dependent variables of the flow and transport equations can be written in vector form as follows

$$\frac{d\mathbf{u}}{dt} = f(\mathbf{u}, \alpha) \tag{1}$$

in which the processes f include the spatial derivatives of the governing equations and any source terms, $\mathbf{u}$ is the vector of semi-discrete dependent variables and the vector α contains all other parameters associated with the problem. In its most general form the parameter space includes initial and boundary conditions, resistance and mixing coefficients, and all other watershed and estuary parameters.

In order to assess the effect of a perturbation of a specific entry of the parameter vector α, we introduce a functional of the corresponding output, which may be written as

$$F(\mathbf{u}, \alpha, T) = \int_0^T \int_\Omega r(\mathbf{u}, \alpha, t)\, d\Omega dt \tag{3}$$

where T is the time at which the effect is recorded, Ω is the solution domain and r is a user-specified response function, intended to establish a measure of the spatial and temporal distribution of the parameter impact in the system. In the present case r is chosen to represent the squared error between the measured and computed concentration at selected monitoring points

$$r(\mathbf{u}, \boldsymbol{\alpha}, x, t) = \sum_{l=1}^{L} w_l(x_l, z_l, t)\left[\mathbf{u}(x_l, z_l, t) - \mathbf{u}^o(x_l, z_l, t)\right]^2 \tag{4}$$

where L is the total number of observation points, w_l are weighting coefficients serving to emphasize certain monitoring points more than others, x_l, z_l are the coordinates of the L observation stations, and $\mathbf{u}^o$ are reference values of solution vector.

An estimate of the behavior of the response function due to changes in the loading vector is obtained by computing the total variation of Eq. (3). The latter can be expressed in terms of the partial derivatives of the response function, as follows

$$\delta F(u^0;\alpha^0;\delta u;\delta\alpha) = \int_0^T \int_\Omega \frac{\partial r}{\partial u_i}\delta u_i + \frac{\partial r}{\partial \alpha_n}\delta\alpha_n \, d\Omega dt \qquad (5)$$

in which (u^0,α^0) represents the base level prior to perturbation of the parameter vector. In a direct optimization scheme, the computation of the parameter gradients requires tRIBS-VEGGIE and T-BEM to be solved N times during each iteration. This cumbersome computation can be avoided, however, by using adjoint sensitivity procedures. The variation of Eq. 1 itself with respect to $\delta\alpha$ is taken formally, which results in

$$L[\delta\mathbf{u}] = \mathbf{S}\delta\alpha \qquad (6)$$

where the operator L is defined by

$$L[\quad] = \delta_{ij}\frac{d}{dt} - \frac{\partial f_i}{\partial \alpha_j} \qquad i,j = 1,2,\ldots I \qquad (7)$$

where δ_{ij} is the Kronecker delta and

$$\mathbf{S} = \frac{\partial f_i}{\partial \alpha_n} \qquad i = 1,2,\ldots,I \qquad n = 1,2,\ldots N \qquad (8)$$

is a spatial influence matrix, depending on the watershed characteristics. Equation 7 represents a system of ordinary differential equations that can be solved numerically, given some suitable initial conditions. For example, we may require that the solution at $t = 0$ be unaffected by any future changes in the parameter vector, i.e., $\delta\alpha_i(0) = 0; \qquad i = 1,2,\ldots I$.

It is possible to compute the variation of the functional F in the adjoint space by introducing the sensitivity or adjoint function $\mathbf{u}^*$. Multiplication of Eq. 5 by $\mathbf{u}^*$ and integration over the entire computational domain and simulation time yields

$$\int_0^T \int_\Omega \mathbf{u}^* \cdot (L[\delta\mathbf{u}])\, d\Omega dt = \int_\Omega [\delta\mathbf{u}\cdot\mathbf{u}^*]_0^T \, d\Omega - \int_0^T \int_\Omega \delta\mathbf{u}\cdot(L^*[\mathbf{u}^*])\, d\Omega dt \qquad (9)$$

in which the adjoint operator L^* is defined by

$$L^*[\quad] = -\delta_{ij}\frac{d}{dt} - \frac{\partial f_j^*}{\partial \alpha_i^*} \qquad i,j = 1,2,\ldots I \qquad (10)$$

Comparison of Eqs. 5 and 9 reveals that the first term of the right hand side of Eq. 9 can be expressed as follows

$$\int_0^T \int_\Omega r\mathbf{u}_i \delta\mathbf{u}_i \, dt = \int_0^T \int_\Omega \mathbf{u}^*(\mathbf{S}\delta\alpha)\, d\Omega dt + \int_\Omega [\delta\mathbf{u}\cdot\mathbf{u}^*]_0^T \, dt \qquad (11)$$

where the term $L^*\mathbf{u}^*$ was replaced by $\partial r / \partial \alpha_i$.

The preceding method provides the ideal means for performing an impact analysis using the best possible physical description of the system. However, in cases where the impact of a parameter variation requires several years to manifest itself in the habitat, tedious computations are needed to obtain the relevant sensitivity information. These must be then repeated for each parameter that can potentially affect the target. Adjoint sensitivity analysis allows us to compute the same impact information extremely efficiently without repetitive runs of the model. By running the adjoint model in the reverse time direction, all sensitivity data for a given habitat component can be computed by a single simulation of the direct and one of the adjoint model, regardless of the number of parameters affecting the target component. Remarkably rich information can be thus retrieved very efficiently, and parameters that have insignificant impact on the habitat can be securely excluded from further studies.

5. Discussion of Results

The present model offers the capability of providing valuable spatially-distributed information for assessment of sustainable practices in the watershed. The latter involves prioritization of areas for erosion control with relevant restrictions on land use change, stream bank stabilization, removal of sediment material to improve in situ fisheries, and alternative planning of the construction of structures in the river water-course.

The research effort described in this paper addresses the sustainability of freshwater estuaries and wetlands that are intricately connected to the Great Lakes and the State of Michigan. For over one hundred years, the lumber and heavy industries, agricultural and urban development have all contributed to dramatic changes in the aquatic habitat of the region's estuaries and wetlands. Now, climatic change threatens these same habitats in ways that are totally unknown and whose impact has never been assessed. Actually, no quantitative impact assessment exists today for any of the practices that are known to affect aquatic habitat. The present research offers the first opportunity for such a quantitative assessment that can provide deterministic estimates of the sustainability of the aforementioned practices. The model outlined in this paper provides a unique tool to scientists and regulatory agencies for identifying the critical parameters in the problem and seeking new land practices that will stop habitat destruction and even reverse the process. The present model is based on sound physical principles and on previously developed modules that have been shown to be reliable and robust. The challenge of the present research is their seamless and efficient integration. This in turn provides an unprecedented wealth of information that has not been previously available and will allow engineers to transform their standard operation methods. Such changes will improve aquatic habitat conditions tens of years into the future and hundreds of miles away from a given project's location.

6. Conclusions and Future Research

Although the existing estuarine, watershed and habitat models provide satisfactory results when used independently, we presented a framework that can create a new paradigm for assessing long-term changes in the corresponding physical systems. The method offers the opportunity for a truly transformative multi-disciplinary approach. The result is a unique model that can be used to assess sustainability issues in a variety of marine and freshwater systems. We believe that the proposed integrated model and the methodology for a formal sensitivity analysis will be of great value to several government agencies, so we expect our efforts to lead to several major proposals. Future research will enable us to create and validate the integrated habitat model and establish collaborations and a knowledge base that does not currently exist. Once the model becomes operational, we will be in better position to evaluate the influence of various aspects of the problem.

We believe that the outcome of this effort will a unique model that will allow us not only to develop an exciting tool for quantitative assessment of sustainable processes, but will also give scientists the experience, data and quantitative information necessary to reverse estuarine habitat damages that have occurred over the last century.

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Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

The Energy-Water Nexus:
Climate Change Impacts on Energy Production and Water Allocation

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Abstract

Although they are often perceived as separate challenges, energy sustainability and water sustainability are in fact highly coupled and interdependent problems. Water, for example, is needed to process fuel and generate electricity, whereas energy is required to convey water across long distances to populous arid regions. Many of the solutions that are presently proposed to satisfy ever-rising energy demand and to combat global warming are highly intensive in their freshwater use. Without careful consideration and foresight, strategies to achieve energy sustainability may precipitate unintended water crises by overcommitment of finite freshwater resources. An anticipated increase in occurrence of extreme weather events such as droughts and heat waves will further exacerbate energy-water interdependency. Sustainable energy and water infrastructure planning must therefore be carried out concurrently rather than sequentially, in order to ensure that future energy and water needs are met in a manner that is technologically and economically feasible for various water use sectors (energy, agriculture, municipalities) and that safeguards the environment and public health.

In this white paper, we identify water quantity and water quality issues related to production of thermoelectric power and biofuels, two sectors of the national energy portfolio where rapid expansion is occurring and is expected to continue in the next two decades. Freshwater conservation technologies are discussed, and the cost, technical barriers, and policy ramifications of implementing these technologies, alone or in combination with carbon mitigation, are considered. The impacts of biofuel production facilities and biofuel-powered vehicles on water quality and ecosystem health are reviewed. Lastly, the use of watershed modeling tools is proposed for integrated energy and water infrastructure planning, and key research issues are noted for conjoining watershed models and climate change projections of surface temperatures, precipitation forecasts and extreme weather variability at prospective future thermoelectric power and biofuel production sites.

1. Introduction: A Look at the Energy-Water Nexus

The recent ascendance of climate change to the forefront of global policy discussions has intensified the debate on how the U.S. and other nations can achieve a sustainable energy portfolio to effectively manage their greenhouse gas emissions. Likewise, the uncertain impacts of global warming on the future availability of freshwater resources has amplified concerns about how to ensure adequate water supplies to the world's populous arid regions. The quests to secure energy sustainability and water sustainability are complicated by the reality that energy and water infrastructures are in fact highly coupled and interdependent systems. Water, for example, is needed to process fuels and to generate thermoelectric power, whereas energy is required for the pumping, conveyance and treatment of water and wastewater. Energy and water infrastructure interdependence achieves its most visible nexus in coal, gas, and nuclear thermoelectric power plants that withdraw and consume massive quantities of freshwater for the cooling of turbine exhaust, desulfurization of flue gases, and other essential process needs. Perceptions notwithstanding, household electricity consumption is as water-intensive as domestic activities that transparently utilize water such as cooking, washing and gardening [1]. Domestic electricity demand is projected to rise 30% in the next 25 years [2], and consequently resource pressures on freshwater will intensify (Figure 1). Yet despite the strong dependence of energy production on water availability, policymaking is hampered by a casual regard for water as an inexhaustible resource. This spawns numerous local conflicts over water [3] and abets an increasingly unsustainable energy-water infrastructure, vulnerable to both seasonal disruptions (e.g. drought) and longer-term surface water redistributions wrought by climate change.

As shown in Figure 2, the energy and agriculture sectors each account for about two-fifths of domestic freshwater withdrawals. Competition between these sectors for limited freshwater is fierce, particularly in historically arid western states and in the southeastern U.S., where a prolonged drought has impacted the regional economy and fueled interstate disputes over management of local water reserves. Even in the traditionally water-rich states of the Midwestern U.S., the subsidy-driven boom in ethanol production has

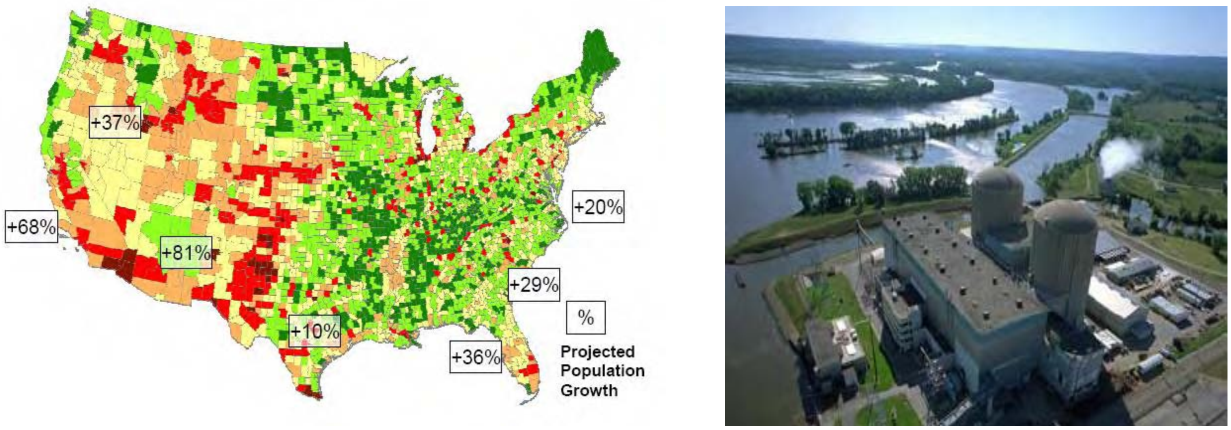

Figure 1. Electricity generation is water intensive. Water shortfalls are projected in much of the U.S. due to population growth and consumption for energy and agriculture. Red and yellow denote counties where water withdrawals exceed precipitation [44].

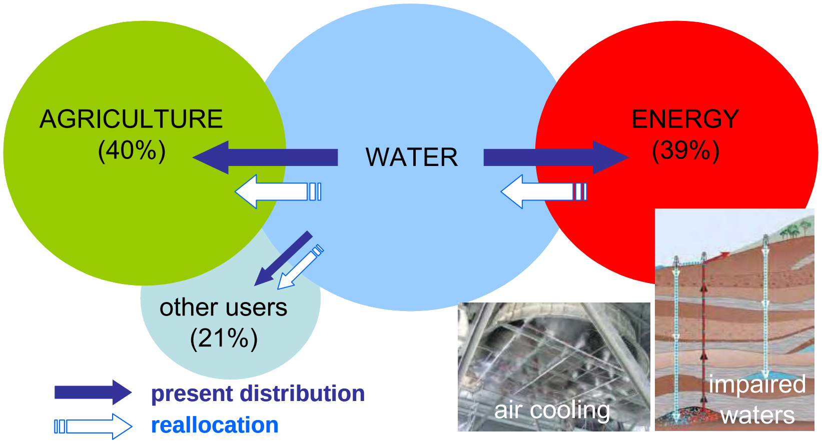

Figure 2. Electricity production accounts for two-fifths of freshwater withdrawals in the U.S. Sector-wide use of hybrid air condenser systems [3] or impaired cooling waters [43] at thermoelectric plants decreases energy-water interdependence and recovers freshwater for agriculture and other uses. Redundant cooling resources and methods improve energy resilience and sustainability.

awakened concerns about the water quantity and water quality impacts of a large scale-up in biofuel production. Inasmuch as energy production is exigent on the marshalling of water resources, it is impractical to develop a roadmap for energy sustainability that does not duly account for present and future water availability. Some of the proposed technologies for capturing and storing carbon dioxide, for example, are water-intensive. Strategies that reduce carbon emissions for sustainable energy must not precipitate water crises by exacerbating energy-water interdependency.

Energy-water interdependencies at the nexus between energy production and water withdrawal and consumption can be categorized in terms of water quantity and water quality issues (Table 1). Reliable energy production can be enhanced through adoption of technologies that reduce freshwater use at thermoelectric power plants, or utilize nontraditional cooling water resources in electric power generation. Likewise, deleterious water quality impacts from energy production can be reduced through more efficient fuel and biomass conversion or wastewater recycle and reuse. Development of water conserving and water preserving energy technologies requires intensive collaboration among engineers and scientists from wide-ranging disciplines. Implementation of technology innovations that address energy-water interdependence will moreover require buy-in from planners and decision makers in both the energy and water sectors. There is thus an important role for social scientists and policymakers, to facilitate acceptance of the economic costs to be borne by energy providers and consumers alike in decoupling the energy-water nexus. Lastly, input from climate change researchers will be needed to anticipate future regional availability of water resources so that resilient and sustainable energy infrastructures can be designed for a range of possible climate trajectories.

Table 1. Water quantity and water quality issues associated with the production of electricity from nonrenewable resources and biofuels from renewable resources.

Energy Production Sector	Water Quantity Issues	Water Quality Issues
Thermoelectric Power **coal-fired, natural gas combined cycle, integrated coal gasification, and nuclear power plants**	• **large withdrawal rates and impingement effects for once-through water cooled systems** • **smaller withdrawals but larger consumption for recirculating wet cooling towers and ponds** • **small withdrawals but parasitic energy losses for air cooling** • **secondary water consumption for stack gas scrubbing, CO_2 capture by amine absorption**	• **surface water thermal pollution from discharges of once-through cooling water** • **demineralization of brackish water resources, blowdown to prevent scale buildup on condenser equipment** • **handling of produced waters from proposed CO_2 storage in saline aquifers, coal seams or depleted oil/gas reservoirs**
Biofuels **ethanol production from corn, cellulose or other routes**	• **large water commitments for crop irrigation and production of ethanol from harvested biomass (four gallons of water per gallon of corn ethanol)** • **depletion of confined aquifers to meet increased water demand for biofuel synthesis in Midwestern states**	• **runoff from excessive nutrient loading of managed croplands** • **concerns about ethanol spills and its solubilizing effects** • **high BOD discharges from ethanol refineries** • **increased sedimentation and erosion from conversion of marginal lands to croplands**

2. Freshwater Use Reduction at Thermoelectric Facilities

Demands on water resources will rapidly become unsustainable if conventional cooling methods are used in the new power plants being constructed to meet rising electric demand. Alternative resources must be expanded to satisfy the cooling requirements of these facilities. Existing and future power plants, moreover, are vulnerable to water disruptions caused by weather-related events and global warming. Redundancy in cooling technologies is essential to provide flexibility for unpredictable surface water availability at thermoelectric power plants.

Steam-driven plants require heat exchange to condense turbine exhaust. Most coal-fired plants and all nuclear plants in the U.S. use “wet” cooling systems based on open-loop or closed-loop cooling cycles. In open-loop or “once-through” systems, cooling water is withdrawn directly from a lake or river and heated water is returned to its source. Because of thermal pollution concerns and entrainment problems on intake screens, open-loop cooling is generally done only with seawater at coastal facilities [4]. Most plants built since enactment of the Federal Water Pollution Control Act in 1972 use closed-loop or “recirculating” wet cooling systems (Figure 3) that dissipate waste heat to the atmosphere rather than to surface water [3]. These systems use a cooling tower to transfer heat to ambient air by conduction, convection and evaporation. Closed-loop systems withdraw less than 5% of the water required for once-through cooling [3]; however, water *consumption* is larger in recirculating systems because of evaporation and blowdown loss to prevent mineral fouling. Though a small fraction of total cooling water recirculation, freshwater losses from evaporation in wet cooling amount to 3.3 billion gallons per day in the U.S., nearly 20% of all nonagricultural freshwater consumption [5].

To meet escalating demand for electricity, it is projected that a new 500 MW power plant must be built in the U.S. *each week* for the next fifteen years [1]. This represents a staggeringly large and unsustainable increase in freshwater appropriation for electric power generation if traditional wet cooling systems are used. One option to reduce thermoelectric freshwater use is to deploy air cooled condensers (Figure 2) for “dry cooling” of turbine exhaust by conduction into ambient air blown by fans across the tube surface. Air cooled condensers eliminate water use, but at the expense of higher installation and operating costs and a plant efficiency reduction of 2 to 5% relative to wet cooled systems [6,7]. In addition, power output at dry-cooled plants decreases by as much as 25% in hot weather [8], so air cooled condensing is potentially most cost-effective for thermoelectric plants in states with wintry climates.

Alternatives to reduce freshwater use at inland plants are to utilize brackish groundwater or wastewater effluents in wet cooling systems (Figure 2). Shallow saline aquifers are found in much of the U.S., as are produced waters from mining operations, oil and gas extraction. However, impaired waters from these sources must be treated to be suitable for thermoelectric cooling. Brackish groundwater typically contains 500-30,000 mg/L total dissolved solids [3], including Ba^{2+}, Ca^{2+}, SO_4^{2-}, and CO_3^{2-} solutes that foul condenser equipment from calcite, gypsum and barite precipitation. Wastewater effluents have high dissolved solid content. Scale reduces heat exchanger efficiency and damages equipment as minerals concentrate from evaporative losses [9]. Desalination

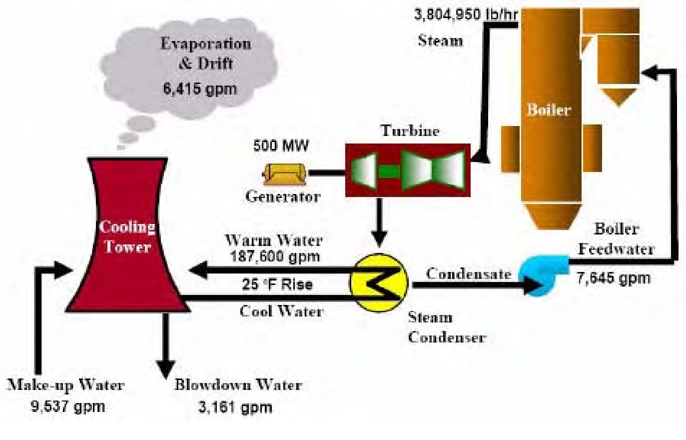

Figure 3. Representative steam and cooling water flowrates for a 500 MW coal-fired steam power plant with a wet recirculating cooling tower [1].

using reverse osmosis [10,11] or chemical demineralization [12,13] must therefore precede impaired water use in thermoelectric cooling.

Ongoing efforts to quantify water resource commitments in electric power generation, and to promote innovations in existing thermoelectric plants that reduce freshwater withdrawal and consumption, have been championed by the Electric Power Research Institute (EPRI) [4] and the DOE National Energy Technology Laboratory (NETL) [1]. A report to Congress on research and technology needs associated with the energy-water nexus was assembled by Sandia National Laboratories with participation from several other DOE national laboratories [3]. Interest in novel power technologies such as integrated coal gasification (IGCC), spurred by the expectation of impending carbon legislation, has drawn attention to the water requirements of these alternative technologies [14]. Thermoelectric cooling constraint indices [15] have been proposed to take into account the available renewable water resources in a region, proportionate to the projected growth of water use for power generation within the region. It has been estimated that the combined cost of water acquisition, delivery, treatment and disposal for thermoelectric power generation ranges between $1 and $4 per thousand gallons of water. For a typical 350 MW coal-fired power plant operating at the middle to high end of this spectrum, water conservation through recovery of evaporative, scrubbing and blowdown losses (Figure 3) can save $2 million to $2.7 million per year in water costs [15].

3. Water Impacts of Biofuel Production

The coming shift from a fossil fuel-based global economy to one based on alternative and renewable energy sources will have sweeping impacts on all sectors of society. The exigent nature of the global warming threat requires that this shift occur at an unparalleled pace. In view of the scale, urgency, and stakes involved, the societal and environmental impacts of the evolving technologies require close scrutiny. Biofuels, particularly ethanol-based fuels, are heralded as an attractive alternative fuel source. In 2006, U.S. production of corn ethanol was 4.9 billion gallons, and the current administration suggests that this level should increase to 35 billion gallons by 2017. Concerns over the environmental impacts of corn ethanol production at this scale, however, are escalating. Much of the current discussion focuses on negative water quality impacts, such as fertilizer and pesticide pollution or sedimentation due to erosion, and water quantity impacts of corn-agriculture, in comparison to other ethanol feedstock alternatives [16]. Even if environmental impact-neutral ethanol production approaches were adopted, additional sources of environmental degradation are possible as ethanol-based fuels are distributed and used. Within the distribution system, pipelines, tankers, ships, and storage tanks represent points of vulnerability. The miscibility of ethanol in water, for example, could cause larger plumes of contamination in water supplies when leaks or spills occur. Lessons from the nation’s experience in using oxygenated fuel components, the most prominent being methyl tertbutyl ether (MTBE), suggest that a holistic assessment of the risks should include not only those of producing the fuel, but also those of its inadvertent release into the environment.

Conversion of cropland or pasture land to grow corn for ethanol will result in the increased application of nitrogen and phosphorus, as corn requires the highest fertilizer application rate of the potential biofuel crops [17]. Greater rates of application of nitrogen and phosphorus and the conversion of other crop acreage to corn over extensive areas in the Midwest will likely further stress areas already suffering from the impact of excessive nutrient loading (Figure 4). High nitrate concentrations are a health concern, as nitrate in drinking water has been associated with several types of cancer [18] and the ingestion of water containing excessive nitrate by infants can lead to methemoglobinemia, a potentially fatal condition [19]. Much of the excessive fertilizer moves from its point of application on the land surface. Nitrate exceeds the maximum contaminant level of 10 mg/L as N in 15% of the samples from 4 major drinking water aquifers [20] and even without the added fertilizer associated with corn-based ethanol production, moderate to severe nitrate contamination of groundwater is predicted in the Midwest [21]. Fertilizer transported down the Mississippi River enters the Gulf of Mexico, creating the second largest hypoxic area in the world [22,23]. Consequently, the possible adverse effects of the utilization of cropland and pasture land for biofuel production must be evaluated, particularly since water resources in the Midwest are already adversely impacted by crop nutrients.

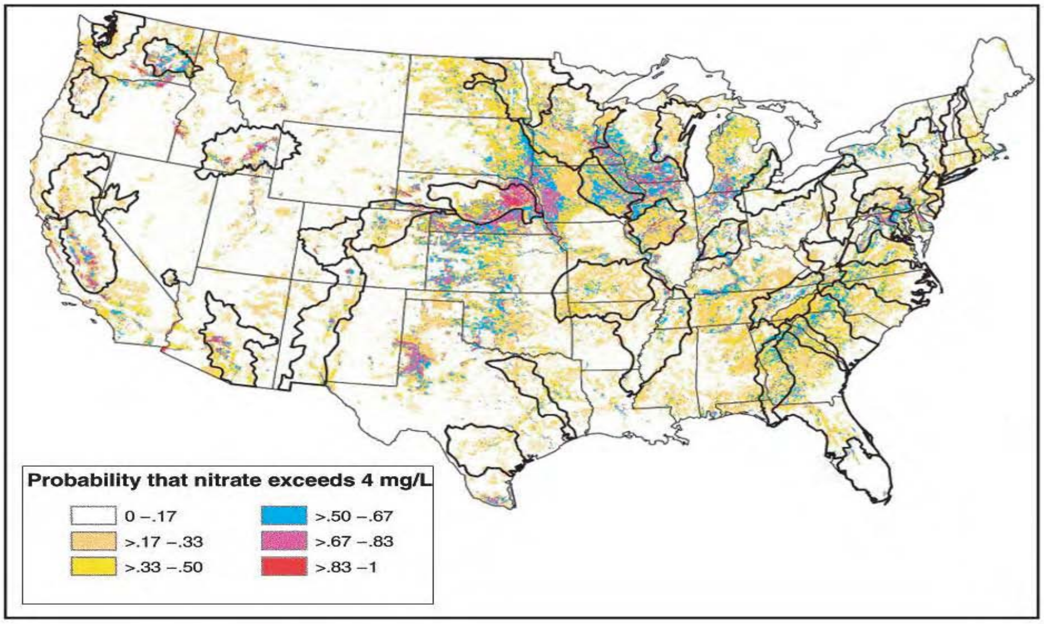

Figure 4. Probability that nitrate exceeds 4 mg/L in major drinking water aquifers, without added fertilizer associated with corn-based ethanol production (Nolan and Hitt, 2006). Many locations of high probabilities coincide with locations where ethanol production will be concentrated.

The impact of fertilizer runoff may be mitigated by switching from corn as the feedstock to another crop that requires less fertilizer such as sorghum or switchgrass. Yet regardless of the crop from which it is produced, ethanol itself may result in undesirable impacts on water quality. As a liquid fuel or fuel component, it will be stored in a storage tank. The EPA estimated that as of 2001, there had been 412,000 releases from underground storage tanks and about half of them reached groundwater [24]. Because of its chemical structure, ethanol is completely miscible in water; consequently very high concentrations are possible. Experiments conducted using gasohol (10% ethanol by volume) showed that residual gasoline saturations in the vadose zone were significantly reduced as the ethanol’s impact on the interfacial properties of the system caused more of it to migrate to the groundwater [25]. Thus, a greater fraction of the spill may end up in ground water. Furthermore, ethanol may alter the rates of biodegradation of more recalcitrant compounds because of its rapid preferential degradation. In fact, it has been observed that ethanol can stop the in situ degradation of carcinogenic compounds in gasoline such as benzene and toluene [26].

Gasoline is sparingly soluble in water. Thus if gasoline is spilled in surface waters, it forms a film or layer on the water’s surface. Then most of it volatilizes, with the rate of dissolution on the order of 0.1% of the rate of volatilization [27]. However, ethanol, as a water-miscible compound has the potential to elevate the dissolution rate, thereby increasing the concentration of sparingly soluble hazardous compounds in the water column. Research by Pinal et al. [28] suggests that the effect could be substantial in that they found that partially miscible organic solvents could increase the solubility of sparingly soluble organics by orders of magnitude, particularly if they contained a polar functional group such as OH, as ethanol does. Once in the water column, ethanol could further compromise the water quality by solubilizing contaminants residing in the sediment. Research has noted the ability of dissolved natural organic matter to solubilize contaminants such as PCBs [29]. As a fuel or fuel component, ethanol could potentially be present in rivers or lakes in considerably greater concentrations than natural organic matter, raising the possibility of solubilizing PCBs, PAHs, or dioxins from the sediment. Although exposure to ethanol itself may not be a human health risk factor, ethanol's impact as a solubilizing agent needs to be evaluated.

The water quality and quantity impacts of refining ethanol from biomass are likely to stress the localities where they are sited. These refinery sites will be clustered in rural Midwest and Great Plains localites. Iowa, for example, currently provides almost one-third of the U.S. ethanol refining capacity [30]. The water requirements to refine corn ethanol, although much less than the water required to grow corn, are still substantial. According to a recent NRC estimate, approximately 4 gallons of water are required to refine one gallon of ethanol, whereas petroleum refineries require only 1.5 gallons of water per gallon of gasoline [16]. Estimates of the water demand for corn-based ethanol, including the water used for growing the crop, are as high as 15 gallons of water per gallon of ethanol. Water resources in many biorefinery areas are often already stressed (Figure 5). Process water in the rural Midwest is often drawn from confined aquifers and increased demands on such sources are not sustainable. Water reuse strategies will need to be developed to allow refineries to be sited in such areas.

To protect regional water quality near biorefineries, significant investments in wastewater treatment technologies will also be necessary. Ethanol refineries typically generate high BOD (biochemical oxygen demand) wastestreams, in excess of 1500 mg BOD/L [31], compared to the organic loadings handled by publicly owned treatment works (POTWs), which are typically about 200 mg BOD/L. In small- to

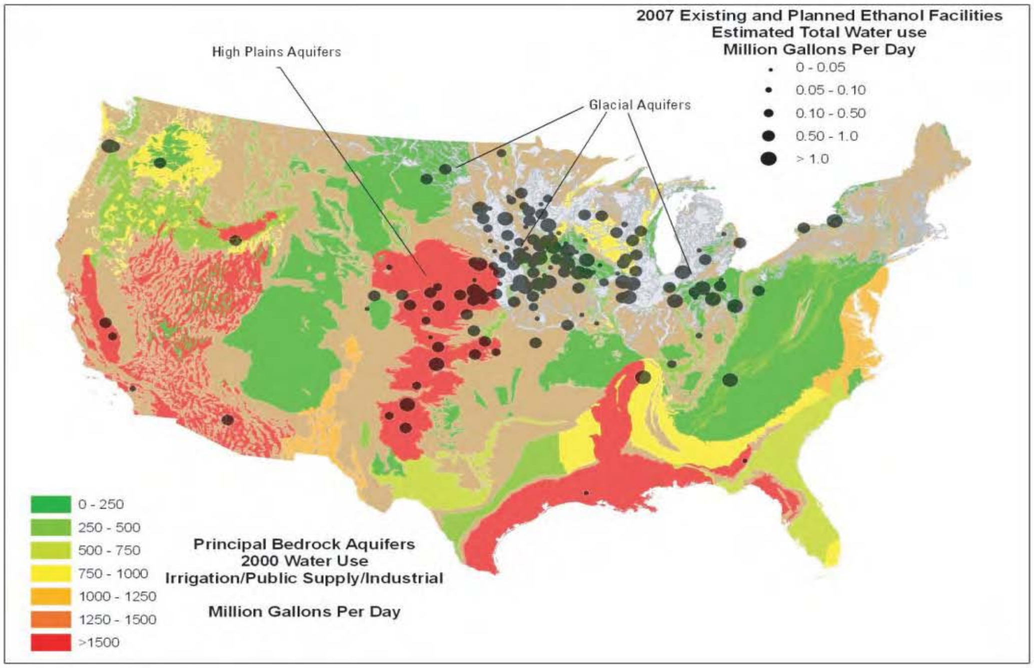

Figure 5. Locations of existing or planned ethanol production facilities as of 2007, and estimated total water use of those facilities, superimposed on color-coding showing the daily quantity of water withdrawn from principal water supply aquifers in 2000 (NRC, 2007).

moderately-sized communities, however, the existing municipal wastewater treatment facilities are unable to handle such high BOD wastewater without significant pretreatment at the refinery and modifications to the POTW. National Pollutant Discharge Elimination System (NPDES) permit violations occurred at the South Bend, Indiana Municipal Wastewater Treatment Plant in the 1980s, for example, when the New Energy of Indiana ethanol refinery's *pre-treated* wastewater was introduced, requiring significant operational changes at the POTW [31]. Investments in existing POTWs will likely be necessary to accommodate even pre-treated wastestreams from biorefineries. Ethanol distilling processes also require high purity water streams that are often produced by membrane treatment [16]. The high total dissolved solids brines from these processes will increase the net salinity load on receiving waters. The development of regional siting criteria for biorefineries may be necessary to minimize the expected impacts of their water demands and organic and salinity loadings on watersheds.

Potential releases into the aquatic environment include BOD and salt from biorefineries; sediment, nutrients and pesticides from croplands; ethanol; and ethanol-solubilized toxic organic chemicals. All of these contaminants have the potential to impact the entire food chain from micro-invertebrates residing in the bottom sediment layer, to fish, and finally to humans. Negative ecosystem-wide impacts resulting from the increasing nutrient loads from agricultural runoff have already been documented in the Gulf of Mexico [22]. Conversion of non-agricultural lands to grow biofuel crops will promote greater erosion and stream sedimentation, altering fish dynamics as some species avoid suspended sediment [32]. Furthermore, habitats, especially in vegetated areas, will be directly impacted by a change in sediment loading. Over time, previously productive nearshore environments can be rendered uninhabitable by aquatic organisms. With enhanced solubility, toxic organic compounds become more bioavailable, causing a shift in fish response to PAHs, for example, from an exhaustion of the cortisol-producing endocrine system [33] to reproductive impairment and liver disease [34].

Ethanol-based biofuels can adversely affect ecosystems if inadvertent fuel releases occur during their transport from refineries to storage facilities. Some of the nation's most important freshwater resources, such as the Great Lakes and the Mississippi River, are located near current or projected refinery locations the heart of the biofuel distribution network [16]. Since ethanol and fossil fuels have such different chemical properties, standard models for spill protection and control will not be applicable. Given ethanol's aqueous solubility, cosolvency effects and biodegradability, new models must be developed to understand the effects of biofuel releases if freshwater ecosystems are to be protected.

Cost/benefit and life cycle analyses of biofuels focus primarily on tradeoffs in greenhouse gas production and energy efficiency [35]. This approach ignores the possible risks to human and ecosystem health

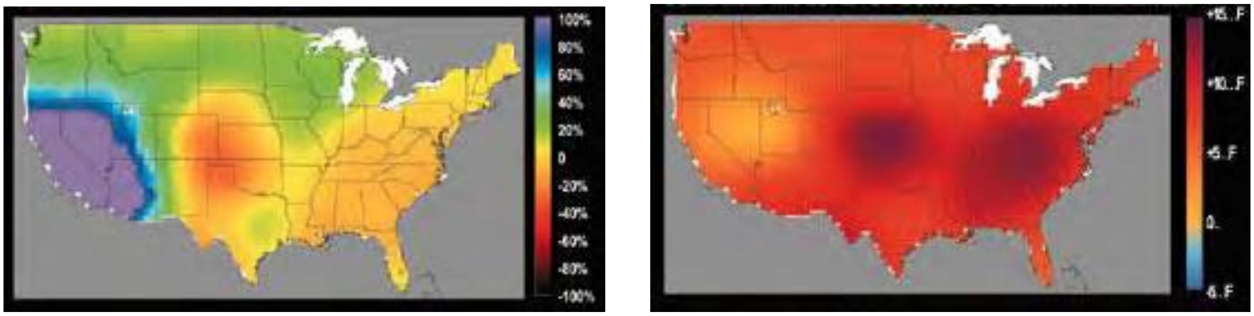

Figure 6. Climate change is projected to increase peak summer temperatures (left) and cause the redistribution of regional precipitation (right) [37]. This will affect decision-making with regard to the placement and mode of operation of future power plants built to meet rising power demand.

caused by release of anthropogenic substances to the aquatic environment. Such analyses must include a risk assessment of the impact of releases to the environment to fairly calculate the costs of various fuel options. Releases may be chronic such as the discharge of waste from ethanol refineries to receiving waters, additional nutrient and pesticide loading and releases from leaking underground storage tanks. The releases may also be acute, such as waste treatment facility failures and spills from pipelines or tankers. Both "typical" and "high-end" exposure scenarios must be considered to properly quantify the cost [36]. Unfortunately, if one were to quantify the costs currently, it would be based on sketchy scientific knowledge of the physical, chemical and biological processes governing the transport and fate of these releases. Given the magnitude of the economic investment contemplated for the switch to biofuels, it is imperative that there be a concomitant investment in understanding the consequences for water resources.

4. Climate Change and the Energy-Water Nexus

It is anticipated that global warming will increase not only mean surface temperatures, but also the magnitude and duration of extreme weather events (Figure 6). Amplification of weather variability will make water availability for electricity and biofuel production increasingly uncertain over the service lifetime of a thermoelectric facility. The abandonment of stationarity as a stock assumption in the management of water requires a rethinking of the design of energy production facilities [38]. Hybrid condenser systems, with redundant wet/dry cooling, are a potential safeguard against these uncertainties for thermoelectric facilities in regions where air-cooled condensing is a cost-effective option. The projected hydrologic impacts from climate change modeling can be used for a range of climate change scenarios to determine where water-conserving technologies might most effectively be deployed to enhance the resilience and sustainability of the national energy infrastructure. The health benefits of measures to enhance electric power reliability are significant, as power failures due to drought or heat wave can result in fatalities from the loss of air conditioning or water conveyance, particularly in urban areas.

Watershed management tools such as WARMF (Watershed Analysis Risk Management Framework) [39], developed by Systech in partnership with EPRI and now accessible on the EPA's website, provide a valuable decision support system for assessment of the water resource impacts of planned additions to electricity generation and ethanol production. These GIS-based tools apply meteorological data to watersheds divided into interconnected catchment basins and surface water segments, yielding spatially dependent data on point and nonpoint loads, total maximum daily load allocations, and hydrologic conditions. Such data can be used to assess the water quality impacts from newly constructed biofuel refineries or thermoelectric power plants. Recently, a WARMF-ZeroNet module was developed by Systech and EPRI in partnership with NETL and Los Alamos National Laboratory [40]. This enhanced watershed modeling tool can be used to assess the impact of extended drought or climate change-induced surface temperature increases on water availability in water-scarce regions where additions to generating capacity are being contemplated (Figure 7).

5. Concluding Thoughts

The importance of achieving energy and water sustainability cannot be overstated. It is equally important, however, to recognize that progress toward sustainable infrastructures for the provision of both energy and water cannot be achieved unless planning and policymaking efforts recognize the complex interdependencies of the energy-water nexus. Diversification of the cooling resources and technologies used at thermoelectric power plants will improve energy reliability by easing these interdependencies, freeing up freshwater for agriculture or other residential, commercial and industrial needs. Similarly,

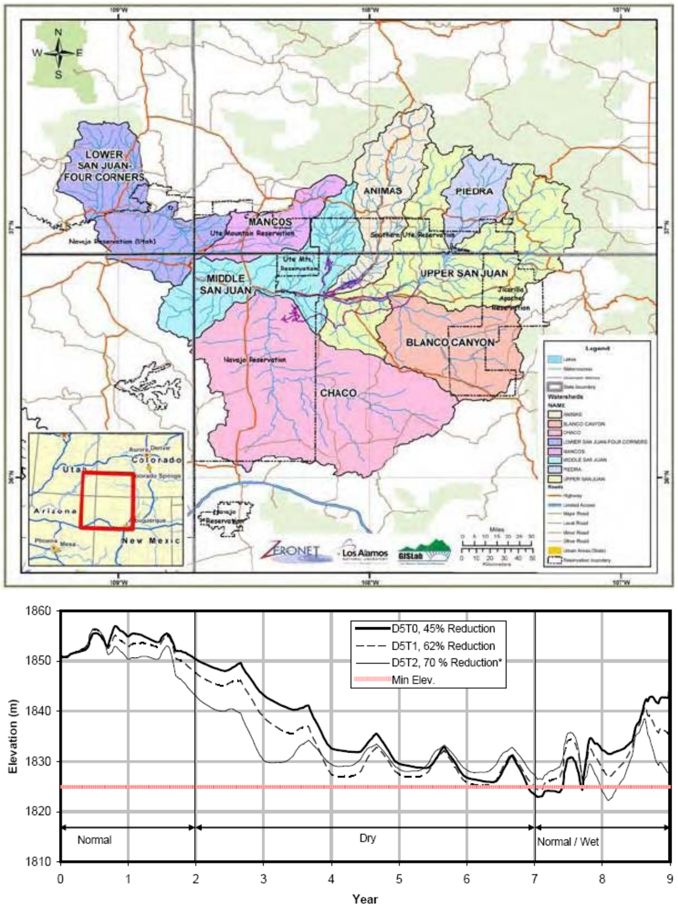

Figure 7. Watershed analysis models such as WARMF-ZeroNet [40] provide insight into the effects of extended drought (bottom) or other climate change impacts on freshwater availability in regions that are critical to energy production and agriculture, such as the San Juan basin (top).

improved feedstocks, synthesis routes, distribution systems and waste management practices in the biofuels sector will allay concerns about the impact of the rapidly expanding ethanol industry. Finally, it is prudent to consider the potential effects of climate change on future availability of freshwater supplies for energy, agriculture and other use sectors, in locales where significant increases in water withdrawal and consumption are anticipated for capacity additions to meet rising energy demand.

Technological innovations, and energy-water infrastructure planning using watershed modeling tools, must be accompanied by socio-economic research and policy formulations to incentivize utilities, biofuel producers, regulatory agencies, and state and local governments to assign proper valuation to water as a finite resource. Policy development is needed to assess how water deregulation affects energy technology selection, stimulates innovation through technology adoption, and impacts technology adoption cycles [41, 42]. In particular, the merits of a market-based approach for technology selection, wherein water value is driven according to the water source, conveyance distance, and consumptive losses, should be compared against the benefits of a subsidy-based approach, in which specific allowances are made for water efficiency objectives; e.g. a 50% reduction of freshwater use or 50% freshwater replacement with impaired water for thermoelectric cooling operations.

Developing nations in Asia, particularly China, and in Africa confront similar problems as the United States in allocating water between their competing energy and agriculture sectors. Hence, the solutions developed and lessons learned from integrated domestic energy and water infrastructure planning will inform progress toward energy/water sustainability in other regions of the world where water is a prized resource.

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March 26-27, 2008

A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater

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K. Karvazy, L. Kelly, L. Macpherson, J. R. Mihelcic, A. Pramanik, L. Raskin,
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Abstract

Wastewater has an image problem. Fraught with hazards requiring diligent attention, we find that new wastewater treatment techniques can not only protect public health and improve ecosystem quality, they are a critical contributor to global sustainability. Yet sustainable water systems can only be realized if the general public and the water industry begin thinking about wastewater differently. This feature article is the product of a workshop involving individuals from professional practice and research who propose the need for a paradigm shift from wastewater as a problem to wastewater as a resource. In the article, the authors contend that the primary problem is not the availability of technology for resource recovery, but the lack of a socio-technological design methodology to identify and deploy the most sustainable solution in a given geographic and cultural context. They acknowledge that the most sustainable solution may not result in maximum, or any, recovery of resources from wastewater. Instead a sustainable water and wastewater decision-making process considers environmental, economic, and social ramifications of decisions across spatial and temporal scales to achieve the best balance identified by the project stakeholders. A central element of sustainability is that stakeholders are defined broadly to include utility managers, operators, regulators, local government officials, end-users, public interest groups, and other parties impacted by the project. The objective of the paper, therefore, is to identify elements of such a decision-making methodology that can provide all stakeholders with the tools needed to advance sustainability, as well as to suggest a set of guiding principles for resource recovery systems in the water industry.

Published in Environmental Science & Technology (2009) 43, 6126-6130

http://pubs.acs.org/doi/pdf/10.1021/es9010515

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Harmful Algal Blooms in the Great Lakes

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1. Introduction

Millions of microscopic photosynthetic cells thrive in nearly every drop of freshwater. Algae, consisting of macroalgae, protista, bacteria and other microorganisms are the energy foundation of the aquatic ecosystem. Under normal conditions, these single-celled organisms photosynthesize and multiply, which provides sustenance to everything from fellow microbes to fishes. Uncontrolled growth with ample sunlight and nutrients creates dense surface blooms in eutrophic aquatic systems that lead to mass mortalities of fish and birds and provide a serious health threat for fish, livestock, pets and humans are known as harmful algal blooms (HABs). In addition to eutrophication and mass mortalities, HABs are dangerous because many of the bloom-forming organisms also produce neuro- and hepatotoxins which can be fatal to a range of species—including humans.

1.1. Cyanobacteria

Cyanobacteria are part of a diverse group of gram-negative photosynthetic prokaryotes. Historically, these unique organisms, which are capable of both aerobic and anaerobic photosynthesis as well as nitrogen fixation, have been studied in the context of eutrophication. The growth of "mats", which results from extremely high rates of photosynthesis and growth, deplete the water of oxygen and often result in substantial fish die-offs. Increased rates of decomposition following a bloom or a massive fish kill further deplete the water of oxygen serving to perpetuate the cycle. Cyanobacteria are found ubiquitously in aquatic systems as well as freshwater ponds, rivers, reservoirs, and lakes. Usually the moderate concentrations of cyanobacteria co-exist with other organisms in a body of water; but when conditions are favorable, the cyanobacteria proliferate and form blooms. Cyanobacteria blooms can be composed of many filamentous cells arranged into chains or strands called trichomes. When the body of water is visibly colored by the cyanobacteria, then it is considered a harmful algal bloom and the concentration of cyanobacterial cells can number more than 10^4 cells mL^{-1}. Some cyanobacterial species (*A. ovalisporum* and *C. raciborskii*) contain gas vacuoles that aid in orienting the bacteria in the water column by regulating buoyancy. Some blooms may result in floating cyanobacterial masses on the surface of the water depending on the buoyancy of the cells. These floating cells are called scum and usually contain about 10^6 cells mL^{-1}.

1.2. Cyanotoxins and Human Health

In addition to the ecologic damage caused by Cyanobacteria, recent studies have suggested that Cyanobacteria also threaten human health. Cyanotoxins are natural compounds produced by some genera of Cyanobacteria. They are classified by their mechanism of action and fall primarily into three categories: protein phosphatase blockers (cyclic peptides, e.g. microcystins), neurotoxins (alkaloids, e.g. anatoxin-a), and cytotoxin (alkaloid, e.g. cylindrospermopsion). Microcystins fall into the category of hepatotoxic cyclic peptides and are produced by several genera including *Microcystis, Anabaena, Planktothrix, Anabaenopsis, Nostoc, and Hapalosiphon* (Wiegand, 2005). Microcystins are the most well known cyanotoxins worldwide and have been shown to be responsible for the adverse effects on animals (e.g. livestock), plants, and even human death (Yin, L. et al., 2006; Pouria et al., 1998; Jochimsen, et al., 1998). Of more than 80 congeners of this compound, microcystin-LR, a Heptapeptide containing the teo L-amino acids, leucine and arginine, has been found to be the most frequent and most toxic. It is synthesized inside the cell and is only released during cell lysis or death. Bloom managers must emphasize extreme caution when using algaecides such as copper sulfate, the subsequent cell lysis, following treatment, will increase the concentration of cyanotoxins to higher, more hazardous levels. Therefore, such treatment should only be considered in non-drinking water settings.

As with all toxins, exposure to microcystin can be defined as either acute or chronic. Common routes of exposure include: 1, direct contact with or ingestion of contaminated water; and 2, the ingestion of dietary supplements made with cyanobacteria. Bathing with contaminated water is acknowledged as a minor route of exposure, as toxins can be aerosolized and then inhaled. In addition, the consumption of contaminated seafood has been proposed as a potential route of exposure (Ibelings, 2007). The risk of food-borne exposure is great enough to warrant the proposal of guidelines for Microcystin concentrations in food (Dietrich and Hoeger, 2005; Ernst et al., 2005).

While acute exposure can result in gastroenteritis, nausea, vomiting, diarrhea, and fever, of greater concern is the effect of long-term chronic exposure, which is thought to cause chronic liver damage and tumor suppression. Microcystins have been found to penetrate the membrane of hepatocytes via the bile acid transport system (Falconer and Yeung, 1992) and the members of organic anion transporting polypeptide superfamily (Fisher et al., 2005). Pichardo (2007) found that microcystin-YR toxicity in *Poeciliopsis lucida* exposed to *Microcystis aeruginosa* after 24 hours resulted in reduction in cell number and size and death by necrosis in hepatic cells. Their toxicity has also been linked to the inhibition of several serine/threonine protein phosphatases (Shen et al., 2003).

Falconer et al. (1983) reported elevated liver enzymes, indicative of liver damage, in a group of Australians whose water supply was contaminated by cyanobacteria. A few years later in China, a link was found between liver cancer and exposure to cyanobacteria. Yu et al. (1989, 1995) concluded that cancer rates were highest in people who received their water from contaminated ditches compared to people in the same area that used groundwater as their main source of drinking water. The most extreme case of human toxicity occurred in Brazil when a large number of haemodialysis patients were exposed to cyanobacteria through their treatment and became severely ill (Pouria, 1998).

2. History of HABs in the Great Lakes and Potential Triggers

One of the rising and emerging freshwater areas of concern within the United States and Canada is the Great Lakes. The Great Lakes cover 94,000 square miles and 56 billion gallons of water are used daily for municipal, agricultural and industrial use. The Great Lakes provide drinking water for 60 million U.S. and Canadian residents and compose of 10,000 miles of coastline in 8 different states. Challenges regarding the Great Lakes include beach closures, nonpoint source pollution, groundwater protection, septic systems, lakes and stream impairment and invasive species. Recently, HABs have been reported with increasing frequency in the waters of every state in the US as well as coastal areas and inland lakes in many parts of the world. Five common toxic HAB forming cyanobacteria live within the Great Lakes. The five species are: *Microcystis aeruginosa, Anabaena circinalis, Anabaena flos-aquae, Aphanizomenon flos-aquae, and Cylindrospermopsis raciborskii.* In fact, virtually every US coastal state has experienced the environmental, human health, and economic impacts of HABs.

Like many major waterways, the Great Lakes have been vulnerable to major ecosystem fluxes in the past few decades due to human influences such as invasive species and increased nutrient and pollutant loading. Harmful algal blooms were common in the Great Lakes in the 1970s and early 1980s due to the phosphorus loading from detergents into the surface waters. Stimulated by concern for the health and quality of the lakes, Canada and the US signed the Great Lakes Water Quality Agreement in 1972 to considerably decrease phosphorus concentrations by setting annual limits on the discharge of phosphorus to Lake Erie (Dolan 1993). The blooms abated following implementation of the Great Lakes Water Quality Agreement with a marked improvement in water quality (Makarawicz and Bertram 1991, Munawar et al. 2002). The trend of infrequent blooms ended in 1995 when a bloom of toxic Microcystis was documented in the western basin of Lake Erie (Brittain et al. 2000). This was the first indication of a reversal in trends of toxic cyanobacterial blooms in the Great Lakes. It was surprising because of the nutrient reductions and overall improved quality of the lake. Around 1986, the nonnative zebra mussel *Dreissena polymorpha* was unintentionally introduced into Lake St. Clair and Lake Michigan, and, by 1988, had spread to Lake Erie (Leach 1993). Zebra mussels have been found to exhibit selective feeding, expelling toxic Microcystis (Juhel et al. 2006, Vanderploeg et al. 2001). Additionally, a model studying the relationship between zebra mussels and Microcystis blooms found that blue-green cyanobacteria presence was only impacted by the presence of zebra mussels due to selective rejection of the toxic cyanobacteria (Bierman et al. 2005). Overall, total phytoplankton biomass and chlorophyll a were reduced dramatically following the introduction of zebra mussels into Lake Erie (Makarewicz et. al 1999). Conroy et al. (2005) and other studies have found that cyanobacteria biomass have increased during the summer, since the late 1980s, in all basins after the dreissenid mussels invasion into Lake Erie. Microcystis 16S rDNA, *mcyB*, and *mcyD* genes in Lake Erie's three basins indicate that toxigenic Microcystis is spatially and temporally widespread (Ouellette et al. 2004).

The problem of toxic harmful algal bloom-forming cyanobacteria other than Microcystis has been re-appearing in recent years since the dreissenid invasion in the Great Lakes. The first documented observation of the potentially toxic cyanobacterium *Cylindrospermopsis* in Lake Erie and Sandusky Bay occurred in the summer of 2005 (16-1,942 trichomes mL^{-1}) (Conroy et al. 2007). In Lake Ontario, *Microcystis* sp. genus is the dominant microcystin producer and concentrations can exceed the WHO guideline value for drinking water, $1\mu\mathrm{g}\ \mathrm{L}^{-1}$ (Hotto et al. 2002). Rinta-Kanto et al. (2005) found that August of 2003 and August of 2004, blooms of potentially toxic cyanobacteria *Microcystis* spp. persisted in western Lake Erie, where large-scale ($> 20\ \mathrm{km}^2$) blooms have been observed.

The rise of cyanobacteria HABs has been linked to several other phenomena. The occurrence of blooms is associated with periods where the heat of summer stabilizes the water column which favors the growth of buoyant cyanobacteria. The combination of favorable light and water column conditions and increased nutrient output from wastewater and non-point sources suggest that the problem is from anthropogenic sources. Johnk et al. (2008) developed a model showing that summer heatwaves boost the development of harmful cyanobacterial blooms. *Cylindrospermopsis* biomass correlates with high temperatures and shallow depths, conditions often found in Sandusky Bay (Conroy 2007). In lakes Muskegon and Mona lakes, which are tributaries of Lake Michigan in the summers of 2002 and 2003, *Cylindrospermopsis raciborskii* blooms were observed and linked to higher temperatures and increased phosphorus concentrations (Hong et al. 2006). Another toxin producing cyanobacteria, *C. raciborskii*, tolerates a rather wide range of climatic conditions and the global warming phenomenon, which provides this species with better environmental conditions for its growth (Briand et al. 2004). Thus, one of the main aggravators of the HAB phenomena is the increasing surface water temperatures of the lakes.

Along with warmer temperatures, other physical factors can predict and promote bloom formation. For instance, Jiang et al. (2007) identified that nitrate and phosphate as well as phosphate and temperature had significant interactive effects on cell growth, respectively, while iron and light had significant interactive effects on the production of microcystins. When nutrient concentrations are low, however, cyanobacteria such as *M. aeruginosa* are superior competitors under iron limitation compared to non-toxic cyanobacteria (Nagal et al. 2007). Hotto et al. (2002) found that microcystin genotypes along the New York State shoreline of Lake Ontario, appear to originate nearshore, and thus, can be transported via physical processes such as wind and currents. Despite the growing consensus regarding environmental factors that correlate with harmful algal blooms, Graham et al. (2004) found that in 241 lakes in Missouri, Iowa, northeastern Kansas, and southern Minnesota, microcystin values were linked to increasing latitude and other physicochemical factors, but with only 50% of the variation explained by these factors.

3. Future Developments and Research Needs

Over the past decade, federal agencies working with state public health and fisheries managers, the science community, and coastal industries have tried to identify uncertainties and data gaps in the current research and have defined the future research needed in order to address the growing problem of HABs in US waters. The objective of much of the current research on HABs has been the fundamental biological, chemical, and physical processes underlying bloom formation and their impacts. Previous studies have revealed that a variety of environmental parameters including temperature, light and nutrients have been associated with cyanobacterial growth and toxin production. Much work is still needed to investigate the influence of other factors on the growth of toxic algal species and toxin production. There is a critical need for research that combines field study, epidemiological investigation, and laboratory model systems to ascertain the biological and chemical processes that promote the growth of toxic cyanobacteria in the Great Lakes and to assess the risks of exposure to toxins. Such research will lead to innovative forecasting and intervention approaches for problems that have significant impacts on water quality and public health. Therefore, we suggest several urgent areas of research designed to address the potential adverse human health effects from the exposure to toxic cyanobacterial blooms including in the Great Lakes region.

3.1. Evaluate the Chronic Effects of the Long-term Exposure to the Cyanotoxins in the Great Lakes on Human and Ecosystem Health.

As noted previously, exposure to cyanotoxins can lead to either acute or chronic effects. Acute exposure can result in gastroenteritis, nausea, vomiting, diarrhea, and fever. Many reports recorded the occurrence of severe acute effects in different parts of the world (See reviews in WHO, 2003). Fortunately, such severe acute effects on human health appear to be rare, but little is known of the scale and nature of either long-term effects (such as tumor promotion and liver damage) or milder short-term effects, such as contact irritation. An epidemiological survey for the causes of primary liver cancer (PLC) in Haimen City, Jiangsu province, and Fusui County revealed a close relationship between PLC and drinking pond and ditch water (Ueno et al., 1996). This data aids in identifying microcystins as one of the risk factors for developing PLC in China. Long term exposure has also been implicated in tumor promotion (Ito et al., 1997, Nishiwaki-Matsumisha et al., 1992). Similar epidemiologic studies are needed to evaluate the risk of people living in the Great Lakes basin who are regularly exposed to toxic cyanobacteria and cyanotoxins. The Native Americans living around the Great Lakes who consume more fish products and drink water directly from the Great Lakes are a potentially high risk group. In order to perform the large scale and long term epidemiology studies, we need to develop methods and techniques for rapid and sensitive field-based detection of toxic cyanobacteria and toxins. The progress in molecular identification techniques of organisms by toxin genotype allows for surveillance and monitoring of drinking, waste and lake waters.

The risk assessment can take on a number of forms: (a) human epidemiological investigation that compares exposed and unexposed populations; (b) effects of HABs on wildlife and the food chain in the Great Lakes; (c) experimental investigations with sensitive cell cultures; and (d) critical assessment of dose-response relationships. HABs represent a real and persistent risk in waters of the Great Lakes, which does not appear to have caught the attention of the scientific community nor the funding agencies. The integration of new techniques and methods necessitate incorporation of new regulations and standards. The rise of harmful algal blooms within the Great Lakes in conjunction with the uncertainty of disease outcomes attributable to chronic and acute exposure creates an uneasy situation such that setting regulations would be the prudent course of action.

3.2. Identify Multiple Environmental Parameters that Can Induce HABs and be Used as Predictors of HABs in the Great Lakes for the Purpose of Better Management

Despite the increasing awareness and research regarding toxic cyanobacteria and harmful algal blooms, there remains a large gap for predicting blooms through models or indicators. One of the main hindrances to developing an accurate and successful model is identification and characterization of the main processes and relationships relating to toxic cyanobacteria in the Great Lakes. A primary relationship yet to be elucidated is the “function” of cyanobacterial toxins within the ecosystem. Rasmussen et al. (2007) found that cylindrospermopsin may be a deterrent on certain protozoa or other predators—not as an antibacterial agent. The list of toxins and functions are far from exhaustive, however, and model organisms need to be identified to successfully design a working model. The role of different physical predictors on HABs is still unclear, and do not fully explain their occurrence (Graham et al. 2004). Additionally, a crucial component to modeling HABs is discovering the “sources” and “sinks” of harmful algal blooms and cyanobacterial toxins in the Great Lakes. For example, a potential “source” of harmful algal blooms would be nutrient loading from point and non point sources. The relationships between different nutrient limitations are still relatively uncharacterized (iron, Medeiros 2006; silica, Carrick and Lowe 2007). Additionally, survival rates and interactions of introduced species and strains from ballast water are still not quantitative nor well understood (Doblin et al. 2007). Sinks would include prey-predator relationships, algaecides (copper sulfate, ozone) and sediment deposition. Characterization of toxins and organisms has made leaps and bounds since the incorporation of molecular techniques into larger temporal and spatial profiles (Wilson 2005, Smith 2005). The ability to predict and characterize blooms will ideally bring insight to effective management and prevention of harmful algal blooms.

3.3. Develop Effective Treatment Technologies

Reducing the level of toxic cyanobacteria and toxins found in both recreational and drinking water can minimize the risk of unfavorable health outcomes. Although some research of several treatment techniques for drinking and waste water has been conducted, none of them have realized a practical method of either destroying the toxin or preventing blooms (Kinnear et al. 2008, Wormer et al. 2007, Lehman et al. 2004, Hoeger et al. 2004). Treating lakes with algaecides such as copper sulfate may reduce cyanobacteria biomass in native waters (Lehman et al. 2004), but it also will result in an increased concentration of toxins in the water due to cell lysis. In two cases of toxin poisoning in Australia, the toxic symptoms occurred after the application of copper sulfate to dense blooms. Similar to other algaecides, toxin concentration increases with treatment of ozone (Hoeger 2002).The most effective method of algae control in reservoirs is though the use of aeration and destratification (Chorus and Bartram 1999). Due to the history of poor watershed management, it is not feasible to focus attention and resources on removing cyanobacteria from natural bodies of water, instead in-plant processes aimed at reducing cyanotoxins should be developed (Chorus and Luuc, 1999; Yoo, 1995). In order to develop effective treatment technology for specific water districts in the Great Lakes region, it is critical to understand the specific toxin of concern in the region because different technologies may have various degrees of efficiency of inactivation/removal depending on the toxin.

The issue of HABs in the Great Lakes and other aquatic environments is very complex; therefore, many research areas need to be addressed. A detailed and comprehensive list of recommendations was compiled by the HARRNESS Share Common Themes (HARNESS, 2005). A multidisciplinary approach is critical to identify what environmental parameters result in HABs and to address this issue in the Great Lakes. There is a critical need for research that combines field study, epidemiology study and laboratory model system to ascertain the biological and chemical processes that underlie the growth of toxic cyanobacteria in the Great Lakes and to assess the risks of exposure to toxins. Such research activities will result in innovative forecasting and intervention approaches for such problems that have significant impacts on water quality and public health.

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Student Abstracts

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Anaerobic Membrane Bioreactors for Treatment of Domestic Wastewater: Fouling and Fouling Control

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Current wastewater treatment in the United States is not sustainable. While treatment regulations are usually met, traditional methods generate high volumes of byproducts and are very energy intensive. Anaerobic treatment produces significantly less biosolids than aerobic treatment, and produces energy as a byproduct. Coupling anaerobic systems and membranes addresses challenges inherent to anaerobic treatment; however, fouling control is required for economic operation of anaerobic membrane bioreactors (AnMBRs). Previous work indicates extracellular polymeric substances (EPS) and struvite ($MgNH_4PO_4$) are present in AnMBRs, and contribute significantly to fouling. In this study, dominant foulants in different wastewater treatment strategies are evaluated, and countermeasures proposed for their effects on membrane flux. As one approach to reducing the influence of these foulants, this study evaluates several commercially available and newly developed membranes, to learn which membrane properties result in improved flux. An ideal membrane not only experiences little fouling, but also exhibits substantial flux recovery without requiring chemical cleaning. The fouling feed streams were actual and synthetic DWW, as well as three biomass samples (activated sludge from a full-scale aerobic MBR system treating DWW, biomass from a full-scale anaerobic digester treating sludge from a DWW treatment system, and supernatant collected from a bench-scale AnMBR), which were selected to provide variability in microbial community, EPS composition, and struvite precipitation potential. The synthetic DWW (500 mg/L COD) used in the current study serves as the influent for the aforementioned bench-scale AnMBR, which is seeded with granular sludge from a full-scale upflow anaerobic sludge blanket (UASB) reactor treating brewery wastewater. Additional feed streams to be examined as part of this study are the synthetic DWW after treatment in the AnMBR, as well each of the biomass samples, suspended in non-fouling buffers. Batch tests are performed in an Amicon cell (Millipore Corporation, Billerica, MA). Each feed and membrane combination is tested in stirred and unstirred tests under 20 psi (139 kPa) of pressure. Membranes are then removed and cleaned by backflushing or water rinsing. After cleaning, flux recovery is tested. For each membrane and input feed concentration, fouling magnitude and predominant fouling mechanisms are identified using flux data, chemical analyses, and/or SEM. Preliminary results have

been generated for a hydrophobic ultrafiltration (UF) polyethersulfone (PES) membrane (Sepro Membranes, Inc., Oceanside, CA). Average clean water flux for this membrane was approximately 900 LMH ($L/m^2 \cdot h$). Fluxes measured for stirred and unstirred batch experiments with synthetic DWW were substantially different, suggesting that this synthetic wastewater has the potential for both internal and external membrane fouling. The results of batch fouling studies of UF PES with the supernatant from the bench-scale AnMBR also indicate a substantial difference between stirred and unstirred tests. Furthermore, they show an improvement in flux over the untreated synthetic DWW. Pre-filtered treated synthetic DWW demonstrated even more improvement in flux, indicating a contribution from microbial foulants. In conclusion, the preliminary results presented in this study suggest that the membrane fouling attributed to synthetic DWW is both internal and external, and is a combination of microorganisms and other foulants.

Key Words
Anaerobic Membrane Bioreactor
Domestic Water

Graham Environmental Sustainability Institute
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Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Applying Geospatial Decision Support Tools to Assess Water Quality and Human Health Risk in the Great Lakes Region

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Applying advanced geospatial tools, water quality instruments, and information derived from satellite imagery has the capability to help inform the research agenda and public decision-making process concerning water quality, environmental change, and public health. The Michigan Tech Research Institute (MTRI), in collaboration with the University of Michigan (UM) and Western Michigan University (WMU), have developed web-based decision support tools that integrate quality data, sediment contamination levels, and customized on-line mapping software. These interactive tools are used to evaluate the potential human health impact from consuming fish from Great Lakes rivers contaminated with mercury and polychlorinated biphenyls (PCBs). We also show how genetic expression of contamination in Kalamazoo River (MI) fish can be used to show which river segments tend to have more contaminated fish in them, providing another way of mapping potential health risk areas. We also developed a water quality web-mapping tool that integrates data from the Automated Langrangian Water-Quality Assessment System (ALWAS) floating data buoy that collects 14 different water parameters, including dissolved oxygen, turbidity, temperature, total dissolved solids, and pH, while also tagging all data with their location using GPS. The water quality web tool displays the ALWAS data using a modified version of the National Sanitation Foundation (NSF) Water Quality Index (WQI), and proposed versions of indices for drinking water, fish habitat, and recreation. At a more regional scale, we have developed methods of analyzing water quality for Lake Michigan, Lake Superior, Lake Ontario, and Lake Erie using moderate-scale satellite imagery with visible spectrum bands, such as the MODIS and SeaWIFS satellites. The regional-scale algorithms estimate the levels of Chlorophyll-A, suspended minerals (SM) and dissolved organic carbon (DOC) seasonally using frequently collected satellite imagery. These are used to assess the overall ecological health of the lake, look for chance in lake water quality patterns over recent years, and to predict patterns likely to occur from climate change scenarios. The ability to assess Great Lakes water quality over past years was the greatest value of the satellite-derived information; we have assessed data from 1998 to 2007. From small stretches of specific rivers to entire Great Lakes, our tools are being used to assess lake water quality, human health, and related issues in the region.

Detection of Ammonia-oxidizing Bacteria and Archaea in a Recirculating Shrimp Aquaculture System Biofilter

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Recirculating aquaculture systems (RAS) for the production of shrimp are a sustainable alternative to traditional shrimp pond culture. Through biological water treatment, RAS are able to recycle water in the system, which reduces the need for water exchange and eliminates the production of an effluent. Biofilters in RAS provide support for ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria to convert ammonia, which is toxic to the shrimp, to nitrate. The biofilter associated with the maturation system of an indoor, zero-exchange shrimp RAS was analyzed. Bacterial 16S rRNA gene clone libraries failed to detect AOB in either the shrimp tank or microbial biomass from biofilters. On the other hand, archaeal 16S rRNA gene clone libraries identified putative ammonia oxidizing archaea affiliated to *Nitrosopumilaceae* and *Cenarchaeacea* as major groups in the system. PCR detection of the *amoA* gene coding for a subunit of the ammonia monooxygenase gene of bacteria and archaea revealed weak amplification of the expected product in the case of bacterial *amoA*, but strong amplification of archaeal *amoA*. We are in the process of confirming these results by further sequence analysis and quantitative PCR. Future work will include a detailed water quality analysis of the system to determine how the system characteristics affect the microbial ecology in the biofilter. This work will increase the understanding of biological water treatment in RAS, which is important because poor water quality can reduce shrimp growth and increase the incidence of disease.

Key Words
Recirculating Aquaculture Systems
Ammonia-Oxidizing Bacteria
Ammonia-Oxidizing Archaea

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Establishing the Research Agenda
March 26–27, 2008

FeS-Coated Sand for Removal of Arsenic (III) under Anaerobic Conditions Coating Method and Characterization

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A method of synthesizing a new reactive medium for permeable reactive barrier under anaerobic condition was developed using reduced iron sulfide (FeS) in the form of mackinawite. This FeS-coated sand is expected to offset the potential failure of iron oxide based reactive materials in treatment of As(III)-contaminated groundwater under reducing environments. In the coating procedure, FeS solution chemistry and the surface properties of silica sand are deemed to be important factors. The pH of FeS solution controls the surface charge of FeS particles and the amount of dissolution. In order to compensate for both effects, the optimum pH was determined to be pH 5.5 for a 2g/L FeS suspension. Also, the surface-modified sand (cleaned with the strong chemicals HCl, $Na_2S_2O_4$ and H_2O_2) and unmodified sand showed pH differences in FeS solution before and after mixing, indicating that the unmodified sand surface contains more proton-consuming sites than the surface-modified sand. The role of the proton-consuming sites was considered to enhance the coating strength of FeS on silica sand. The highest amount of FeS coating obtained was 3.99 mg FeS/g sand; this measurement was verified by observing aggregated FeS nano-particles covered on the silica sand surface using scanning electron microscopy. In As(III) sorption experiments in anaerobic batch systems, the efficiency and behavior of As(III) removal of FeS-coated sand showed a similar trend with that of pure FeS for 1ppm As(III) in pH conditions ranging from pH 3 to pH 12. The adsorption edge of As(III) showed two local maxima at low pH (< pH 5) and pH around 9, indicating two different As(III) removal processes at each pH condition. It thus appears that As(III) removal occurs through precipitation at low pH and via adsorption at high pH. This result demonstrates that FeS-coated sand may be potentially used to remediate As(III)- contaminated groundwater under reducing environments.

Key Words
FeS-Coated Sand
As (III) Removal
Permeable Reactive Barrier

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WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Biological Mediated Simultaneous Removal of Arsenic, Perchlorate, and Nitrate from Drinking Water

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A variety of technologies are available to remove contaminants, such as perchlorate, nitrate, and arsenic, from drinking water sources. The co-existence of these contaminants in groundwaters suggests that the development of strategies for their simultaneous removal may lead to a more cost-effective treatment strategy. A fixed-bed biologically active carbon (BAC) reactor amended with acetate as the electron donor simultaneously reduced perchlorate and nitrate in a synthetic groundwater at typical concentrations of 75 µg/L and 25 mg/L, respectively, to below their detection limits. At the empty bed contact time used (20 min), sulfate in the groundwater was not reduced. Biomass from this BAC reactor was used as the inoculum for batch experiments. It was determined that adding arsenic up to 1 g As(V)/L to the synthetic groundwater did not inhibit the biological reduction of perchlorate and nitrate in these experiments. The results of batch experiments performed with the effluent of the BAC reactor amended with acetate, ferrous iron, and As(V) arsenic acid species indicated that the microorganisms present in the BAC reactor were capable of sulfate reduction, resulting in ferrous sulfide precipitation. The results also showed that As(V) was reduced to As(III) biologically. Ongoing work is focusing on the characterization of the precipitated iron sulfide, the arsenic adsorption capacity of the precipitated iron sulfide, and microbial community analysis. These results suggest that a sequence of two fixed-bed BAC reactors may be an effective treatment strategy to simultaneously remove perchlorate, nitrate, and arsenic from drinking water sources.

Key Words
Perchlorate
Arsenic
Fixed-bed
Bioreactor

Microorganisms Responsible for Anaerobic Biodegradation of Benzene under Nitrate-Reducing Conditions

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Monoaromatic hydrocarbons, Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) are commonly found in petroleum products and frequently contaminate ground water and soil. Among these compounds, benzene is of major concern due to its high water solubility and toxicity. Benzene can be oxidized in the absence of oxygen to harmless products by microorganisms under different electron-accepting conditions. Denitrifying cultures that degrade benzene have been enriched in our laboratory. The isolation of bacteria responsible for benzene degradation in order to allow determination of kinetics and other characteristics is the main focus of this research. The method involves serial dilution of cultures. The first generation of dilutions from different cultures degraded benzene within a few weeks. Subsequent plating of this generation on agar plates resulted in the appearance of white colonies. Polymerase chain reaction (PCR) targeting the 16S rRNA gene, cloning, and sequencing were performed for some of these colonies. The results indicate the presence of *Dechlorosoma* and *Dechloromonas* related species in some of the cultures, indicating that these species may be responsible for degradation of benzene under nitrate-reducing conditions.

Key Words
Aromatic Hydrocarbons
Bioremediation
Denitrification

Remediation of Groundwater with Iron Sulfide and Zero-Valent Iron: Interaction with Calcium Carbonate and Implications for System Longevity

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As water demand increases, provision of clean groundwater, and thus remediation of contaminated groundwater is of paramount importance, both in the United States and worldwide. The efficacy of energy-intensive traditional approaches, such as pump and treat, has been called into question (National Research Council, 1994), and new systems are needed. Permeable Reactive Barriers (PRBs) are a promising approach to the remediation of contaminated groundwater. In a PRB, a contaminated plume flows through emplaced media (traditionally zero-valent iron, ZVI) under a natural hydraulic gradient. The geochemical conditions created by the media result in the degradation or entrapment of the contaminant, allowing clean water to exit the barrier, all without additional energy input or maintenance effort. Currently, iron sulfide (FeS) is being investigated as an alternative reactive medium for use in PRBs for the removal of heavy metals. As a source of sulfide, FeS may sequester heavy metals through sorption or the formation of highly insoluble metal sulfide phases. Indeed, work performed as part of this project has shown that, under anaerobic conditions, the removal of arsenic by FeS is greater than that by ZVI. In the 12 years that PRBs have been installed in the field, they have, with few exceptions, met their stated cleanup goals. There are, nonetheless, outstanding questions about their longevity. In a statistical review of PRB performance performed as part of this project (Henderson and Demond, 2007), it was found that alkalinity, an indicator for potential precipitation of carbonate solids, was correlated to increased risk of PRB failure. For application to the field, therefore, the interaction of the reactive media – either ZVI or FeS – with carbonate is crucial. A combination of experimental and geochemical modeling approaches is being used to investigate permeability loss due to calcium carbonate formation in FeS and ZVI systems. While ZVI columns show accumulation of calcium carbonate and reduction in permeability, initial column tests using FeS-coated sands have not resulted in similar behavior. For example, deoxygenated water at a pH of 5.5, containing 7mM calcium and carbonate, was injected into a column packed with FeS-coated sand. The effluent pH and aqueous calcium concentrations were essentially the same as the influent, suggesting that the buffer capacity of carbonate prevented a pH increase, thus precluding the precipitation of $CaCO_3$(s). Geochemical modeling is also being used to model experimental conditions and investigate a wider suite of natural groundwater conditions. This work will help establish FeS as a suitable reactive media for removal of heavy metals, such as arsenic, from groundwater. Furthermore, understanding of the interaction of porous reactive media and precipitating calcium carbonate will aid in the design of longer-lasting, more sustainable PRB systems.

Reference

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National Research Council. 1994. *Alternatives for Ground Water Cleanup.* Washington, DC: National Academy Press.

Key Words

Groundwater Remediation
Permeable Reactive Barrier
Iron (II) Sulfide
Heavy Metals

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Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Development of a Spectrophotometry-Based Method for Evaluating Disinfection Kinetics

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Disinfection of microorganisms in the drinking water treatment processes is one of the critical steps to eradicate microbial pathogens in drinking water and protect public health. It is important to evaluate the efficacy of a variety of disinfectants against different bacterial pathogens under different conditions in order to develop a versatile disinfection approach for killing pathogens in drinking water. Traditional culture based methods used to determine disinfection kinetics have been used widely and been regarded as a golden standard in the industry. However such methods are labor, material and time intensive. Here we report the development of a spectrophotometer-based method for evaluating the disinfection kinetics of *Escherichia coli* exposed to monochloramine. K (disinfection rates) values of 0.292 mg/L.min (r^2 = 0.8184), if the cells were exposed to higher concentrations of monochloramine (6 mg/L) compared to values of 0.197 mg/L.min (r^2 = 0.9721) when the cells were exposed to lower (1 mg/L) concentrations of monochloramine. Our data suggest that this method is independent of any bias due to the choice of plating medium, the degree of dilution, and the type of filtration used to prepare the *E. coli* cells for growth. Time and material savings are also substantial compared to traditional methods.

Key Words
Disinfection Kinetics
Spectrophotometry
Monochloramine

Comparative Assessment of Waterborne Toxic Impacts on Aquatic Ecosystems and Human Health Using the USEtox Model

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USEtox is a multimedia fate and exposure model developed to consistently compare the environmental impacts of chemicals on human health and ecosystems. Within the SETAC-UNEP (United Nation Environmental Programme) Life Cycle Initiative, an international comparison of six models firstenabled us to identify the crucial fate, exposure and effect issues that made models differ. We then have created a parsimonious (as simple as possible but as complex as needed) and transparent consensus model within a matrix framework, containing only the most influential model elements. Covering more than 2000 substances, USEtox provides human toxicity and aquatic ecotoxicity characterization factors – a comparative measure of the impact per kg emitted substance into (urban) air, freshwater and agricultural soils. The present study applies the model to analyze the major factors affecting both human toxicity and ecotoxicity impacts, with illustrations for key chemicals emitted to water. The fate part relates emission flows to masses in the environment (e.g. transport to water and residence time in water) and is common to both human- and eco-toxoxicity assessment, with typically 5 orders of magnitude variations between chemicals. For human toxicity, exposure factors multiply by fate to yield the intake fraction – the fraction of the emission that is taken in by the human population. Intake fractions typically range from 10-2 for POPs and metals that bioconcentrate in the food chain down to 10-8 for the inhalation of shortly degraded VOCs. Effect measures for both human- and exotoxicity are based on the best estimate of the hazard concentration that generates 50% of response for humans and 50% of species affected or disappeared for ecosystems. As a whole the characterization factors vary by 12 orders of magnitude for human health and 10 for ecotoxicity. A regression analysis shows that for an emission to water, there is a highly significant ($P<0.0001$) but low correlation ($R^2=0.14$) between human- and eco-tox characterization factors, mainly linked to the common fate part of the analysis. USEtox intake fractions are then compared to those calculated using a multi-scale multimedia fate and exposure model that has been developed with high resolution in the Laurentian Great Lakes region. This comparison demonstrates that it is essential to account for both toxic potential (i.e., TEFs) and environmental transport/exposure (i.e., intake fraction) to weight the water emissions of the 29 WHO dioxin-like compounds.

Key Words
Antibiotic Resistance
Human Health

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WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Environmental Fate of Brominated Flame Retardants in Lake Huron and Lake Erie Sediments and Aquatic Organisms

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Brominated flame retardants (BFRs) are used to impart flammability resistance to plastic and foam components utilized in a large number of household products and consumer goods. However, in recent years it has been recognized that BFRs may pose a worldwide pollution problem due to their persistence, long-range transport capability and predisposition to bioaccumulate. BFRs such as polybrominated diphenyl ethers (PBDEs) and polybrominated biphenyls (PBBs) share structural similarities to polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT) and hence are suspected endocrine disruptors. We report results for a Level IV fugacity-based dynamic bioaccumulation model of the fate of hexabrominated biphenyl discharges into the Saginaw Bay region of Lake Huron. PBBs were manufactured at the Pine River facility of the Michigan Chemical Corporation as the active ingredient in the FireMaster flame retardant compound until 1977, when production was halted in the aftermath of a 1973 food chain contamination episode in which FireMaster was inadvisedly used as a calcium supplement in cattle feed at several farms in southeastern Michigan. We present a non-equilibrium multimedia environmental model that predicts transient concentration profiles of hexabromobiphenyl in Lake Huron water and sediment during the 1970s, 1980s and 1990s. The PBB concentrations in the environmental compartments are used as inputs into a food web model for Lake Huron aquabiota, and we compare the predicted bioaccumulation factors from trophic modeling with measurements of PBB concentrations in lake trout during the period 1980-2000. The cumulative effect of PBB in the sediment appeared most significant among the environmental compartments (air, soil, water, and sediment). Sensitivity analysis proved that the contributions of input parameters did not remain constant over time; the sediment half-life became an increasingly more sensitive parameter as time increased. In this dynamic bioaccumulation simulation, both gut absorption efficiency for organic and PBB half-life in the sediment were critical parameters that significantly affected the bioaccumulation in food chains. For the application of the developed model, emission rates of 2,2’,4,4’-tetrabromodiphenyl ether (BDE-47) into Lake Huron and Lake Erie were estimated based on the PBB fate simulation. This study demonstrates that the developed fugacity-based dynamic model may be reliably used to predict the fate of emerging BFR contaminants, such as PBDEs. It also shows that two fugacity-based multi-compartment models can be consecutively combined to solve complicated problems related to the fate of chemicals in different environmental systems.

Key Words
Anaerobic Membrane Bioreactor
Domestic Water

Describing a Chlorinated Phenol-Dependent Antibiotic Resistance Mechanism in the Opportunistic Pathogen *Pseudomonas aeruginosa*: Consequences for the Water/Human Health Interface

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An area of growing interest at the global water/human health intersection is the role of environmental pollutants in the proliferation of bacterial antibiotic resistance. Selective pressure for antibiotic resistant strains is thought to come from widespread use of antibiotics in medicine and agriculture, industrial metal pollution, and from competition within natural microbial communities. Evidence is also emerging for another possible environmental selective pressure: organic chemical contamination. This talk will introduce the conference community to new evidence for an elucidated mechanism that links sublethal concentrations of chlorinated phenols with antibiotic resistance in *Pseudomonas aeruginosa* PAO1, a commonly encountered opportunistic pathogen linked to cystic fibrosis. The consequence of this mechanism in drinking water distribution systems and other environments where chlorinated phenols can proliferate will be discussed. *Pseudomonas aeruginosa* is able to develop multidrug resistance (MDR) rapidly with selective pressure. Previous work by our group has demonstrated that upon exposure to the environmental contaminant pentachlorophenol (PCP), *P. aeruginosa* PAO1 increases expression of multiple multidrug efflux pumps, including the MexAB-OprM pump. More recently, we have shown definitively that PCP and other di- and tri- chlorinated phenols induced MexAB-OprMdependent antibiotic resistance. *mexB* expression analysis showed that PCP induction of *mexABoprM* is reversible upon removal of PCP in batch-grown cultures. Thus, chlorinated phenols have the potential to contribute to the evolution and maintenance of efflux-mediated antibiotic resistance in relevant environmental bacterial strains. The consequences of these findings are important because they contribute to our growing knowledge of mechanisms that contribute to the survival of this pathogen in the environment. Indeed, recent studies examining the diversity of a wide variety of isolates of *P. aeruginosa* found that clinical strains are distributed evenly throughout the environment and should be considered potential pathogens. As we have shown for the first time that chlorinated phenols are among those environmental pollutants that can contribute to the survival of this MDR-prone opportunistic pathogen, it is interesting to ponder the link with drinking water treatment. Interestingly, chlorine-based treatment of drinking water has been linked by Shrivastava et al. (2004) to the emergence of MDR *P. aeruginosa* strains using phenotypic (not genetic) screening methods. Free chlorine is known to react with phenols of natural organic matter and antimicrobials in drinking water to form, among

other by-products, chlorinated phenols. Coupled with the outcomes of our efforts, these studies suggest that the link between chlorinated anthropogenic compounds and the development of MDR bacterial phenotypes in the environment needs to be further evaluated. Chlorination is the most common disinfection process used to treat drinking water in the US, and is increasingly being used in developing countries that are moving toward higher levels of treatment for drinking water. Therefore, it is imperative to determine the specific relevance of a chlorinated, chemical-induced MDR phenotype to the survival of *P. aeruginosa* and other opportunistic pathogens in natural and built environments.

Key Words

Multidrug Efflux Pumps
Chlorophenols
Disinfection By-Products

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Neglected Toxic Metals in the Great Lakes

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What do the following trace elements have in common – vanadium, molybdenum, antimony, bismuth, germanium, palladium, platinum, boron and thallium? They occur in detectable amounts in waters of the Great Lakes and are human toxins but we know little about our exposure to them or their risks to our health. The dissolved concentrations of most of these elements are well above the levels for the “Big Three” metals (cadmium, lead and mercury) and several times higher than the concentrations of many organic pesticides in the Great Lakes. Each element fits the US EPA’s definition of persistent, bioaccumulative and toxic and some are biomagnified in the aquatic food chain. The goal of the presentation will be to briefly review the information available on these neglected elements in the Great Lakes, and to raise awareness about the potential hazards associated with cumulative exposure to these toxic metals in our drinking water. With recent advancements in our ability to quantify these metals in water samples, it would seem prudent to re-assess the risks associated with exposure to these metals that have so far been confined to the “non-detect” waste basket. The heightened need for paying more attention to these neglected metals comes from the fact that some of their compounds can disrupt the endocrine function.

Key Words
Toxic Metals
Endocrine Disruption
Persistence

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WATER
Health + the Environment:
Establishing the Research Agenda
March 26–27, 2008

Arsenic Uptake and Release on Sulfide Nanoparticles

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Descriptions of molecular-level processes that control the uptake and release of As on sulfide nanoparticle surfaces were obtained from microbeam, spectroscopic, and quantum mechanical modeling techniques. The precipitation of As-sulfide phases on nanoparticulate mackinawite (FeS) is identified as a possible mechanism for As(III) immobilization under anoxic conditions (Gallegos et al. 2007). A major challenge in identifying As-sulfide growth phases is their nanoscale dimensions. High-angle annular dark field scanning-TEM and energy-dispersive X-ray spectrometry were used to identify amorphous AsS phases precipitating on FeS nanoparticles after As(III) adsorption at pH 5. The oxidation state of As in the surface As-sulfide precipitates was determined to be “realgar-like” from X-ray photoelectron spectroscopy results showing an As 3d binding energy of 43.0 eV. The reverse process, the oxidative dissolution of realgar (As_4S_4) and orpiment (As_2S_3) nanoparticles, is a mechanism by which As is released back into natural waters. *Ab initio* quantum mechanical methods were employed to describe indirect electronic perturbations (proximity effects) between surface adsorbates on As_4S_4 nanoclusters. Proximity effects between O and $(OH)^-$ ion adsorbed on a single As_4S_4 cluster were determined to be on the order of 1 eV, depending on the O-$(OH)^-$ distance. Calculations also show that adsorption of $(OH)^-$ to As_4S_4 could affect the adsorption energy of O to a neighboring As_4S_4 separated from the former by a van der Waals gap (as is the case in As_4S_4 molecular crystals). The findings suggest that As_4S_4 is more susceptible to oxidative attack with the co-adsorption of $(OH)^-$ ions. The results of this study can be used to improve adsorption isotherms and surface complexation models that describe the factors that control As concentrations in natural waters.

Key Words
Arsenic
Mackinawite
Realgar
Iron Sulfides

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Fate Factors and Emission Flux Estimates for Emerging Contaminants in Surface Water

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Pharmaceuticals, personal care products, hormones, and wastewater products are identified as emerging environmental concerns because of their potential for endocrine disruption at a very low chronic exposure level. The environmental occurrences and sources of these emerging contaminants in water, soil, sediment and biota in European nations and the United States are well-documented. This work reports a screening-level emission and fate assessment of thirty compounds, listed in the National Reconnaissance of the United States Geological Survey (USGS, 1999-2000) as the most frequently detected organic wastewater contaminants in U.S. streams and rivers. Estimations of the surface water fate factors were based on Level II and Level III multimedia fugacity models for a 1000 km^2 model environment, the size of a typical county in the eastern United States. The compounds are categorized into three groups based upon the sensitivity of their predicted surface water fate factors to uncertainties in their physicochemical property values and the landscape parameters. The environmental fate factors, mass distributions, and loss pathways of all of the compounds are strongly affected by their mode of entry into the environment. The surface water fate factors predicted by the fugacity models were used in conjunction with the surface water concentrations measured in the USGS reconnaissance to obtain emission flux estimates for the compounds into U.S. streams and rivers. It is observed that thirteen out of the thirty compounds are highly soluble and mobile, resisting to partition into the air or to the organic rich media. Therefore, treatment methods other than air stripping or carbon-based adsorption would necessary have to be devised for an effective removal of these contaminants from wastewater effluents.

Key Words
Emerging Contaminants
Fate and Transport Modeling

Microbial Community Analysis of Biofilms in Drinking Water Distribution Systems

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The survival of microbial pathogens in tap water is a significant public health risk, particularly for individuals with weakened immune systems. Research indicates that the presence of opportunistic pathogens in biofilms in drinking water distribution system (DWDS) increases their resistance to disinfection. While some resistance mechanisms have been proposed including the protective effects of biofilms, there remains an inadequate understanding of the DWDS biofilm environment. Therefore, characterizing these biofilms would be useful in designing innovative and effective control strategies to maintain the safety and quality of drinking water in the DWDS. Biofilm samples were obtained from two different distribution pipes from the City of Ann Arbor's DWDS. DNA was extracted from biofilm samples and the 16S rRNA gene was amplified using the polymerase chain reaction (PCR) with general bacterial and eukaryal primers. Amplified PCR products will be cloned and sequenced. Bacterial and eukaryal clone libraries will be constructed to perform a detailed phylogenetic analysis. Specific target populations will be visualized via fluorescence *in situ* hybridization (FISH). In particular, we will use FISH to determine if some bacterial pathogens can persist in DWDS by surviving within amoeba. The knowledge gained through this work has the potential to ultimately help form new drinking water treatment strategies by improving the understanding of the microbial ecology of the DWDS.

Key Words
Water Quality
Public Health
Biofilm

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Effects of Culture Conditions on Mixed Species Biofilm Development

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Biofilms in drinking water distribution systems (DWDSs) are mixed-species consortia and may harbor microbial pathogens, a significant concern to public health. Understanding the development of mixed-species biofilms is likely to improve our understanding of the mechanisms contributing to bacterial pathogen persistence in DWDSs. Two commonly used strains, *Escherichia coli* K-12 and *Pseudomonas aeruginosa,* were chosen to study the dual-species biofilm development. We compared single- and dual-species biofilm formation in different culture conditions, static growth with minimal media in a Petri dish and dynamic growth with continuous fresh media in a flow cell. Microscopy revealed distinct biofilms in both systems. In Petri dishes, mixed species biofilms were composed primarily of single attached cells interspersed with microcolonies, in comparison to the uniform and thick layers of pure *E. coli* biofilms. In the flow cell system, stable dual-species biofilms were formed and occupied all available surfaces, while at the same time only a few aggregates were observed near the edge of the flow cell in pure *E. coli* system. This suggests that culture conditions affect species interaction and thus mixed-species biofilm formation. Our results showed that the presence of *P. aeruginosa* promoted biofilm formation in dynamic growth mode but retreated in static culture.

Key Words
Biofilms
Mixed Species
Bacterial Interaction

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Profile of Antibiotic Resistance of *Acinetobacter* spp. and Antibiotic Resistant Genes in the Wastewater Treatment Process and Its Receiving Water

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The occurrence and spread of multi-drug resistant bacteria is currently the world's most pressing public health problems. The emergence of bacterial resistance to antibiotics is quite common in areas where antibiotics are heavily used, but antibiotic-resistant bacteria also increasingly occur in aquatic environments. The purpose of this study was to evaluate the impact of the wastewater treatment process on the prevalence of antibiotic resistant bacteria and antibiotic resistant genes (ARG) in the water cycle. *Acinetobacter* spp., ubiquitous in the natural environments, were isolated from water samples and used as the environmental bacterial indicators for the antibiotic susceptibility test. Real-time PCR assay was used to quantify antibiotic resistant genes in the water cycle. During two different events (high-temperature, 31℃; and low-temperature, 8℃), 366 strains of *Acinetobacter* spp. were isolated from five different sites, including three sites in a wastewater treatment plant (raw influent, second effluent, and final effluent) and two sites in the receiving body (upstream and downstream of the treated wastewater discharge point). The antibiotic susceptibility phenotypes were determined by the disc-diffusion method for the antibiotics amoxicillin/calvulanic acid (AMC), chloramphenicol (CHL), ciprofloxacin (CIP), colistin (CL), gentamicin (GM), rifampin (RA), sulfisoxazole (SU), and trimethoprim (TMP). In addition, antibiotic resistant genes, including two sulfonamide resistant genes (*Sul I* and *Sul II*) and two tetracycline resistant genes (*tet O* and *tet W*), were quantified using quantitative real-time polymerase chain reaction (Q-PCR) assay. The prevalence of antibiotic resistance of *Acinetobacter* isolates to AMC, CHL, RA, and multi-drug (three antibiotics or more) significantly increased from the raw influent samples (AMC, 8.7%; CHL, 25.2%; RA, 63.1%; multi-drug, 33.0%) to the final effluent samples (AMC,37.9%; CHL, 62.1%; RA, 84.5%; multi-drug, 67.2%), and was significantly higher in the downstream samples (AMC, 25.8%; CHL, 48.4%; RA, 85.5%; multi-drug, 56.5%) compared to that in the upstream samples(AMC, 9.5%; CHL, 27.0%; RA, 65.1%; multi-drug, 28.6%). In total DNA extracted from those water samples, the quantities of four ARGs were higher in the downstream samples than in the upstream samples, respectively, whereas they showed different patterns in the wastewater samples. These results suggest that wastewater treatment process contributes to the occurrence of multi-drug resistant bacteria and to the spread of antibiotic resistant genes in the water environment.

Graham Environmental Sustainability Institute
WATER
Health + the Environment:
Establishing the Research Agenda
March 26-27, 2008

Survival Mechanisms of Bacterial Pathogens in Biofilms in Drinking Water Distribution System

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Microorganisms are present in the bulk water and in biofilms in drinking water distribution systems despite the presence of disinfectant residual. Biofilms, in particular, are responsible for a range of water quality problems, including increased bacteria levels, taste and odor problems, and red or black water. Biofilms also cause distribution system operational problems, such as loss of disinfectant residuals, reduced dissolved oxygen, microbially induced corrosion and break of pipes, hydraulic roughness, and speeded aging of pipe materials. In addition, biofilms may harbor opportunistic pathogens, which is a significant concern to public health. A collaborative project, directed by Drs. Raskin and Xi, focuses on the elucidation of molecular mechanisms of persistence of bacterial pathogens in drinking water distribution systems using genomic tools. In this project, we are studying (1) the microbial ecology and development of biofilms in drinking water distribution systems; (2) disinfection of bacterial pathogens in biofilms; and (3) interactions of bacterial pathogens with mixed species bacterial biofilms and eukaryotic organisms in these biofilms. We have developed and applied several methods including flow cytometry, DNA microarray technology, engineered bioreactors, advanced imaging tools, and molecular techniques to identify and characterize specific genes in pathogens that are involved in resistance to disinfectants and in interactions and adaptation in biofilms in drinking water distributions. In this presentation, we will present an overview of the data acquired and present several survival strategies used by bacterial pathogens in drinking water distribution systems. This research project primarily contributes to two GESI focal areas: "Sustainable Infrastructure, Built Environment, and Manufacturing" and "Human Health and Environment".

Key Words
Biofilms
Drinking Water
DNA Microarray

Effects of Phosphorus Addition on Microbial Communities in Biologically Active Carbon Reactors

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We investigated the effects of phosphorus addition on the structure and function of microbial communities in a bench-scale and two pilot-scale biologically active carbon (BAC) reactors, which were operated to remove perchlorate and nitrate from groundwater. The structure of the microbial community in the bench-scale system was studied using 16S ribosomal RNA gene targeted clone library analysis and quantitative polymerase chain reaction (PCR). Their function was evaluated by monitoring reactor performance. Clone library results indicated *Dechloromonas* species were the only perchlorate reducing bacteria (PRB) in the system. This group can also use nitrate as an electron acceptor. Quantiative PCR results showed that the addition of phosphorus to the bench-scale BAC reactor significantly increased the relative abundance of *Dechloromonas* species. In addition, it was found that effluent perchlorate and nitrate concentrations decreased after the addition of phosphorus. The combination of these results suggests that PRB were phosphorus limited before the addition of phosphorus to the influent. Addition of phosphorus to the two pilot-scale BAC reactors resulted in a similar improvement in reactor performance. Microbial community analyses will be performed for the pilot-scale systems and similar changes in microbial population dynamics in these reactors are expected.

Key Words
Biologically Active Carbon
Dechloromonas
Phosphorus
Perchlorate

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