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limu was constrained to not fall below a specified level. When a stock constraint is imposed, the optimal paths of water extraction, aquifer-head level, and price for water are non-monotonic. In other words, extraction, head, and price increase and then decrease over time or vice versa. The aquifer is optimally depleted below its long-run equilibrium steady-state level initially and is then built back up to the steady-state level in the period that follows. This contrasts with conventional management according to maximum sustainable yield. While the alternative backstop technology (desalination of seawater), is never required in the market value scenario (due to the assumption of a stationary demand function), it is implemented for all stock constraints that meet or exceed 75% of the current stock. Maintaining a tight stock constraint requires substantial water conservation which could be implemented by higher consumer prices at the margin.

The growth function of the stock of limu is difficult to estimate in situations where the stock is small relative to its size without predators. Thus in the third approach we imposed a constraint on the intrinsic growth rate, which can be alternatively stated as a constraint on the groundwater discharge level. Limu growth is a function of submarine groundwater discharge entering the nearshore marine environment due to its nutrient-augmentation and salinity dilution effects. Inasmuch as discharge is associated with a particular aquifer head level, the growth rate constraint is ultimately imposed as a head-level constraint. For head constraints that represent a reasonable range of growth rates given the ocean salinity at the study site (1.8%-2%), the optimal approach paths for head, pumping, and price over time are either strictly increasing or decreasing. The head level rises over time in all scenarios as the optimal rate of extraction declines over time. With the growth constraints, desalination is never used. Again, the stricter the constraint, the more water conservation is required.

Krulce, D.L., J.A. Roumasset, and T. Wilson. 1997. "Optimal management of a renewable and replaceable resource: The case of coastal groundwater," *American Journal of Agricultural Economics*, 79:1218–1228.

Water Resources Research Center
University of Hawaii at Manoa
July 2009 Bulletin

Assessing Concentrations and Potential Public Health Significance of Four Human Pathogenic Marine *Vibrio* spp. in Hawaiian Coastal Water Environments

Dr. Roger Fujioka, WRRC Researcher, University of Hawaii at Manoa, Principal Investigator.

Introduction:

Vibrios are naturally occurring bacteria indigenous to marine and estuarine waters. Of the 65 known species of these bacteria, several are pathogenic to both marine animals and humans. Depending on the species involved and the nature of the exposure, infection can be asymptomatic, cause mild to severe gastroenteritis, or result in septicemia (blood infection) or wound and soft tissue infection. A total of twelve different *Vibrio* spp. are known to be pathogenic to man, but the following four species account for most of the human infections.

1. *V. vulnificus*: contracted primarily by ingestion of marine food or contact with marine waters resulting in gastroenteritis, and wound infections, often leading to septicemia and death.
2. *V. cholerae*: contracted primarily by ingestion of contaminated water, resulting in gastroenteritis, often leading to death.
3. *V. parahaemolyticus*: contracted primarily by ingestion of contaminated marine foods, often leading to gastroenteritis.
4. *V. alginolyticus*: contracted primarily by contact with marine waters, leading to skin and ear infections.

All four of these pathogenic *Vibrio* spp. have been documented to cause human infections in Hawaii. *V. vulnificus* infections have recently resulted in two deaths related to exposure to coastal waters. One death occurred on the Big Island and a second death occurred on Oahu. *V. cholerae* infections have also been documented in Hawaii, though the source of these infections has not been determined. Infections of *V. parahaemolyticus* and *V. alginolyticus* have also been reported in Hawaii.

No approved methods exist for the recovery of human pathogenic *Vibrio* bacteria from environmental waters, thus the risk of aquiring Vibrio infections from contact with these waters has never been determined. Therefore water quality standards, which may help predict the presence of potentially pathogenic *Vibrio* spp., have not been established.

Project Goals and Experimental Approach:

The goal of this study is to determine the prevalence of these four human pathogenic *Vibrio* spp. in four categories of coastal water environments in Hawaii, and to determine the relative risk that these pathogens may pose to people who use these coastal waters for recreational purposes.

Gayatri Vithanage, a graduate research assistant at WRRC and Ph.D. candidate in Microbiology is conducting this study as part of her dissertation research. The experimental design of her study is to determine the prevalence of human pathogenic *Vibrio* spp. in the following four categories of coastal waters:


Gayatri Vithanage

1) Primary swimming sites on Oahu. This category includes popular beach sites which have been designated for public swimming. The waters at these sites are characterized by active ocean water circulation and desirable water quality including low turbidity and high salinity (32-36ppt). [Figure 1 - pg. 3, sites A1-A20, blue dots].
2) Secondary swimming sites on Oahu. This category of waters includes sites designated for public swimming but considered secondary sites because water quality is compromised by nearby land-based discharges - streams or storm drains. The waters at these sites are characterized by moderate ocean water circulation and some undesirable water quality parameters such as increased turbidity and low

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WRRC Researcher Clark Liu Named 2009 Engineer of Distinction by the University of Mississippi*

WRRC's Dr. Clark Liu was recently honored by his alma mater, the University of Mississippi. Liu was named the 2009 Engineer of Distinction, joining the ranks of ExxonMobil executives and NASA chiefs. The title is bestowed annually on a truly exceptional engineer associated with the University of Mississippi School of Engineering. Dr. Liu graduated with a master's degree from "Ole Miss" in 1969.

A graduate of National Taiwan University, Liu arrived at Ole Miss in 1967 in response to an offer from Sam DeLeeuw, retired chair and professor of the Department of Civil Engineering. After earning his degree Liu went to work for the New York State Division of Water Resources until 1973, when he entered Cornell University for Ph.D. study. He completed his doctorate there in 1979.

Dr. Liu conducting an hydraulic experiment at the USDA National Sedimentation Lab in Oxford, Miss. in the Summer of 1968.

He joined the University of Hawaii faculty in 1980 and started work as a P.I. for WRRC in that year. Liu was promoted to full professor at UH in 1989. He has been on the WRRC faculty since 2002. For 29 years Liu has served as the principal investigator of more than ten research projects sponsored by the U.S. Environmental Protection Agency, U.S. Geological Survey, NSF, USBR and other agencies. In all, his research efforts have yielded more than 70 scientific publications.

In recent years Liu has completed two federally sponsored research projects: an NSF project to develop an engineering system for open ocean mariculture using nutrient-rich deep ocean water and a U.S. Bureau of Reclamation project to develop a wind-powered reverse-osmosis system for water desalination and treatment.

Dr. Clark Liu receiving his award last April in Mississippi

Since January of 2008 Liu has been working at the National Science Foundation headquarters in Washington where he's been serving as the environmental engineering program director. He is due to return to Hawaii this summer.

The award ceremony was held in Mississippi in April. "I was very excited by the news of being selected to receive the Engineer of Distinction award," Liu said. "It is not only a great honor for me but also presents an opportunity for me to revisit a place that has been so important to my personal and professional development."

"An expert in environmental fluid mechanics, Liu's research has earned him the appointment in the nation's most prestigious science and engineering research funding organization," said Alex Cheng, chair and professor of civil engineering at Ole Miss. "The University of Mississippi School of Engineering proudly recognizes him for his career achievements and scholarship."

He is a fellow of the American Society of Civil Engineers and a member of the Chinese Lutheran Church of Honolulu. Liu and his wife, Diane, are the parents of three children and have three grandchildren.

We congratulate Dr. Liu on the occasion of his recognition by the University of Mississippi School of Engineering.

*With thanks to *Ole Miss Engineer* Vol. 49 No. 1 Spring 2009

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This newsletter is financed in part by the U.S. Department of the Interior, Geological Survey, through the Hawaii Water Center. The contents of this publication do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the U.S. Government.

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calculated [(final tip score – initial tip score) / initial tip score] / sixteen days.

Principal Findings and Significance

Native algae growth and nutrients:

In order to simulate submarine groundwater discharge in a controlled environment, we ran trials with four levels of salinity (11%, 19%, 27%, and 35%) and corresponding levels of other nutrients, the proportional relationship of which others have estimated for the North Kona Coast of the Big Island of Hawaii. The mean growth rate, percentage change in apical-tip number, and apical-tip number/mass were calculated for each level of salinity. Only the 11% treatment differed significantly in both mean specific growth rate (lower than the others) and in vivo pigment absorption (higher than the others). Nearly half of the samples in the 11% treatment group died rapidly while the other half grew at rates similar to the other treatment groups. Therefore it is likely that the lower salinity concentration threshold for the viability of *G. coronopifolia* is close to 11%.

Significant results were obtained for both measures of tip development. The 27% salinity-level treatment showed at least twice the branching rate of any of the other treatments. Since most growth of marine algae occurs at the apical tips, it is clear that those samples with more tips per mass will have higher growth rates.

In the botanical experiment, maximal *G. coronopifolia* growth rate increased with increasing salinity, within the 11%–27% range. Within the 27%–35% salinity range, however, the maximal growth rate actually decreased with increasing salinity from 3% per day for the 27% treatment to 1% per day for the 35% treatment (ocean salinity), i.e. the growth rate declined by about 67%.

This study demonstrated that the calculation of tip scores and the percent of new apical tips are valid and useful methods for quantifying changes in morphology of marine algae. Water chemistry conditions which simulate moderate amounts of freshwater discharge maximize the growth rate of *G. coronopifolia* when compared to ambient ocean-water controls.

Bio-hydro-economic model results

We used data from the Kukio area located along the North Kona Coast of the island of Hawaii to numerically solve for the optimal groundwater-management program. The *G. coronopifolia* growth curve estimated in the lab likely overstates the true intrinsic growth rate, inasmuch as the controlled experiments do not simulate fish herbivory, competition with invasive algae or other plant species, and human harvesting. The bio-hydro-economic analysis takes these factors into account by adjusting the growth rate downward and explicitly including harvest as a subcomponent of the model.

Upon establishing a functional relationship between *G. coronopifolia* growth and submarine groundwater discharge, we were then able to proceed with numerical simulations of the model. In the first of three approaches, we used the actual market value of *G. coronopifolia* and found that optimal water extraction is less than extraction when *G. coronopifolia* is ignored, although the difference is slight. This is likely due to the fact that the value of *G. coronopifolia* is small relative to the value of water. Market value accounts for only the consumptive value and ignores other potentially significant cultural and ecological values.

We addressed cultural and ecological value by imposing a safe-minimum standard on the *G. coronopifolia* stock in the second approach, i.e. the stock of

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Former Outfall Project Researcher Awarded PhD

The Water Center extends congratulations to Brendan (Chip) Barrett, a long-time researcher and research assistant on the ongoing WRRC Ocean Outfall Biomonitoring project. Barett has recently been granted a PhD from the National University of Ireland in Galway, and had his thesis *"A survey of the deep-sea polychaetous annelids of the Porcupine Bank and adjacent areas to the west of Ireland, with particular focus on the phylogeny and taxonomy of the Family Amphinomidae Lamarck, 1818 and Genus Paramphinome M. Sars in G. O. Sars, 1872"* accepted by his committee.

While at WRRC Barett honed his taxonomic skills identifying benthic invertebrates in samples of sediment taken from around the City of Honolulu's ocean wastewater outfalls. This identification work has been carried out at the Center for over 20 years, and has provided valuable training, experience and support for many Zoology students at the University of Hawaii. Many of these alumni have gone on to distinguish themselves in subsequent academic endeavors and research careers.

2009 L. Stephen Lau Scholarship Awarded to Krishna Lamichhane

Krishna Lamichhane is the winner of the 2009 L. Stephen Lau Scholarship. Krishna is a PhD student in Engineering at UH Manoa working with Dr. Roger Babcock.

WRRC's former (1971–1990) director Dr. L. Stephen Lau and his wife Virginia Lau generously established the Scholarship Fund in 2004 to advance the cause of water education at the University of Hawaii. Dr. Lau has been a leader in water research in Hawai'i for many years. He continues to serve as an emeritus professor of Civil Engineering at the University of Hawaii


L to R: Ronald Lau, Mrs. Lau, Dr. L. Stephen Lau, Jim Moncur, Roger Fujioka, Philip Moravcik, Krishna Lamichhane

Lamichhane's work at WRRC involves an investigation into the design of household wastewater systems that save water, recycle nutrients and reduce water pollution. Central to the design is a point of use mechanism to separate liquid and solid human waste at the source. Such systems hold out the promise of reducing water pollution and preserving valuable nutrients in places where the usual wastewater treatment plants are economically and technically unfeasible. Conventional treatment plants, as are widely in use, fail to remove hormonal compounds - predominantly found in urine. These compounds pose a threat to human and animal health. Separation of the waste would permit advanced treatment of the liquid portion to remove these compounds.

Current WRRC Director Dr. James Moncur invited Krishna, Dr. and Mrs. Lau and their son Ronald, and a few others to a celebratory luncheon at the Kirin Restaurant in May.

A Decision Support Tool for Managing the Pipe Network of the Honolulu Board of Water Supply

Dr. Amarjit Singh, Associate Professor, Civil and Environmental Engineering and Dr. Chittaranjan Ray, Professor, Civil and Environmental Engineering, University of Hawaii at Manoa

America's water and wastewater systems face unprecedented financial problems because of aging infrastructure, deferred maintenance, and unsustainable rate structures. According to the Water Infrastructure Network (WIN, 2008) America's water and wastewater systems will have to invest $23 billion a year more than is currently spent over the next 20 years, to meet the national environmental and public health priorities in the Clean Water Act and Safe Drinking Water Act and to replace aging and failing infrastructure.

The USEPA's 2002 Gap Analysis Report also points out the need to invest between $331 billion and $450 billion in capital between 2000 and 2019 for the wastewater sector. Similarly, between $154 billion and $446 billion in capital spending is needed for the drinking water sector during the same period (USEPA, 2002). The operation and maintenance (O&M) needs are also high. For any investment, the utility agencies are advised by the General Accounting Office (GAO, 2004) and the Environmental Protection Agency to develop comprehensive asset management plans for the repair, replacement, and upgradation of infrastructure, which will enable them to make appropriate rate adjustments over the life cycle to keep service levels adequate.

It is common for water utilities to defer maintenance because the unpopular rate hikes that would be needed to fund this are often suppressed by city councils or boards that govern them. As a result, cities do not build funds for emergency replacement of pipes or other assets. An example is the deferred replacement and maintenance of sewer pipes in the City of Honolulu. This was blamed for a 48 million gallon sewage spill that occurred in the spring of 2006 when sustained heavy rains fell on the city. Finally, EPA forced the city to take action on pipeline replacement under the threat of severe fines.

Similarly many of the pipes in the Honolulu Board of Water Supply (BWS) network are near the end of their useable lifespan. The corrosive soils and saline environments found on Oahu cause excessive corrosion of cast iron pipes. As a result, the BWS experiences many pipe breaks. Broken mains often lead to flooding damage to nearby houses that the BWS's insurer must pay for. In addition, breaks

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Decision Support Tool, continued from page 4...

cause holes in the ground, often on roadways, adversely affecting traffic flow during repair.

While increased investment in new capital projects and O&M would help utility agencies comply with federal regulations and improve reliability and service levels, funds are limited. As a result, agencies must prioritize spending among many competing needs and develop asset management plans to help them identify needs and plan future investments wisely. Currently BWS manages a network of 2,000 miles of 4-inch and larger diameter pipes. Under budgetary restrictions, the BWS needs to prioritize which pipe sections must be replaced so that it meets the requirements of the Safe Drinking Water Act (SDWA) and provides a high level of service to its customers.

Improved prioritization of pipeline replacement will help the BWS allocate its resources effectively for maximum benefit. It will help them not only to meet the goals of the SDWA, but to consistently provide water of high quality without disruption of supply or the necessity of issuing boil orders in areas affected by pipeline ruptures. Disruption of traffic will be reduced. Thus, a decision tool that utilizes existing burst information and other factors that affect pipe failure will help the BWS to optimize O&M spending.

Nature of this project: The principles of "Asset Management" have been traditionally used in the finance and investment sector where securities and real estate are managed to meet specific investment goals. The same principles can be applied to water supply utilities where new investments can be evaluated in terms of returns in meeting health and wellbeing goals for customers, and the achievement of a high level of customer satisfaction. The GAO wants all water utilities that receive federal funds to develop asset management models to guide them in their investments.

Managing asset investment for utilities is not easy, as there are competing goals. For example, if a water utility receives funds for capital improvement, it must decide whether to spend that money on pipeline replacement, pump station replacement, replacement of housing for pumping infrastructure, roads for vehicular access, etc. If money has to be spent on more than one of these, what amount should go to each of those capital projects? The utility must decide how to prioritize expenditure within each category such as pipeline replacement or rehabilitation. For example in pipeline replacement, it must be decided which part of the city should be done first and what the diameter and length of the pipes to be replaced in year 1, year 2, and subsequent years should be.

Scope: The scope of this project is to work with BWS in examining their in-house decision tool currently used for strategizing pipeline replacement, and to improve it based on the most recently available information. Further we will examine decision tools used by selected water utilities elsewhere in the country and abroad, and gather other information that can be easily obtained in the form of Geographic Information System (GIS), databases, and mathematical models.

Pipeline replacement strategies that are reactive versus proactive will be examined. For example, failures that have low probability but severe consequences and failures that are of high probability and minor consequence will be assessed in terms of risk. Statistical quality control principles will be applied and linear programming techniques will be explored.

Research Objectives: The research is for a period of one year. Tasks that will be undertaken include:

(a) Review current decision tools used by the BWS for the replacement of pipelines,

(b) Collect historical records of pipe breaks and other details such as pipe age, diameter, and material, system pressure at the break point, and other details that are readily available from BWS files,

(c) Collect other relevant information such as soil properties - resistivity, pH, organic carbon, water holding capacity, and hydraulic conductivity; and depth of burial of the pipes, and pipe coupons for further analysis of data,

(d) Prepare a decision tool that will provide probability of failure versus consequences of failure for various sections of pipes in the BWS network and look into the feasibility of using other software for managing annual pipeline replacement,

(e) Present a decision tool that will determine for BWS the number of miles of main that should be replaced in a given year.

WIN, 2008. Water Infrastructure Now: Recommendations for Clean and Safe Water in the 21st Century, http://www.win-water.org/reports/winow.pdf. Water Infrastructure Network.

GAO, 2004. Water Infrastructure: Comprehensive Asset Management Has Potential to Help Utilities Better Identify Needs and Plan Future Investments. Report to the Ranking Minority Member, Committee on Environment and Public Works, U.S. Senate, Washington, D.C., p. 62.

USEPA, 2002. The Clean Water and Drinking Water Infrastructure Gap Analysis. US Environmental Protection Agency, Washington, D.C., p. 50.

Project Report: Coastal Groundwater Management in the Presence of Positive Stock Externalities

Dr. James Roumasset, Professor of Economics and WRRC Researcher, University of Hawaii at Manoa

Problem and Research Objectives

The nearshore marine environment of Hawaii is a major recreational and ecological resource that supports indigenous fish and marine vegetation. Freshwater discharge from groundwater aquifers mixes with seawater along the coast to create an ecological system with lower salinity than that of ocean water. Onshore extraction of freshwater affects the salinity of the nearshore ecosystem since lower aquifer-head levels result in reduced freshwater discharge into the ocean. The state of the aquifer is thus directly linked to the cultural, recreational, and economic values of the community.

The objective of this research is to determine the optimal management scheme for groundwater resources in Hawaii - taking into consideration both the benefits of water consumption and the environmental consequences of freshwater extraction.

Understanding the environmental consequences of freshwater extraction requires an assessment of the linkages between submarine groundwater discharge and the nearshore ecosystem. Native marine algae, identified by the Hawaiian word *limu,* play an important role as primary producers in the food web of endemic and other organisms. Algae can therefore serve as appropriate indicators of the surrounding environment's overall health.

To gain a better understanding of how groundwater discharge affects the nearshore marine environment we monitored, in a controlled laboratory environment, the physiological response of a selected species of *limu* to varied levels of salinity and nutrients. We chose the edible endemic species of marine algae *Gracilaria coronopifolia* for our study.

Methodology

Our research agenda is inter-disciplinary and it involves two sub-programs. The first uses a bio-hydro-economic model to solve for optimal levels of groundwater use and *G. coronopifolia* production. The second is a laboratory study of the relationship between salinity, nutrients and the biological productivity of *G. coronopifolia.*

Bio-hydro-economic Model

The model used is an application of optimal control theory and follows the framework laid out in Krulce, Roumasset, and Wilson's (1997) study of the Pearl Harbor aquifer. The objective is to choose the paths of groundwater extraction and desalinated-water production over time to maximize the present value of net social surplus from water. For this purpose social surplus includes both traditional water-use benefits as well as external benefits (or costs) of freshwater extraction on the nearshore ecosystem. Our particular study focuses on *G. coronopifolia* as the nearshore resource affected by submarine groundwater discharge but the model is general and can therefore be applied to any other nearshore resource.

Gracilaria coronopifolia, (Limu manauea) the edible Hawaiian seaweed used in this study

G. coronopifolia was chosen for this investigation in order to assess the impact of varied levels of submarine groundwater discharge on the nearshore environment. The physiological parameters we measured include growth rate, branch development, and in vivo pigment absorption. Growth rate was measured as changes in wet-tissue mass over time and branch development was measured by quantifying the rate at which new growing tips were formed in reference to the initial tips and initial mass. To accurately measure these physiological responses to isolated variables a digital growth chamber was modified to support a unidirectional flow-through saltwater system.

In order to quantify changes in wet weight and morphology, three variables were calculated. The specific growth rate was calculated [(final wet mass – initial wet mass) / initial wet mass] / sixteen days. The percent change in apical-tip number relative to initial-tip number was calculated in a similar manner: 100*[(final apical-tip number – initial apical-tip number) / initial apical-tip number] / sixteen days. In order to quantify the number of apical tips in reference to initial weight, apical-tip number / mass was calculated as the tip score. The change in tip score was then

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to variable salinity (3-30ppt). [Figure 1, sites B1-B26, green dots].

3) Sites on Oahu not designated for swimming; this category of waters includes harbors, canals and other inland waterways, which have poor ocean water circulation and receive discharges from multiple land-based sources. Though these waters are not designated for swimming, individuals who engage in other recreational activities (fishing, boating) may come into contact with them. The water quality at these sites is classified as poor and unfit for swimming because of high turbidity, high fecal bacterial concentrations and low to variable salinity [Figure 1, sites C1-C11, D1-D3, E1-E3].

4) Sites on the Island of Hawaii which receive groundwater discharge [Figure 2]. These sites generally have poor ocean water circulation and variable salinity. The geology of Hawaii, the youngest of the Hawaiian islands, features highly porous lava rock which permits rapid and direct movement of groundwater. Evidence of *V. vulnificus* transmission has been found at some of these sites.

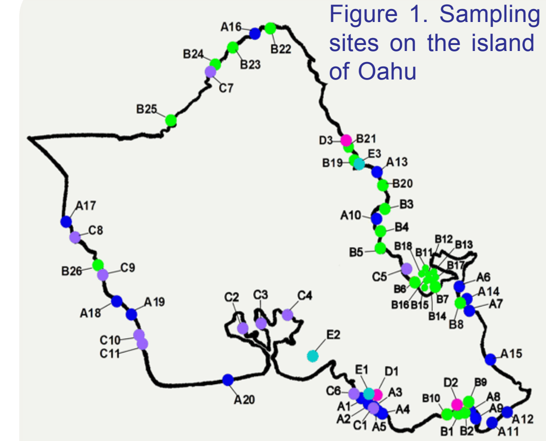

Figure 1. Sampling sites on the island of Oahu

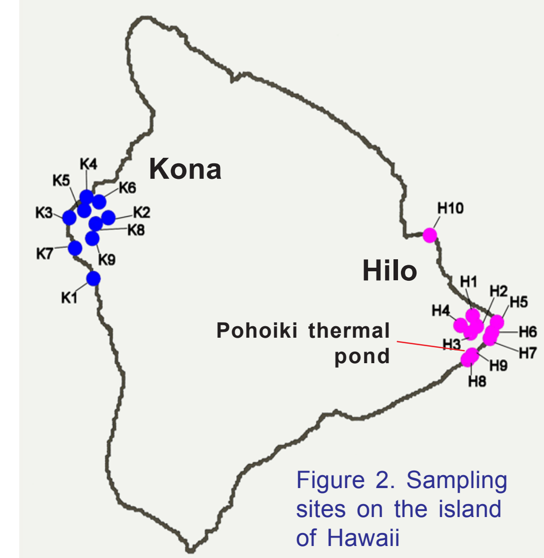

Figure 2. Sampling sites on the island of Hawaii

Pohoiki thermal pond on the Big Island, where *V. vulnificus* caused a fatal infection in a swimmer.

Based on previous studies done at WRRC and elsewhere, the three most feasible and reliable culture methods to recover and enumerate the four pathogenic Vibrio spp. are TCBS (thiosulfate-citrate-bile salts-sucrose) media, CPC (cellobiose-polymyxin B-colistin) media, and CHROMagar Vibrio media. These three media are being used in the present study. In addition to the microbial testing, water samples will be assayed for salinity, conductivity, pH, turbidity and a nutrient marker such as total organic carbon or phosphorus. Biochemical assays and molecular methods will be used to confirm the identity of the isolated *Vibrio* spp.

Preliminary Findings:

Significant differences have been found in the prevalence of pathogenic *Vibrio* spp. in the four different water categories.

A summary of our results to date:

1. Primary swimming beaches (Oahu) had a predominance (100% of sites) of *V. alginolyticus* while *V. vulnificus* and *V. parahaemolyticus* were not recovered.

2. Secondary swimming waters (Oahu) showed a predominance (100% of sites) of *V. alginolyticus*, and moderate recovery of *V. vulnificus* (33% of sites) and *V. parahaemolyticus* (33% of sites).

3. Non-designated swimming waters (Oahu) had a predominance of *V. alginolyticus* (100% of sites), a moderate recovery rate of *V. vulnificus* (33% of sites) and a moderate-to-high recovery rate of *V. parahaemolyticus* (67% of sites).

4. Water samples obtained from the Island of Hawaii had a predominance (89% of sites in Kona, 100% of sites in Hilo) of *V. alginolyticus*, moderate recovery rates of *V. vulnificus* (22% Kona, 50% Hilo) and moderate to high recovery rates of *V. parahaemolyticus* (22% Kona, 60% Hilo).

5. *V. cholerae* was not detected at any of the sampling sites